The effect of water repellence on plant emergence and manganese uptake and growth of lupins in a dry soil

by William Linklater Crabtree (B. Sc. Agric.)

This thesis is submitted for the degree of Master of Science in Agriculture of the University of Western Australia.

Soil Science and Plant Nutrition,

Faculty of Agriculture,

University of Western Australia

July, 2001

ABSTRACT

Crop and pasture establishment and production are greatly reduced by water repellent soils, despite significant amounts of rain falling prior to the desired time of seeding. A series of 19 crop (barley [*Hordeum vulgare* L.], wheat [*Triticum aestivum*] and lupins [*Lupinus angustifolius* L]) and pasture field experiments were conducted on water repellent soils from 1987-1989 along the south coast of Western Australia to investigate ameliorative techniques for crop establishment on water repellence sandy soils. Measurements included plant emergence, plant growth, crop grain yield, pasture composition, soil repellence, seasonal climatic factors and soil wetting. The techniques investigated included furrow shape, the position of compaction, press wheel use, banded wetting agent, the residual effectiveness of a wetting agent and deep fertiliser placement. A single glasshouse experiment was also conducted to determine the ability of lupins to take up Mn from dry soil.

With two 1987 barley establishment trials, I investigated: (i) spraying various rates of banded (2 cm wide) wetting agent while furrow seeding with press wheels, (ii) seed placement either in a furrow or in the side of a ridge, and (iii) compaction with press wheels or a Flexi-Coil® land packer. The application of wetting agent increased seedling emergence from 110 to 170 plants m^{-2}, dry matter production from 4.2 to 6.0 t ha^{-1} and grain yield from 1.96 to 2.60 t ha^{-1}, despite more weeds growing (which were not controlled) with increasing rate of banded wetting agent. Use of press wheels, which also resulted in a furrow sowing condition, increased seedling emergence from 72 to 101 plants m^{-2} and grain yield from 1.70 to 2.13 t ha^{-1}. Furrow sowing, at 18 cm row spacings with full soil disturbance, in the absence of heavy press wheel compaction, had no effect on seedling emergence or grain yield. The application of wetting agent increased topsoil wetting and decreased spatial variability of emergence. Increased soil wetting may have increased plant nutrient availability (from fertiliser and soil), reduced evaporation and possibly reduced water loss to subsoil on this duplex soil. The optimum degree of compaction required for water repellent soils is not known and needs further research.

From 13 field experiments conducted in 1988 and 1989, emergence of wheat and lupins were compared with ameliorative techniques. The responses were greatest when seeds were sown into dry soil. Compared with conventional sowing, furrow sowing increased wheat and lupin emergence by an overall average of 16 and 41% respectively. Increases in emergence due to the use of a press wheel were sometimes small, although they always occurred (1-19%). It was visually observed that press wheel use gave more uniform seeding depth, reduced clods and ensured more accurate placement of banded wetting agent. Banded wetting agent consistently improved wheat and lupin emergence, particularly where early rains were light and press wheels were used. The wetting agent increased the cross-sectional area of wet topsoil (0-10 cm) which was positively related to increased wheat emergence (R^2 = 0.91). At 0.5 L ha^{-1} of banded wetting agent, the soil along the furrow was four times wetter than without wetting agent. Wetting agent at 0.5 and 1 L ha^{-1} (with press wheels) increased wheat emergence by 6 and 11% and lupin emergence by 13 and 11%, respectively. The high rates of banded wetting agent gave highest plant densities. Grain yield was only measured at three sites. Furrow sowing did not increase grain yield, however, press wheel use with furrow sowing increased grain yield by 30%. Banded wetting agent increased grain yield. The highest rate increased grain yields by a further 9% above the values for press wheels and furrow sowing.

In the first of two pasture experiments, conventional level sowing (flat planting) was compared with furrow sowing using press wheels. Five pasture species were included and the furrow-sown treatments involved a banded wetting agent applied at four rates. Furrow sowing with a seeder having press wheels increased the average emergence at 14 days after sowing by 133% relative to the conventional treatment and emergence was further increased by 44% by banding 4 L ha^{-1} of wetting agent in the furrows. In the second pasture experiment, there was a six-fold increase in early pasture production (330 to 2,010 kg ha^{-}

^{1}) and a large effect on pasture composition due to the residual effect of a wetting agent applied 2 years previously. The proportion of subterranean clover (*Trifolium subterraneum*) in the pasture increased from 6 to 33% due to the use of a wetting agent.

Two manganese (Mn) placement experiments were conducted during 1987 and 1988 with lupins. The experiments were conducted on an acidic sandy soil near Esperance to determine if deep placed Mn fertiliser increases lupin grain yield. Mn at 4 and 8 kg ha^{-1} was placed below the surface immediately before sowing at 4, 20 and 30 cm and 4, 8, 12, 16 and 20 cm in 1987 and 1988 respectively. Foliar Mn was also applied at 1 kg ha^{-1} when the first order laterals were in mid-flowering. Increasing the depth of Mn placement increased grain yield in both years. The deepest placed Mn increased grain yields by 255 kg ha^{-1} (10%) and 430 kg ha^{-1} (106%) in year 1 and year 2 over the shallow (4 cm) placed Mn. The higher responses to deep placed Mn occurred in year 2, the year with the driest spring and most intense aphid infestation. Foliar applied Mn was as effective as most deep placed Mn treatments, except for the highest rate (8 kg ha^{-1}) at the greatest depth (20 cm) in year 2. The higher rate of applied Mn gave the highest grain yields.

In a glasshouse experiment, a split root experiment determined the ability of lupins to take up Mn from dry soil either when young or at mid-flowering of the primary branches. Three soil watering regimes (maintained at field capacity, maintained below wilting point and alternating from field capacity to well below wilting point) were imposed after taproots had grown through topsoil and into a nutrient solution below. Four sequential harvests (11, 22, 37 and 49 days after planting) were taken to determine the effect of soil drying on lupin growth, Mn uptake and soil extractable Mn. Soil drying, early in the lupin plant's life, stopped the growth of lateral roots in the soil and slowed the growth of roots grown in sub-soil solution and of lupin tops. Soil drying decreased uptake of Mn in the tops to 13% of what was taken up under continuous wet soil conditions. Of the 13%, most (11%) was taken up while the soil was drying. Soil re-wetting enabled the plants to resume uptake of Mn and soil re-drying (just before anthesis) decreased the Mn concentration in the lupin stems to 4.8 ug/g, whereas stems of lupins grown in the wet and dry soils contained 10.3 and 3.3 ug/g respectively. Easily reducible and plant available soil Mn were not affected by soil wetting and drying treatments. This work confirms that the uptake of Mn by lupins may be severely restricted by drying of surface soil at both the beginning and end of the lupin plant's life. The decrease in root length restricted Mn uptake rather than the chemical form of Mn.

The techniques developed during this study are being adopted by farmers as water repellence becomes a widespread problem throughout

Western Australia. Of more significant long-term impact on the problems investigated in this thesis, although of higher cost, is the highly suitable technique of claying as pioneered by Mr Clem Obst from Mundulla, South Australia.

ACKNOWLEDGMENTS

Thanks to Monique, my dear wife, you have always helped me to do my best. Thanks also to my four wonderful children for letting me work during some of our family hours! I am grateful to my three patient thesis supervisors who encouraged me to finish the Masters – during an exciting and intense working period as Scientific Officer with the Western Australian No-Tillage Farmers Association (WANTFA) under the kind and helpful supervision of Mr Geoffrey Marshall.

Initially (1990) my thesis supervisors were Professor Alan (A.D.) Robson and Dr Gerry (G.S.P.) Ritchie and then Professor Bob (R.J.) Gilkes urged and encouraged me to complete the write up. Alan, thank you for your clear thinking and your ability to teach me to write and reason more clearly and for focussing on issues that would be most helpful to me. You have been an inspiration to many graduates. Bob, you have pushed me over the finish line and have been a great encouragement - many thanks!

Thanks to the Grain Legumes Research Council (now GRDC) for the stipend while I was at UWA during 1990-91 and Agriculture Western Australia (AGWEST) who gave me leave without pay for 20 months. AGWEST also provided me the opportunity to do the trials presented in this Thesis. The following numerous people have helped me conduct the

trials, over the last 12 years, which are reported in this Thesis – many thanks!

For the first banded wetting agent work with barley, I thank Peter King for inspiring this research. Bruce Radford, Craig Henderson, Anne Hamblin, Mike Bolland, John Hamblin, Mike Perry, Malcolm Oades and David Smith for helpful comments and discussions. Ian Mickel for the loan of his press wheels. For technical assistance, thanks to John Moore, Gary Dean, Max Crowhurst and Mike Clarke, and Leon Slattery for the land.

For the testing of banded rates of wetting agent I thank Paul Blackwell for the initial encouragement to publish the work. Thanks to the following who help conduct the trials: Craig Henderson, Max Crowhurst, Bill Sharpe, Merve Waddington, the late Ted Fox, David Lisle, Grant Morrow, Dave Nicholson, Charlie Nash and Anita Doswell. The farmers who loaned their land and gave ideas (Luberda, English, Savage, Phelps, Esperance Rural Properties, Halbert, Frazer, Slattery and Royce). Wetta Soil® donated the Wetta Chem® Pty Ltd. Primary Sales® Pty Ltd in helping design the press wheels used.

The pasture wetting agent work. Thanks to Gary and Jan English who helped conduct the experiment and WettaChem and Dolmar chemical companies who donated wetting agent.

For the manganese placement trial, thanks to Ross Brennan who appreciated the merit of the idea and his professional expertise and Mark Seymour for your professional and technical assistance. For technical assistance I thank Mark Kennedy, Colin Norwood, Max Crowhurst and the late Ted Fox, who worked at Esperance Downs Research Station. For the glasshouse experiment I thank Bill (W. J.) Simmons for help in interpreting the chemical analysis and R. John for statistical advice.

LIST OF TABLES AND FIGURES

CONTENTS

1. Background to the research activities and review of the literature

1.1 Statement of structure of thesis and collaborative work

This thesis contains the results of research activities carried out over several years while W.L. Crabtree was an employee of Agriculture Western Australia. Some of the research was in collaboration with Agriculture Western Australia employees but in each instance W.L. Crabtree was the lead researcher and was responsible for interpreting and publicising the data. Five publications appeared in the Journals of American Agronomy, Plant and Soil and the Australian Journal of Agricultural Research and now form the basis of this thesis. Contributions of co-workers are identified and acknowledged where appropriate.

Additional glasshouse experimental data for manganese nutrition was obtained when W.L. Crabtree was a postgraduate student, and this too has been published and is included in this thesis. Thus the thesis consists primarily of a collection of published papers with a brief general introduction and a final interpretive chapter. The papers have been edited to remove unnecessary duplication of text and reference list.

1.2 Overview of the nature and consequences of water repellent soils

Water repellent soil restricts uniform soil wetting, which consequently affects crop and pasture establishment and nutrient availability. About 4 million hectares of water repellent soils exist in southern Australia. There has been little work published on quantifying the impact of water repellence on crop and pasture establishment and the effect of amelioration on plant nutrition. This Thesis attempts to do this.

Water repellence is typically associated with a relatively high amount of organic matter occurring in soils with low clay contents (McGhie, 1980; Summers, 1987). Sandy soils throughout the world commonly experience water repellence (DeBano, 1981), especially if they are dry for part of the year. There are at least one million hectares of water repellent soils in the south coast region of Western Australia (Summers, 1987). This area has increased since that study, due to an increasing soil organic matter contents associated with more legume production and greater adoption of no-tillage seeding systems.

Water repellent soils resist wetting and, in a Mediterranean climate, the topsoil (10 cm) may take months to wet uniformly, despite the top 5-10 mm wetting readily. Reduced and non-uniform topsoil wetting causes patchy weed emergence that results in crops being sown late, thereby reducing crop yield potential's (King, 1981). In water repellent soils, water ponds in depressions, below which the soils wet in a fingering pattern (Dekker and Ritsema, 1995). Once these patches become wet in late autumn, or early winter, they usually remain wet throughout the winter growing season.

As for crops, pasture establishment is also adversely affected. Farmers commonly report large reductions in emergence for pasture sown into water repellent soils with conventional level sowing practices. Conventionally sown seeds, in water repellent soil, may not germinate despite normally adequate rainfall, resulting in patches of bare soil between emerged plants and an overall poor pasture establishment. Natural re-establishment of pastures is similarly poor.

Pasture composition is adversely affected by water repellence (King, 1985). Some pasture species, including subterranean clover, generate a near random placement of seed over a soil surface and are disadvantaged compared to airborne weed seeds that accumulate in hollows where water ponds after rainfall. These low lying areas of microrelief on water repellent soils may become wet with little rain as they act as water basins or sumps in which soil becomes wet and can support weed growth. Subsequently, the weeds in these vegetated patches can support insects that attack desirable seedlings as they emerge later. Thus uneven soil wetting and consequent poor plant growth should be avoided.

Water repellence also impacts adversely on several soil conservation factors. The risk of water and wind erosion is increased (Wetherby, 1984). With wettable soils, weeds proliferate and provide root materials that promote clod formation which can protect the soil from erosion at seeding time (Crabtree, 1990). In contrast, water repellent soils contain dry patches which may remain prone to erosion during early crop establishment. Preferred pathways for water infiltration with repellent soils and delayed seeding may increase recharge to the watertable.

Weed control is frustrated by staggered weed emergence associated with water repellent soils. Weeds that germinate in hollows from a ‘false break’ rainfall, which occurs after a typical summer drought in south Western Australia, grow vigorously and rarely experience drought before crops are planted. After an adequate rainfall, or ‘true break’, occurs for planting crops, higher than normal rates of herbicides are needed to control these older weeds, thus increasing a farmer’s herbicide cost. In addition, sowing is often delayed to ensure that most weeds germinate before applying knockdown herbicides. Soil applied herbicides, such as simazine [2-chloro-4,6-bis(ethylamino)-1,3,5-triazine] or atrazine [6-chloro-*N*-ethyl-*N*-(1-methylethyl)-1,3,5-triazine-2,4-diamine], are commonly used in growing *Lupinus angustifolius* L. But, they may be ineffective because to be fully effective they require soil wetting to be even.

Several techniques have been used to reduce the impact of water repellence in southern Australia. Cultivating in the rain physically mixes the surface 0-10 mm soil, which readily wets, with the remaining dry topsoil (100 mm). However, this technique relies on extended rainfall events, so that farmers can cultivate large areas while the surface soil is wet or while rain is falling. Cultivation also increases the risk of wind erosion (Wetherby, 1984). The addition of clay to topsoil eliminates water repellence at application rates of 70-200 t ha^{-1} (Ward and Oades, 1993) but may not be economical if appropriate clay is not found close to the site of application.

Increasing the depth of ponded water, which increases the hydraulic head, can improve water entry into repellent soil (Emerson and Bond, 1963). Bond (1972) found improvements in both emergence and grain yield in small plots on water repellent sand when barley was sown in the bottom of the furrow compared to sowing in the side of the ridge.

Surface soil compaction can improve plant emergence under these circumstances (Stout et al., 1961; Pathak et al., 1976). Earlier work has shown that furrow sowing (Bond, 1972; King, 1985) has increased emergence and grain yield of barley (*Hordeum vulgare* L.) (Bond 1972).

Using press wheels, while furrow sowing, on water repellent soil has not been investigated in Australia. This is surprising as press wheels are known to reduce average pore size and increase seed-soil contact (Hyder et al., 1955) giving better movement of soil water to the seed (Stout et al., 1961). Many farmers in southern Australia have used Flexi-Coil® land packers (a herringbone pressing pattern) at seeding to increase cereal establishment on sandy soils with some improvements in emergence (Crabtree, 1990). In the early 1990’s many farmers in the south coast region of Western Australia adopted press wheels, furrow sowing, and no-tillage sowing to improve emergence and limit wind erosion on these water repellent soils.

The value of wetting agents in improving water infiltration on water repellent sands has been known for years (Pelishek et al., 1962). McGhie (1983) and Carnell (1984) improved the formulation and effectiveness of wetting agents, and McGhie (1983) banded them over the seed, at an application rate of 10 L ha^{-1}. However, the wetting agent was not placed in the furrow, press wheels were not used, and there was no economic improvement in grain yield. King (1974, 1985) also experimented with wetting agents and concluded that they were too expensive for agricultural use.

Severity of water repellence and the seasonal conditions may affect the impact of these treatments. The degree to which the soil dries over summer and the soil temperature when rain falls has a great impact on the wettability of repellent soils in Mediterranean climates. Cold and very dry soils will decrease the wettability of soil (King, 1981; Wetherby, 1984).

Dry soil conditions associated with water repellence are also known to limit the uptake of nutrients due to increasing tortuosity for the diffusion of nutrients through soil pores. Reduced uptake of phosphorus by medics (*Medicago truncatula*) (Scott 1973) and copper by wheat (*Triticum aestivum*) (Grundon 1980) have been related to dry surface soil conditions.

"Split seed" or Mn deficiency in lupins has been shown to be more severe with later plantings (Perry and Gartrell 1976). This is perhaps due to the lupin pods filling later, under drier soil conditions, than earlier sown lupins. Mn can be moved from the stem and taproot to young growing tissue but not from other above ground plant material (Radjagukguk 1981; Hannam *et al.* 1985).

Deep placement of Mn has increased the efficacy of Mn fertilisers for lupins during pod fill lupins obtained more Mn from moist subsoil than from the drier surface soil (Crabtree 1998). Decreased Mn uptake by lupins from dry surface soils occurs despite extractable Mn (in phosphoric acid) being found to increase with soil drying in some situations (Leeper 1947; Hammes and Berger 1960).

Mn deficiency, or split seed, in sweet white-lupins (*Lupinus angustifolius*) has been common prior to the use of Mn fertilisers. The sweet, white lupins have a greater Mn requirement than many other crops (Gartrell and Walton 1984). On acid sandplain soils in Western Australia, 4 kg ha^{-1} of Mn drilled with the seed usually gives adequate control of split seed (Gartrell and Walton 1984). On alkaline soils, drilled Mn becomes unavailable to lupins, so foliar applied Mn is commonly used (Hannam et al., 1984).

Lupins are unable to mobilise Mn once deposited in leaf tissue and lupins need a constant Mn supply to meet pod fill requirements. If the surface remains dry or dries during pod-fill, then the applied soil Mn may not be available (Harter and McLean 1965, Gartrell and Walton 1984) for plant growth.

In Western Australia lupins are mostly grown on sandy soils that have little clay (often < 6%) in the near surface soil horizon and consequently these soils have poor water holding capacities (Nelson and Delane 1990). Climatic conditions of southern Australia are typically Mediterranean and grain fill of crops occurs during spring when temperatures are increasing and soil is drying. At this stage of growth plants obtain water and some nutrient requirements from subsoil horizons.

This thesis draws from studies that examined the effects of water repellence on plant growth and nutrition. When water repellent soils are dry due to uneven wetting they are likely to behave like dry soils, therefore many studies of dry soil were included in the review. In this thesis water repellence is discussed in relation to its causes, factors affecting its severity, its impact on sandy Australian soils and its measurement; particularly where plant growth studies have been done in dry soils.

Plant growth studies reviewed are those with different water regimes. The emergence, growth and grain fill aspects of many crops were investigated. The main plant reviewed was lupins (*Lupinus angustifolious*), as this was the plant to be studied for watering regimes, in this thesis. A similar crop plant, soybean (*Glycine max*), being a broad acre, annual legume crop, was also a focus of this review. Plant factors that might be affected by soil drying were also considered; these include redistribution of nutrients, microbial interactions, plant age, root exudates and osmotic adjustments.

Plant nutrient availability with relation to soil moisture was reviewed for some of the main macro and micro nutrients. Manganese being a major focus due to this thesis including results of an experiment looking into manganese availability to lupins in drying soil. Using dry soil studies, the impact of water repellence was discussed in relation to microbial interaction, soil pH, root function, the dissolution of fertilisers and nutrient movement to roots.

Until recently there has been little knowledge of the economic impacts of water repellence. The present work, along with more recent work by several workers (eg D. Carter and P. Blackwell), attempts to quantify some of the economic impacts of water repellence on sandy soils of southern Australia.

2. LITERATURE REVIEW

2.1 Introduction to water repellence

Water repellent or non-wetting soils are those soils that resist wetting with water. They are defined as soils having a soil-water contact angle of greater than 90 degrees (Emerson and Bond 1963). On such soils delayed and patchy emergence of crops and pastures occurs. Water repellent soils have been reported in at least eight countries and were first reported in peat soils (Stelwaag 1882). In Australia they were first recognised by Greig-Smith (1910) in N.S.W. In Western Australia, Teakle and Southern (1937) reported their occurrence on the Swan Coastal Plain. Water repellence can occur on a range of soil types, however, it is on sandy soils where water repellence causes most agricultural concern. Consequently this review will focus primarily on water repellence in relation to sandy surfaced soils.

2.1.1 Causes of water repellence

It has long been known that water repellence in soils is induced by organic materials (Schreiner and Shorey 1910, Prescott and Piper 1932, DeBano and Rice 1973). Numerous workers have demonstrated a positive relationship between soil organic matter and degree of water repellence in soil (Bornemisza 1964, DeBano *et al.* 1970, Scholl 1971, McGhie and Posner 1980, McGhie and Posner 1981, Summers 1987). One worker was unable to find such a relationship (Bond 1969). This anomaly may be explained by different types of organic material having differing levels of hydrophobicity (McGhie and Posner 1981) and the counter effects of clay (Harper and Gilkes 1994).

A survey of water repellent sandy soils on the south coast of Western Australia has shown that at least 0.7% of organic carbon in the soil was required to induce water repellence (Summers 1987). At a 2% level of soil organic carbon severe repellence was induced. The nature of the repellent organic molecules and the factors that affect their build-up will now be discussed.

2.1.1.1 Molecules that cause water repellence

The earliest reported molecules that were thought to contribute to water repellence were "essential" oils (Prescott and Piper 1932) found in soils from underneath xerophytic vegetation. However, more precise identification of the organic fraction responsible for inducing water repellence in soils has only recently been achieved. Work in this field has focused on finding an effective organic solvent to extract the organic matter fraction responsible for water repellence.

Extraction with ether or other lipid solvents left soils water repellent, so lipids were rejected as a possible cause (Jamison 1942, Van't Woudt 1959, Bond 1968). In contrast, the successful removal of organic coatings from sand grains treated with strong alkali solvents, such as hot diethyl ether, ethanol and benzene led Roberts and Carbon (1972) to conclude that compounds within the very stable humic fraction were mainly responsible for inducing water repellence. Other research confirms this finding (Wladitchensky 1966, Savage *et al.* 1969a, Tschapek *et al.* 1973, Adhikari and Chakrabarti 1976, Singer and Ugolini 1976). The inability of non-hydroxylic solvents to extract lipids has now been ascribed to either molecular reorientation of water-repellent organic matter (Ma'shum and Farmer 1985) or a redistribution of hydrophobic matter on exposed hydrophilic surfaces (Ma'shum *et al.* 1988).

Recently the efficiency of 8 organic matter extractants to remove and restore hydrophobicity have been compared (Table 2.1) (Ma'shum *et al.* 1988). The amphiphilic mixture of iso-propanol/ammonia removed all hydrophobic materials from a water repellent soil and the extract restored hydrophobicity on acid washed sand to near original levels in the soil. The organic material contained free and esterified long-chain (16-32 carbon atoms) fatty acids, with the most hydrophobic fraction being molecules with extensive polymethylene chains. Ma'shum *et al.* (1988) were able to simulate the naturally occurring water repellent sand by treating acid washed sand with either cetyl alcohol or other polymethylene compounds (palmitic acid).

Table 2.1: The effectiveness of solvents to extract water repellent material from soil (MED value 3.5), the hydrophobicity of the residues and the extracts when applied to acid washed sand (from Ma'shum *et al.* 1988).

Extractants	material extracted (mg/kg)	MED values (Molarity)	
		A	B
Benzene/ethanol(2:1,v:v)	1180	2.0	6.5
Chloroform	600	3.5	5.0
Ether	200	3.0	4.0
Tetrachloroethylene	650	3.5	5.2
Methanol	1230	0.6	2.9

n-Propanol	1330	2.2	3.3
n-Propanol/water(7:3,v:v)	1690	0.1	3.4
n-Propanol/15.7M Am[C](7:3,v:v)	1880	0.0	3.4

[A] = hydrophobicity of residues
[B] = hydrophobicity of extracts on acid washed sands
[C] = ammonia

The fact that varying degrees of water repellence were induced when the extracts were applied to acid washed sand suggests that some components of the extracts were more effective at inducing water-repellent surfaces than others. Some of the extracts removed hydrophilic organic material but Ma'shum *et al.*, (1988) did not examine this fraction. It is possible that fulvic acid is part of the hydrophilic organic material since Chen and Schnitzer (1978) found that increasing the amount of fulvic acid in soils increased soil wettability.

The water repelling polymethylene chains are thought to originate from lignin in plant cell walls - being the water proofing materials in plants (M.E. Tate pers comm) and it is possible that it is this organic fraction that the micro-organisms find most difficult to digest.

Hydrophobic organic material has been found to accumulate in the soil in four ways: (i) leaching from live plant material (Van't Woudt 1959; Letey *et al* 1962, Roberts and Carbon 1971, Ma'shum *et al* 1988), (ii) root exudates (Netzly and Butler 1986), (iii) products of metabolism of microorganisms, in particular from the basidiomycete group of fungi (Bond and Harris 1964, Fehl and

Lange 1965, Savage *et al.* 1969b) and (iv) the remains of organic material.

Products of metabolism of microorganisms and the remains of organic material may similarly lead to increased repellence. Because the breakdown of organic material is via microorganisms the microorganisms may cause an increase in repellence by (i) the hydrophilic material from organic material being utilized by microorganisms leaving the more concentrated repellent material in the soil and (ii) the creation of new hydrophobic molecules in the metabolic processes.

2.1.1.2 Factors that affect the severity of water repellence

The amount and type of organic material, soil type and climatic conditions all affect the degree of the expression of water repellence. Any factor that increases the production of organic material alone will increase the potential for water repellence. Water repellence is usually worst on soils that (i) grow plants having high levels of water repellent organic residues (ii) are sandy and of low clay content, (iii) receive higher winter rainfall (but with surface soil drying over the summer), (iv) have cold and late breaks to the season and (v) are cultivated dry (Crabtree and McGhie 1990).

2.1.1.2.1 Plant species

Both native and agricultural plant species have been found to induce repellence. Some native plant species in Western Australia known to induce water repellence are the brown mallet (*Eucalyptus astringens*) (McGhie and Posner 1981) and various

Banksia species (Crabtree, unpublished data). Similarly, in America, Holzhey (1969) refers to numerous native species associated with water repellent soils.

Water repellence has been induced within 8 years of clearing (Crabtree 1983) by the introduction of species that have been found to be associated with induced water repellence. Some of these include *Phalaris tuberosa* and lucerne (*Medicago sativa*) (Bond 1964), clover (*Trifolium subterraneum*) and lupin (*Lupinus angustifolius*) (Summers 1987) and sorghum (*Sorghum bicolor* L.) (Netzly and Butler 1986).

Addition of organic material to soils will increase the water repellence of a sandy soil. To study the effect on water repellence of adding organic material to a sandy soil, McGhie and Posner (1981) incorporated finely ground plant tops into fired sand. All species and varieties tested induced soil-water contact angles ranging from 50 to 92° and from 62 to 114° from the addition of 2 and 5% respectively of plant material (Table 2.2). At both levels of incorporated tops, clovers and *Eucalyptus* species induced more severe repellence than cereals and annual grasses.

However, comminuted tops contain organic fractions that would be quickly lost once a plant undergoes biological decomposition. Biological activity on the comminuted tops may either increase or decrease the hydrophilic fraction in this material. This may explain the apparent conflict that soils growing W.A. blue lupins are usually water repellent while its comminuted tops induced only low contact angles.

Water repellence is likely to become more severe and widespread throughout the areas occupied by sandy soils in

Western Australia as organic material increases in these soils. Legumes are generally observed in the field to make water repellence worse as they contain more hydrophobic organic material and they promote more nitrophilous plant growth which increases total soil organic material. However, this is not supported by this laboratory study (see Table 2.2) by McGhie and Posner (1981).

The area of land planted to lupins should increase throughout Western Australia as higher yielding and phomopsis (*Phomopsis leptostromiformis*) resistant cultivars are now available and as lupins offer many benefits to following cereal crops (Nelson and Delane 1990).

Table 2.2: The effect on water repellence of mixing dry comminuted (<1mm) tops of plants with fired sand (from McGhie and Posner 1981).

Group	Species or variety	Contact angle after tops mixed (%)	
		2	5
T. subterraneum	Geraldton	87	110
	Tallarook	79	95
	Mt Barker	73	96
	Clara	92	99
	Uniwager	79	95
	Dinninup	71	80
	Yarloop	80	102
	Nungarin	90	102
Medicago spp.	*littoralis* (Harbinger)	71	94
	scutellata (Snail)	89	114
	truncatula (Cyprus)	77	108
	tornata (Tornafield)	86	97
	sativa (Lucerne leaves)	62	95
Legume pastures	Serradella (*Ornithopus sativus*)	92	111
	Rose clover (*T. hirtum*)	80	97
	W.A. blue lupin (*L. cosentinii*)	50	62
Cereals	Wheat (*Triticum aestivum*)	61	82
	Oats (*Avena sativa*)	67	86
	Barley (*Horduem vulgare*)	59	82
Grasses	Perennial veldt grass (*E. calycina*)	52	92
	Buffalo lawn (*S. secundatum*)	52	71
Trees	Mallee (various *Eucalypt spp.*)	89	96
	Elata (*E. redunca*)	70	93

	Marri (*E. calophylla*)	81	98
	Eucalyptus astringens	84	104
	Heugel's *Casuarina* (*C. heugeliana*)	92	114

2.1.1.2.2 Soil type

The soils most severely affected by water repellence in southwestern Australia are sandplain or duplex soils with less than 5 % clay in the top 100 mm of soil. However, other soils with high clay contents can still become water repellent but require much more hydrophobic organic material to do so. Soils with 15% clay may require 17 times more organic material than sandy soils (2% clay) to induce similar levels of water repellence (Ma'shum *et al.* 1988). The large surface area per unit volume with clay soils means much more hydrophobic organic material is required to coat the hydrophilic clay surfaces (DeBano *et al.* 1970).

Sandy surfaced duplex soils can become as severely water repellent as deep sands (Bond 1969). However, less rain is required for duplex soils to wet to the surface as the clay restricts free drainage and these soils often wet from below due to a saturated subsoil. If rainfall is poor then these duplex soils may not evenly wet at the surface (Crabtree *et al.,* 1991).

2.1.1.2.3 Environmental conditions

Water repellence is more severe where climatic conditions favour a build up of organic material, and where hot fires have burnt litter. Also seasonal conditions will affect the severity with which water repellence is expressed. Conditions that cause more severe expression of water repellence are dry and cold breaks to the season, soil moisture content of between air dry and wilting point and cultivation of the soil when dry.

Climatic conditions that favour increased dry matter production, such as long growing seasons with high rainfall, will increase repellence due to a faster accumulation of organic matter in the soil.

Hot fires (>250^{O}C) on non-cultivated American chaparral, grasslands and forests soils commonly increase the severity of water repellence (DeBano 1981). The effect of burning is to move repellent material into the soil, via distillation and condensation, along a temperature gradient, which then condenses and coats the soil surfaces. Water repellence is worse with hotter fires on dry and coarse textured soils.

The impact of repellence on plant emergence is also dependent upon the amount and timing of rainfall. In wetter areas there is more chance of substantial rains falling in early autumn when temperatures are warm. Severely water repellent soils will wet if enough rain falls, particularly if the soil is warm when the rain falls. Dry and cold autumns are likely to lead to a more severe impact of repellence on plant emergence (King 1981).

Increasing the soil temperature increases the rate of water drop entry into soil; the temperature range tested was from 0 to 40^{O}C (King 1981). An 18-fold increase in soil infiltration was found as the soil temperature was increased from 15 to 30^{O}C. King (1981) also found small variations in water repellence associated with soil moisture content. Repellence was most severe at wilting point and it decreased as soil water content decreased to oven dry or increased to field capacity.

Dry cultivations tend to make water repellent soils more water repellent, whereas cultivating in the rain improves soil wetness since the wet and dry soils are physically mixed, thereby reducing repellence (King 1981). Dry cultivations on sandy soils shatters soil structure and decreases soil bulk density. This may decrease capillarity resulting in decreased soil wettability.

2.1.2 Impact of repellence on sandy Australian soils

Since water repellence is associated with organic matter build up, the soil horizon containing the organic fraction becomes most water repellent. In sandy Australian soils the plough layer, or the top 10 to 12 cm, is usually the only water repellent horizon in these soils (King 1985, Summers 1987). Water repellence results in dry patches in these topsoils giving patchy wetting patterns resulting in decreased and delayed plant emergence, decreased dry matter production and crop grain yield, poor weed control, increased diseases in following crops and an increased risk of soil degradation.

2.1.2.1 Soil wetting groups

When water falls on water repellent sandy soils it usually penetrates to the subsoil via columns of least repellence or accumulates in low lying areas so that hydrostatic pressure aids water entry (Bond 1968, 1972). The water then flows through the wettable subsoil which wets uniformly laterally to a limited extent (i.e. finger flow). Where clay subsoil exists the water may accumulate above this layer due to restricted water flow through the finer textured soil. A restriction on water flow in the subsoil will force the soil to become wet from below.

The 4 main soil wetting patterns that occur early in the season on water repellent sandy soils are (see Fig 2.1); (i) the surface 1 cm which will wet and dry readily throughout the year, (ii) pathways or columns of topsoil that remain mainly wet throughout the growing season, (iii) patches of dry topsoil that stay dry for long periods after the break or may not wet up in dry seasons and (iv) subsoil that usually remains wet throughout the growing season.

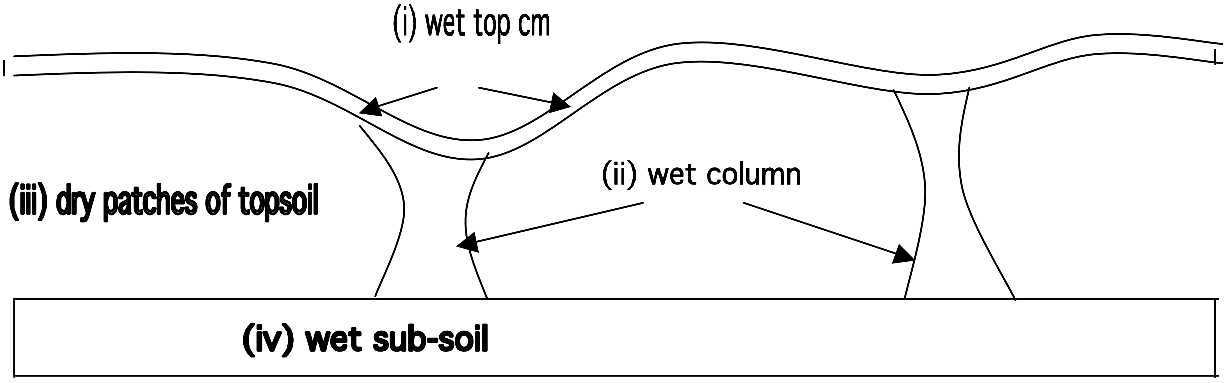


Figure 2.1: Typical soil wetting groups in water repellent sandy soils.

Seeds located in the dry top 100 mm of soil will not germinate throughout a growing season, often despite average rainfall but may remain viable and germinate in the following winter.

2.1.2.2 Plant establishment and growth.

Establishment of crops and pastures can be severely retarded by water repellence (Bond 1972, Crabtree *et al.* 1991). Bond (1972) compared barley emergence for dry patches of soil and wet soil and found 12 times more plants in the wet soil than in the dry soil. Similar differences were also found with barley grain yield. However, these measurements were done on 1 m rows only and the better rows would have received water that ran off the repellent areas. With larger plots (25 x 1.6 m) Crabtree *et al.*, (1991) showed wetting-agent-treated soil increased barley emergence by 50%, decreased spatial variability from ranges of 44-212 to 124-220 pl/m^2 and increased grain yield by 25% over furrow sowing. The grain yield improvements were attributed to less evaporational loss, better wetting of the nutrient rich topsoil with better nutrient uptake on the wetting agent treated soils (Crabtree *et al.* 1991).

Conventional establishment techniques with pastures have produced only one quarter of the density achieved when using amelioration techniques (Crabtree *et al.* 1991) with larger seeded species responding better. Also, early pasture production (3 July) has been increased seven-fold by the residual effect of wetting agent applied to soil two years previously (Crabtree *et al.* 1991).

2.1.2.3 Weed control.

Pastures on water repellent soils often become dominated by less desirable species. Rains in autumn result in water running into hollows where the more mobile seed heads of less desirable pasture species (capeweed; *Arctotheca calendula*, turnip; *Brassica tournefortii,* mustard; *Sisymbrium orientale*, geranium; *Erodium botrys*, silver grass; *Vulpia myuros* and brome grass; *Bromus diandrus*) accumulate and consequently germinate (King 1985). The few clover plants that germinate, compete poorly with the large numbers of other species, and the resultant pastures are usually low in clover content (Crabtree *et al.* 1991) and can remain patchy throughout the year. Insects that grow on early germinated pasture plants may severely attack plants emerging later (Crabtree and McGhie 1990).

Similarly, cropping on water repellent soils is made difficult by the staggered emergence of weeds both before and after sowing. Extra herbicide applications are frequently required to control these germinations as some grass weeds can germinate as late as spring (Bond 1969). While these late emerging weeds may slightly decrease grain yield they can have more adverse impact on the following crop by increasing its weed and disease problems.

Soil-incorporated herbicides are not as effective on water repellent soils. King (1985) found that simazine washed into the furrows where the lupins (*Lupinus angustifolius*) were placed and severely retarded the lupins, while the weeds on the ridge germinated later without being affected by simazine. Better weed control can be achieved by planting later, after the soil has mostly wet up. However, such sowings are usually later than the optimum, giving decreased potential yield (King 1981) and increased risk of soil degradation.

2.1.2.4 Soil degradation

Salinity and wind and water erosion are likely to be aggravated by water repellence. Decreased water use by late establishing pastures and crops is likely to increase groundwater recharge and run-off. The decreased pasture production and the late sowing of crops means a less efficient use of water, since early winter rains can escape from the root zone via preferred pathways to the groundwater (R.A. Nulsen pers comm).

Delayed sowing can increase the risk of wind erosion (King 1981) as was demonstrated on the Eyre Peninsula of South Australia during the drought of 1977 (Wetherby 1984). This results in decreased grain yield, loss of soil - including plant nutrients and incurs the cost of repairing fences, roads and dams which can be buried by sand blown from water repellent soils (Wetherby 1984).

Water erosion from water repellent sands can occur in Western Australia on sloping ground and can be aggravated by firebreak cultivations (D. Carter pers comm). It is a common problem downslope of water repellent duplex soils on lateritic breakaways of the Narrogin area (McGhie and Posner 1980) and with fire induced water repellence in America (DeBano 1969).

2.1.2.5 Area affected in Australia

Some 1.3 million ha of sandplain soils on the south coast of Western Australia are currently water repellent (Summers 1987). The majority of the 1.5 million ha of sandplain soils on the Swan Coastal Plain and West Midlands are water repellent (P.S. Blackwell pers comm) and are well suited to lupin growing. Other sandy surfaced soils scattered throughout the State also have the potential of becoming water repellent. There are about 0.8 million ha of water repellent soils in South Australia (King 1985) and there is a similar area of water repellent soils in Victoria (P.M. King, pers comm). Small areas have been reported to be water repellent in New South Wales (Greig-Smith 1910) and in the Australian Capital Territory (Crockford unpublished data).

2.1.3 Measurement of water repellence

There are 4 main methods of measuring soil water repellence. They are water drop penetration (WDPT), contact angle, infiltration rate and molarity of ethanol drop (MED) tests. The WDPT is a measure of the time taken for a drop of water to penetrate a soil (Letey 1969). The contact angle test measures the angle of contact that a water droplet makes with the soil surface and can be measured photographically (Bond 1969) or estimated by a capillary rise method (Emerson and Bond 1963), or from the rates of water and heptane entry into horizontal columns of soil (Bahrani *et al.* 1973). The infiltration rate test is a measure of water infiltrating soil from a ring infiltrometer (Bond 1968). Finally, Watson and Letey (1970) used droplets of ethanol to calculate a soil's surface tension, later modified by King (1981) who measured the concentration of ethanol in a droplet (0-4 M) that penetrated the soil's surface within 10 seconds.

The results of these techniques have all been found to be closely related to each other (King 1981) (Table 1.3). The relationships were essentially linear for contact angles greater than 81° and curvilinear below this angle. At angles greater than 93° the MED test appears to be able to detect differences in water repellence that the contact angle may not.

Table 2.1.3: Relationships between the repellence tests; MED, contact angle (CA), water drop penetration test (WDPT) and small ring infiltrometer (SRI - measured in mm/min) (Source King 1981).

Relationship	n^A	$100r^2$
MED = -15.5 + 0.191CA	83	75

$\log_{10}$WDPT	=	$42.1 - 1.12CA + 0.00761CA^2$	25	85
[B]$\log_{10}$SRI	=	$- 6.9 + 0.3CA - 0.0025CA^2$	101	85
[C]$\log_{10}$SRI	=	$13.7 - 0.15CA$	83	76
MED	=	$1.7 - 1.2\log_{10}SRI$	86	92

[A] Number of soils used in the regression.

[B] Quadratic relationship for all soils.

[C] Linear relationship for soils with $CA>81^o$.

Each procedure has some limitations. Speed of measurement and the measurable range of severity of water repellence are important practical implications for the tests. The contact angle, and to some extent, the infiltrometer tests, are slow and this limits the number of samples that can be done. The WDPT is only useful for soils with low to moderate repellence, which is equivalent to contact angles of 75-90 degrees (King 1981). The MED test is the most widely used measure of water repellence in Australia. However, the MED test does not reflected the improved soil wetting, associated with use of wetting agent and lime (D Carter pers comm). This anomaly is yet to be explained.

Excessive sieving and increased temperature and moisture contents (from wilting point to field capacity) decrease the severity of water repellence (King 1981). For this reason, measurement of soil water repellence should be done on soils that are lightly sieved, oven or air dried, and at a moderate temperature.

2.2 Lupin responses to nutrient uptake under water regimes that occur in water repellent soils

Dry soil or soil drying will inhibit lupin or plant emergence, growth, symbiosis, nutrient uptake and plant function. Lupins are predisposed to disease and insect attack when the plant suffers from limiting soil moisture. The effect of water *per se* on lupins will also be discussed since water is a plant nutrient. The nutrient manganese will be a focus of discussion since manganese has been a major yield limiting nutrient in lupins grown on Western Australian sandy soils (Perry and Gartrell 1976). Lupin responses to soil water regimes that are to be discussed include; growth, redistribution of nutrients within plants, symbiosis and pathogenicity, changes with plant age, root exudates and osmotic adjustment.

Only limited work has been done with lupins since they are a relatively new agricultural crop. Consequently, this review will involve other plant species, bearing in mind that soybean (*Glycine max*) is a plant species with some similarity to lupins, being an annual legume grown in broad acre crops.

2.2.1 Growth

Most agricultural plants grow and function optimally when the soil water content is near field capacity. Drier soil is well documented to inhibit plant growth (Russell 1983) and, as discussed earlier (section 2.3.8), dry soil will decrease nutrient uptake due to a more tortuous soil water path. The amount of water a plant receives is an important factor in determining the potential yield of crops (French and Schultz 1984). Since water repellence affects the amount and distribution of water in soils water repellence will adversely affect potential growth and grain yield.

2.2.1.1 Emergence

Plants germinate most quickly when the soil water is at field capacity; drier conditions will delay or inhibit germination (Bouaziz and Bruckler 1989a). The threshold soil water potential for germination varies with plant species; for wheat it is below 15 bars (Owen 1952), for some grasses it is a little more than 15 bars (McGinnies 1960) and for corn (*Zea mays* L.), rice (*Oryza sativa*) and soybean it has been found to be 12.5, 7.9 and 6.6 bars (Hunter and Erickson 1952). Wheat germination may occur at lower soil moisture levels if soil temperatures are cold (eg 5°C) (Lindstrom *et al.* 1976).

Seeds may begin imbibing water at very low soil moisture levels, for wheat imbibition has been found to commence at about 31 bars (Bouaziz and Bruckler 1989a). A critical seed moisture content must be reached before seeds can germinate and for wheat it has been found to be 0.27 kg/kg (Bouaziz and Bruckler 1989a) and for corn, rice and soybean it has been found to be 0.30, 0.26 and 0.50 kg/kg (Hunter and Erickson 1952). If seeds partially imbibe, but fail to achieve the critical seed moisture level, then bacteria and fungi may invade the seed rendering it non-viable (Hunter and Erickson 1952, Lindstrom *et al.* 1976).

On water repellent soils lupin and cereal emergence is severely restricted by poor and uneven wetting of the topsoil (Crabtree and McGhie 1990). This will also have adverse consequences for plant growth since there is less moist topsoil available for plant roots to explore. However, water repellence can also be used to improve plant emergence by creating furrows as has been shown by Bond (1972).

2.2.1.2 Root and shoot development

Decreasing soil water content will limit plant top and root growth (Russell 1988). Many studies have shown that nutrient uptake from dry soils is almost negligible compared to nutrient uptake in wet soils. Increasing soil water increases nutrient uptake, as in phosphorus uptake in corn (Olsen *et al.* 1961). The extent of wheat, oat and barley root growth is closely related to the level of soil moisture (Salim *et al.* 1965). When the soil water was held at 13 bar compared to 0.2 bar, for 17 days, wheat roots were 300 mm long compared to 600 mm in the wetter soil (Bouaziz and Bruckler 1989b).

For soil that is dryer than wilting point there is conflicting evidence on the ability of plant roots to grow through this dry soil and take up nutrients. This might be attributable to four main factors; (i) the relative dryness of the soils used, (ii) differences in plant species and genera, (iii) the thickness of the dry layer and (iv) whether the soil-root system used was open or closed to evaporational effects.

Most of the work indicates that plant roots stop growing soon after penetrating very dry soil. It is useful for the purpose of this review to adopt a universal term for how dry the soil is in different work. To this end, I have adopted the term % of wilting point, being the per cent of gravimetric moisture content compared to the gravimetric water content with each soil at permanent wilting point. If the soil had a permanent wilting point of 2.0 % and the soil used had a 1.0 % soil water content, then this would be termed 50 % of wilting point. For these very sandy soils that contain relatively little water at greater suction this approximation is an acceptable indicator of water available to plants.

Cereal roots would not penetrate soil that was drier than 60 % of wilting point by more than 25 mm. Salim *et al.* (1965) found that cereal root growth ceased after penetrating the dry soil by a range of 6 to 25 mm; the variation was with both plant species and genera. Similarly, sunflower plants (*Helianthus annuus*) would not grow far into dry soil (Hendrickson and Veihmeyer 1931) nor would seedlings of 29 different genera (Loomis and Ewan 1936) grow more than 10 mm into soil that was 56 % of wilting point.

It would appear that corn, tomatoes (*Lycopersicon esculentum*) and xerophytic plants (Shantz 1927) are capable, in a closed system at least, of limited root growth into dry soils. Hunter and Kelley (1946) and Volk (1947) demonstrated that corn roots were able to grow more than 40 mm into soil of less than 10 % of the wilting point in a closed system. Likewise, Thorup (1969) showed that tomato roots were able to penetrate 20 mm into soil that was 30 % of wilting point. Additionally these workers found that moisture was moved into the dry soil from the wet soil, and Volk (1947) and Thorup (1969) showed that corn and tomato roots were able to take up small amounts of nitrogen and phosphorus respectively from the very dry soils.

In an open system, the plant species *Cynodon dactylon* L. was able to move large amounts of water from wet to dry soil (VanBavel and Baker 1985). The stolonic nature of this bermudagrass made water movement from one soil section to another relatively easy compared to other plant species with different root morphology. Many dryland agricultural plants are adapted to harsh soil moisture conditions and have root systems very different from bermudagrass.

The thickness of the dry layer may also effect the ability of roots to grow into dry soil. Nambiar (1976) found that lucerne, clover, oats and wheat were all able to penetrate through 15 mm of soil at 92% of wilting point in a closed system and grow into moist subsoil. All plants were able to grow lateral roots into the dry soil, with the wheat roots proliferating the most. Nambiar (1976) also found that all plants were able to take up appreciable amounts of radioactively labelled zinc from this thin layer of soil held at 92% of wilting point. The roots grown into dry soil frequently had large amounts of mucilage around them and he suggested this mucilage may facilitate the transfer of zinc to the root in dry soil.

Uptake of manganese from dry soil has also been reported, but the data presented are not convincing. Ryegrass (*Lolium multiflorum* Lam.) roots were grown through topsoil and into subsoil, the topsoil was then allowed to dry to 21% of wilting point, during which time, 3 sequential defoliations were taken (Nambiar 1977). Shoot uptake of manganese decreased with drying with each defoliation from 27.2 to 8.4 to 3.3 ug/pot. However, the amount of manganese in the topsoil roots was not measured at any of the defoliations, therefore the small amounts of manganese that moved into the tops after topsoil drying may have come from manganese stored in the topsoil roots prior to topsoil drying.

Interest in plant root growth and nutrient uptake as the soil dries is usually generated from field observations of the inhibitory effect of topsoil drying on these plant functions. So, it is significant that observations on the soil-root systems that is closed to the environment may be dissimilar to those recorded in the field. Topsoil in the field is usually subject to harsh evaporational conditions due its proximity to winds and solar radiation. Of the papers reviewed here only those roots that were grown in a closed system demonstrated appreciable growth in dry soil.

Work done with mulch has demonstrated the benefits of a closed system to the plant's ability to absorb manganese from a drying soil. A three-fold increase in manganese uptake was achieved by applying mulch to the surface of a drying soil (Nambiar 1977). The mulch allowed the soil to stay moist for longer due to less evaporation allowing the plant roots to take up manganese more effectively.

Interestingly, water repellent soils have been shown to behave similarly to mulch, in that they slow the rate of evaporation through reduced capillarity (Letey *et al.* 1962). This decreased capillarity may lead to a slightly less evaporational loss of soil water and consequently slightly greater nutrient uptake by plants in spring on water repellent soils than on wettable soils, provided of course, that the water repellent soils were uniformly wet prior to soil drying. However, decreased capillarity on water repellent soil is also the reason for the patchy wetting nature of such soil, particularly at the beginning of the season.

This patchy wet and dry pattern in the surface soil that is common on water repellent soils must inhibit plant growth and therefore nutrient uptake while dry patches exist in the soil. There is no doubt that plant growth and nutrient uptake are severely inhibited in dry soil compared to wet soil. Further there is no evidence that any agricultural plant can grow more than 10 mm into soils that are as dry as air dry when plants are grown in an open system. The patchy nature of plant growth observed in the field is further empirical evidence for the inhibitory effect of water repellence on plant growth (Crabtree and McGhie 1990).

2.2.1.3 Flowering and grain fill

Under field conditions lupin crops mature in drying soil which decreases plant growth, flowering, grain yield and nutrient uptake. An experiment conducted 40 km north of Perth, Western Australia, compared the effects of applying 80 and 160 mm of water at flowering. The dryer treatment decreased the number of lupin flower nodes, dry matter and grain yield by 19, 44 and 41% and increased flower drop by 28% compared to the wetter treatment (Biddiscombe 1975). Reducing water from 480 to 120 mm during pod filling had less dramatic plant effects with a decrease in flower nodes, dry matter and grain yield of only 1, 1 and 20%. Soybean flower abortion and pod yield have been similarly affected by drought during flowering (Shaw and Laing 1966) and drought during seed filling may have more adverse affects on soybean than lupins. The reason for these decreased grain yields may not be due to water shortage alone but also to a lack of nutrient uptake from the dry soil. Similar moisture stress treatments imposed during flowering of *Lupinus albus* have shown decreased seed weight of between 43 and 72% compared to well watered plants (Withers and Forde 1979).

Much glasshouse and field work has demonstrated that deep placement of fertilizers improves the uptake of nutrients when the topsoil dries. Some examples are; phosphorus and borate in lucerne (Simpson and Lipsett 1973), phosphorus in medics (Scott 1973), phosphorus in corn (Marais and Wiersma 1975), nitrogen and phosphorus in wheat (Alston 1976), phosphorus in clover (Cornish and Myers 1977), copper in wheat (Grundon 1980) and manganese in lupins (Crabtree and Brennan 1996). The increased uptake of nutrients from the subsoil compared to the surface soil is due to the subsoil being more moist for longer periods. If plants are able to acquire sufficient nutrients prior to the soil drying at grain filling then they may be able to mobilise these nutrients to the fruit and escape grain yield penalties (Hannam *et al.* 1985) provided the plants have access to sufficient moisture (Hocking 1982).

2.2.2 Redistribution of nutrients

The ability of plants to redistributed nutrients varies with the type of nutrient, plant species, interactive effects of nutrients, plant age and moisture supply to the plant. Nutrients have been classified as mobile (nitrogen, phosphorus and potassium), variably and intermediately mobile (copper, zinc, manganese, sulphur, magnesium, iron and molybdenum) or immobile (calcium, and boron) (Loneragan *et al.* 1976). Mobile nutrients are able to move freely from older leaves to younger leaves, variably mobile nutrients can only be remobilized under certain plant conditions and immobile nutrients are unable to be moved from plant tissue in the phloem.

The mobility of the variably mobile nutrients such as zinc, copper and sulphur has been shown to be related to the level of supply of these nutrients. Increasing the level of supply increases their mobility (Loneragan *et al.* 1976). Magnesium mobility is very dependent upon plant species as it has different mobility patterns in wheat compared with clover (Scott 1990). The variable mobility status of manganese has recently been questioned and manganese has now been shown to be immobile in some plant species.

Recent work has shown that manganese does not move in the phloem from old leaves of subterranean clover (Nable and Loneragan 1984) and lupins (Hannam *et al.* 1985, Radjagukguk 1980). Field experiments have indicated that manganese may be mobile (Radjagukguk 1980). However, this apparent mobility may be explained as leaching of manganese from the leaf's surface by rainfall, as Hannam *et al.* (1985) were able to remove 40% of leaf manganese by washing them in water. Results of glasshouse experiments indicating some mobility of manganese in lupins (Hocking 1982, Hocking and Pate 1977, 1978) are questionable as some conclusions cannot be confirmed by the data given and the variability of the data is not given.

However, results of some glasshouse work done in the absence of rainfall or dew support the idea that manganese may be mobile in oat and soybean plants (Vose 1963, Heenan and Campbell 1980). Species differ in the movement of manganese from roots to leaves. Radjagukguk (1980) has shown that different species and varieties of lupins vary in their ability to move manganese from roots to young leaves.

The interactive effects of nutrients may restrict the mobility of nutrients. For example, the application of nitrogen to wheat plants of marginal copper status increased the copper levels of wheat tops but severely decreased copper mobility, and consequently grain yield (Chaudhry and Loneragan 1970). The poor translocation of copper to the grain resulted from the delayed senescence of leaves due to the effect of the added nitrogen (Loneragan *et al.* 1976, Hill *et al.* 1978).

A lack of moisture during lupin grain filling will result in less efficient mobilisation of nutrients from the older leaves to developing fruit. Hocking (1982) showed that lupins grown in the glasshouse were able to move between 27 and 144 % more nutrients, during pod fill, from leaves of well watered plants than from leaves of poorly watered plants. Soil drying in pots is likely to be more sudden than in the field as deep rooted lupin plants would have access to a greater soil volume. The mobility of nutrients varied greatly between nutrient types.

The effect of water repellence on the mobilization of nutrients within lupins is likely to be adverse but variable depending on seasonal conditions. Early nutrient uptake will be hindered by dry patches in the surface soil which occurs in most years on water repellent soils. The uptake of nutrients during winter should be mostly uninhibited provided the soil becomes uniformly wet. Indeed uptake of nutrients on water repellent soils in winter may be greater on water repellent soils than on wettable soils. Since less nutrients may have been leached from the dry patches in the water repellent soil, plants with established root systems will be able to take up more nutrients from these recently wet patches. This benefit, however, is likely to be small compared to the loss of plant growth incurred due to the poor early wetting and nutrient release from the topsoil. Drying of the surface of water repellent topsoil during grain fill may have a negative impact on lupin grain yield.

The severity of the topsoil drying will determine the impact of the water repellence on lupin growth and nutrient remobilisation to the seed during spring. The possible mulch effect of water repellent soil (section 3.1.2) will be of little benefit if climatic conditions in spring are dry for long enough to impede even rewetting of the water repellent topsoil. If rains fall after such a dry period and preferred wettable pathways in the topsoil occur again, as at the beginning of the season, then lupins would have a limited soil nutrient pool to access, and indeed may have to rely on remobilized nutrients from older plant tissues for grain yield to be maintained. Manganese is needed in continuous supply in order for grain yield of lupins to not be adversely affected unless the plant is able to accumulate enormous supplies of manganese prior to pod filling (Hannam *et al.* 1985).

2.2.3 Microbial interactions

Microbial interactions with lupins may be beneficial to plant growth, as with nitrogen fixing *rhizobia* spp., or harmful, as with pathogens. In Western Australia the pathogenic microorganisms of agricultural significance in lupin crops are; *pleiochaeta setosa, rhizoctonia solani, sclerotinia scerotiorum, phomopsis leptostromiformis, macrophomina phaseolina* and cucumber mosaic and bean yellow mosaic virus's (Nelson and Delane 1990). Three diseases of lupins that are known to invade the lupin plant as the plant senesces from soil drying are; *phomopsis leptostromiformis, macrophomina phaseolina* and *sclerotinia scerotiorum* (Nelson and Delane 1990). No work has been done comparing the effects of different soil water regimes on these diseases of lupins so other related work will be discussed here.

The effect of different soil moisture regimes on microorganisms varies with microbial species. Increasing soil moisture to field capacity may either increase or decrease root rots in plants. *Rhizoctonia solani* has been found to cause more severe plant damage at lower soil moisture levels compared to in soil that is nearer to field capacity (Roth and Riker 1943, Bateman 1961). In contrast, damage from *thielaviopsis basicola* and *pythium ultimum* increases with increasing soil moisture content (Bateman 1961). The infectivity of plant diseases may also be influenced by a plant's nutritional status.

Numerous studies have shown the beneficial impact of good manganese nutrition on a plant's ability to resist disease attack (Huber and Wilhelm 1989). Resistance may be due to either; (i) the production of compounds that inhibit the pathogen or vector, (ii) the accumulation of toxic quantities of manganese at the site of pathogen attack or (iii) the improved resistance of the host plant to pathogen attack (Huber and Wilhelm 1989). There are 53 pathogen-by-plant associations where the pathogen activity has been inhibited by the effect of manganese. Of these plant diseases there are four pathogens known to have an adverse effect on lupins grown in Western Australia, namely aphids, *Rhizoctonia solani, Sclerotinia sclerotiorum* and viral diseases. No effect of manganese nutrition on these diseases of lupins has yet been identified.

Nitrogen fixing nodules benefit from a continuous and plentiful supply of water. Periods of drought have been shown to cause beans to shed their nodules (Wilson 1931). Separated nodules from soybean plants showed that when nodule fresh weight is decreased by 20% due to moisture stress, irreversible and detrimental changes occurred in the nodule (Sprent 1971). Since nodules are dependent on nutrient supply from plants, the nodules will be adversely affected if plant growth is decreased. Limiting water has been suggested to limit nitrogen fixation by restricting export from the nodules (Pate *et al.* 1969).

On water repellent soils, microbial activity will be limited in soil sections that remain dry. Microbial activity in dry soils will be restricted to mainly mycelial growing microbes. At the end of the growing season soil drying may occur that is not easily reversible. Such drying could result in decreased microbial recycling of nutrients, decreased nitrogen fixation, increased attack from some pathogens and increased pathogen attack - due to poorer plant resistance owing to decreased plant manganese uptake from the topsoil.

2.2.4 Plant age

Lupin plants have a root system comprising a taproot and lateral roots. In sandy soils of Western Australia the taproot can grow to 1 m depth within 6 weeks and may reach a final depth of 2.5 m (Nelson and Delane 1990). Lateral roots of lupins, as with many plant species, will proliferate in the more fertile topsoil (Mengel and Barber 1974, Russell 1988). However their effectiveness at taking up soil nutrients will be greatly affected by soil moisture (see section 2.1.2).

Young roots of cereals are more efficient at taking up nutrients than older sections of roots since the cortical cells of aging roots lose nuclei, senesce, and are dislodged (Weaver 1926, Henry and Deacon 1981). For this reason new root growth will continue in an area rich in nutrient supply but will be constrained by moisture supply. If rewetting of a fertile zone of topsoil is patchy, as may occur with water repellent soils during lupin pod fill, then new root growth may occur in the wet but not in the dry patches.

As plants approach senescence their incentive to maintain root mass diminishes. Corn that was grown in soil kept at field capacity had peak, active root mass when the plant was changing from vegetative to reproductive growth (Mengel and Barber 1974). At this stage the older roots in the top 15 cm were dying at the same rate as new roots were being produced at depth. Even so, most of the roots were still closer to the surface. With root density, by the end of senescence, decreasing by about 20% with each 15 cm horizon of soil. During grain fill the corn plants lost more old roots than they gained in new roots, similar results have been found with wheat (Gregory *et al.* 1978). It is likely that lupin roots would behave similarly although *L. angustifolius* express some indeterminate growth habits particularly when soil moisture is continually available for plant growth (Nelson and Delane 1990).

2.2.5 Root exudates

It is likely that all species of plants exude inorganic and organic materials from roots, including lupins. Root exudates include sugars, amino acids, peptides, enzymes, vitamins, organic acids, nucleotides, unidentified compounds that are eelworm hatching and attracting factors (Rovira 1969) and phenols and lipids (Netzly and Butler 1986). Also whole cells that are sloughed off from the root are considered as root exudates since it is difficult to determine between leakage from the root and dislodged cells. Wheat plants may lose up to 17 % of total carbon assimilates to the soil as root exudates (Martin 1977).

Plants exude root materials for one or more of the following five reasons; (i) to provide a substrate for friendly microorganisms that compete effectively with plant pathogens (Deacon and Henry 1980), (ii) for inhibitory affects on pathogens (Buxton 1957), (iii) for inhibitory affects on competitive plant species (Netzly and Butler 1986), (iv) to solubilize or precipitate elements to make them either more available for increased plant uptake or less available to decrease elemental toxicity on plants (Godo and Reisenauer 1980, Olsen *et al.* 1981) and (v) as a function of metabolic adaptions when subjected to water stress (Svenningsson *et al.* 1990).

Increasing soil moisture stress increases the production of soluble organic carbon within plants (Svenningsson *et al.* 1990) and the amount of root exudates (Hale *et al.* 1978). Some of these root exudates have been shown to be hydrophobic (Netzly and Butler 1986, Svenningsson *et al.* 1990) and are therefore likely to contribute directly to water repellence. It is therefore possible that lupins may also exude hydrophobic root exudates.

Since soil drying increases root exudates and root exudates can directly increase manganese availability (Godo and Reisenauer 1980) then soil drying may increase manganese availability via the excretion of root exudates. This is, of course, dependent on the whether root exudates vary significantly in type and quality according to different stimuli promoting their excretion.

2.2.6 Osmotic adjustment

Osmotic adjustment is the accumulation of solutes in response to water deficits (Barlow 1986). This accumulation enables plants to maintain physiological activity and photosynthesis of solutes under drying soil conditions. Osmotic adjustments in lupins (Turner *et al.* 1987) have been shown to be similar to osmotic adjustments in other legumes (Shackel and Hall 1983).

Lupins grown on water repellent soil are unlikely to have adverse osmotic effects compared to wettable soil. At the beginning of the season lupins will only grow where soil moisture is, and consequently osmotic relations may be better on the plants grown on water repellent than the wettable soil as there would be fewer plants per area than on the wettable soil. At the end of the season, plants grown on both wettable and repellent soil would have access to a similar amount of soil water and possible differences in surface soil drying would have only minimal effects on osmotic regulation within the plants.

2.3 Effect of water repellence on soil factors affecting nutrient reactions within soils

The effect of water repellence on soils is to alter soil wetting patterns, and this will affect soil microbial activity, pH, soil temperature and nutrient reactions within soils. The soil wetting patterns associated with water-repellent soils (see section 2.1.3.1) are dynamic both within seasons and from season to season. The same soil fractions may be exposed to the same wetting patterns year after year, particularly if not disturbed by cultivation, and the effects on the soil could be cumulative. Conversely, the effects may only impact on a soil volume in one season.

Surface micro-relief, intensity, amount and timing of rainfall, depth to clay or an impermeable layer and erosion of topsoil are the factors primarily responsible for inducing non-uniform soil wetting patterns on water repellent sandy soils. Surface micro-relief can be generated by cultivation, movement of machinery and stock and soil erosion. Disturbed soil will alter surface micro-relief which may lead to different soil wetting patterns. However, pasture paddocks which are not cultivated for many years may have unaltered soil wetting patterns through the soil profile. Pasture paddocks are top-dressed with fertilizers (deposited on the surface) and this has implications for the effectiveness of the fertilizer on water-repellent soils.

Plant nutrients may be considered in three main forms; organic, inorganic or in solution, and they may be leached, taken up by plants or remain undissolved (Fig 2.3.1).

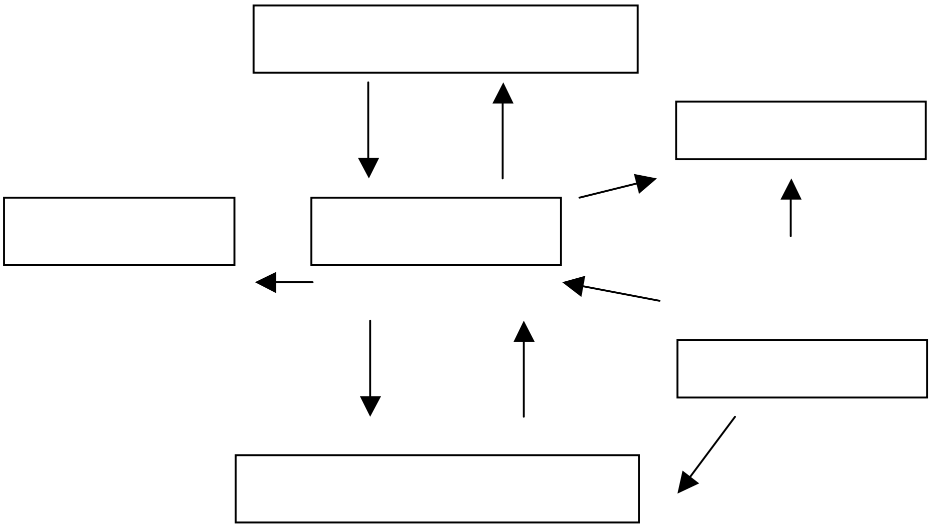


Figure 2.3.1: Plant nutrient flow chart showing pathways within the soil.

2.3.1 Microbial activity

Soil microorganisms can have both a direct and indirect effect on plant growth. Direct effects may be through pathogenic, symbiotic or allelopathic activities and the indirect effects are through the breakdown and recycling of soil nutrients. Both effects are dependent on soil moisture for the growth and survival of the associated microorganisms. The direct effects of microorganisms on plant growth will be covered in section 2.3, while the indirect effects of microorganisms on nutrient recycling will be discussed here.

The microorganisms responsible for breakdown of humus in soils are bacteria, actinomycetes, fungi, algae, protozoa and viruses (Darbyshire 1975). Their activity in soils is dependent on food supply, aeration, temperature, pH and soil water. The amount of soil water can affect all of the above factors. Microorganisms usually require large amounts of soil water (but less than waterlogging) to function optimally, and fluctuations in moisture to less than field capacity will retard the activity of many microorganisms (Hutchinson and King 1982).

The thickness of the soil water films is important for aeration and motility of bacteria and protozoa. Aeration improves with drying since oxygen diffuses some 10,000 times more quickly through air than water (Currie 1961). However, motility is also important, particularly for predatory soil animals which require water films thicker than themselves to move freely in the soil to find food.

Undrained soil has been found to give optimal soil moisture conditions for the population growth of larger soil protozoa. Population numbers of Calpoda and *Azotobacter protozoa* grown for 35 days in soils ranging from 0.0 to 0.5 bar suction showed that the reproduction of the small Calpoda protozoa was not affected by any of the moisture regimes tested (Darbyshire 1975). In contrast, the 10 times larger *Azotobacter protozoa* did not increase in number at 0.5 bar suction and reproduction was slightly inhibited by 0.03 bar suction as opposed to the 0.00 bar suction. Darbyshire (1975) attributed this difference to the thin water films of the dryer soil which gave poor mobility of the larger protozoa and restricted their predatory ability. In contrast, mobility through water films is not important for hyphal microorganisms.

Filamentous fungi and actinomycetes can cross open air spaces using hyphae and can therefore function adequately in conditions drier than 100 bar (Griffin 1972). Similarly, Chen and Griffin (1966) have shown that fungi can survive and grow in soil as dry as 390 bar and Jasper *et al.* (1989) showed vesicular-arbuscular mycorrhizas to remain highly infective after the soil they were in was dried to 210 bar water potential. Nutrients located in pores isolated from most microorganisms by thin necks may be accessed by hyphae. Microorganisms that grow hyphae are therefore likely to predominate in dry soils.

In water-repellent soils microbial activity is likely to be high where the topsoil is wet until the substrate becomes limiting. The wet and dry cycles experienced by the topsoil may decrease microbial number, which could limit their activity. The topsoil which remains dry will have very limited microbial activity with the consequence of poor nutrient recycling.

If the dry topsoil does become wet, which is likely during the cold wet months, then microbial activity can commence with a release of nutrients for plant growth. This delayed microbial activity will also be slower, due to colder temperature, but will supply nutrients to a bigger root system more able to uptake those easily leached nutrients. This could compensate somewhat for the decreased availability of nutrients early in the season.

2.3.2 Soil pH

Soil acidity has the effect of inhibiting plant growth through the toxic effects of some elements, decreased availability of various nutrients and decreased root growth which limits nutrient uptake. A decrease in soil pH increases the concentrations of soluble aluminium and manganese ions and a loss of base cations, a decreased cation exchange capacity and changes in biological activity (Bache 1980). Decreased root growth, as affected by acidity (Islam *et al.* 1980), and a decreased availability of calcium, magnesium, phosphorus and molybdenum, due to acidity, will combine to decrease plant growth.

Rainfall and the cycling of carbon and nitrogen within soils can lower soil pH. Rain water will do this by reacting with carbon dioxide in the atmosphere to form weak carbonic acid. In pre-industrial times it is estimated rain water had a pH of 5.65 and 1 mm of rain would have deposited 0.022 eq H^+/ha (Ulrich 1980). The burning of fossil fuels has increased the atmospheric content of carbon and sulphur dioxides, nitrogen oxides and chlorine, all of which can react with water to form acids. However, in Western Australian agricultural ecosystems such inputs, other than water and carbonic acid in rainfall, are considered to be minor, as in pre-industrial times (Hingston and Gailitis 1976).

Respiration and mineralisation of nitrogen both contribute to soil acidity (Rowell 1988). Respiration produces CO_2 which dissolves to give H_2CO_3 with dissociation to H^+ and HCO_3^-, the latter is leached along with some H^+ and exchanged Ca^{2+} and Mg^{2+}. Oxidation of NH_4^+ to NO_3^- liberates two hydrogen ions in the process. Both of these reactions require water for them to proceed and make the soil solution more acidic.

The production of these acid solutions in soil leads to hydrogen ions displacing base cations (Ca, Mg, Na and K) from exchange sites followed by leaching (Haynes and Swift 1986). The loss of these cations destabilises the clay lattice which results in the dissolution of aluminium oxide from the clay, generating more hydrogen ions and thus decreasing soil pH further (Russell 1973). The extent to which rainfall, respiration and mineralisation of nitrogen decrease soil pH is dependent mainly on the buffering capacity of a soil and the amount of organic matter in the soil.

Increasing soil acidity decreases beneficial and antagonistic microbial activity. The soil microbial population changes from a dominance of bacteria to actinomycetes fungi as the soil pH decreases (Alexander 1980). Bacteria responsible for nitrification are mostly inactive at pH less than 5, with legume nodulation also decreasing below this pH (Alexander 1980).

Different wetting patterns on water-repellent soils can result in considerable leaching from the top 1 cm of soil, and wet preferred pathways in the topsoil. In this zone the loss of hydrogen ions to the soil solution from the nitrogen and carbon cycles will result in a decreased soil pH. The amount of water passing through the pathways may be several times more than would occur on wettable soils not subject to these wetting patterns.

The pH of the topsoil, that remains dry, should not be affected until, and if, it wets. If the topsoil does wet, it may wet progressively or within a day. In either case, much less leaching would be expected in this soil volume compared to the preferred pathways. When the remainder of the soil profile wets up there should be little vertical water flow occurring, particularly on shallow duplex soils that wet from below. The N and C cycles would progress in this soil section once wet and would therefore contribute to a decrease in soil pH.

The subsoil of water repellent sandy soils is uniformly wettable (Bond 1969) and therefore may be only minimally affected by rainfall or effects from the N and C cycle. The ionic strength of the soil solution after passing through the more fertile topsoil may exceed the ionic strength of the subsoil (thereby depositing cations, rather than removing them, from the subsoil exchange sites).

Applying lime to a water repellent soils is likely to give non-uniform pH changes in the topsoil and subsoil. This is due to the preferred water pathways and fingering that occur in water repellent soils. However, there is evidence that on acidic soils lime additions can improve soil wettability (Roper 1998). This is discussed in section 2.4.3.3.

2.3.3 Nutrients

Additions of phosphorus, nitrogen, copper and zinc fertilizer are essential for achieving adequate plant growth on sandy surfaced lateritic soils of south-western Australia. For some of these soils, or for some crop species, manganese, sulphur and/or potassium are also required. These soils typically have small amounts of kaolinitic clay (1-6%), iron and aluminium oxides, and organic material in the topsoil may contain a substantial portion of the cation exchange sites within these variable charge soils (Barrow 1985).

Water is the medium through which nutrients are adsorbed onto, and desorbed, from the surface of soil particles. Applied granular fertilizers require water for their nutrients to dissolve and be adsorbed onto soil surfaces. Nutrient adsorption is affected by time, nature and number of sites, ionic strength, concentration and speciation of the adsorbent, temperature, soil pH and amount of soil water.

Increasing clay and organic matter content of soils increases the number of adsorption sites making nutrients less likely to be leached from these soils. The sandy textured soils that are to be investigated in this work are prone to nutrient leaching.

If dissolved nutrients are removed from solution, whether by plant uptake, precipitation or leaching, then the nutrient equilibrium in the soil-solution will be disturbed. A new equilibrium will then be achieved by more nutrients being desorbed from the soil surfaces into the soil solution. Similarly the addition of fertilizers will also disturb the soil-solution nutrient equilibrium, but in this instance nutrients will be adsorbed onto soil surfaces.

Most anions are not adsorbed as strongly to the surface as multivalent cations and are therefore more easily displaced from the soil to solution (Uehara and Gillam 1981). Water movement through the soil can easily leach most soil anions, while multivalent cations are more firmly adsorbed onto the soil surface and are less likely to be desorbed.

Field studies have shown how some nutrients accumulate in the surface soil in the absence of surface soil inversion, and may indicate the relative leachability of nutrients (Fig 2.3.2) (Drew and Saker 1978; Mahler *et al.* 1985). However, the accumulation of certain nutrients in the soils surface does not give a clear indication of the leachability of nutrients as plants can extract nutrients from depth and deposit them on the soil surface as litter.

Consequently leaching studies where fertilizer is placed on the surface of undisturbed soil columns give a better estimate of the potential for a nutrient to be leached. Such studies using fertilizer granules showed sulphur (as sulphate) leached rapidly from the soil (Williams 1969; Aylmore *et al.* 1971; Gilkes *et al.* 1975), phosphorus (as phosphate) also leached rapidly but was adsorbed onto soil lower down in the profile (Williams 1971; Gilkes *et al.* 1975), copper and zinc salts did not leach and calcium salts leached more than phosphate but less than sulphate (Gilkes *et al.* 1975).

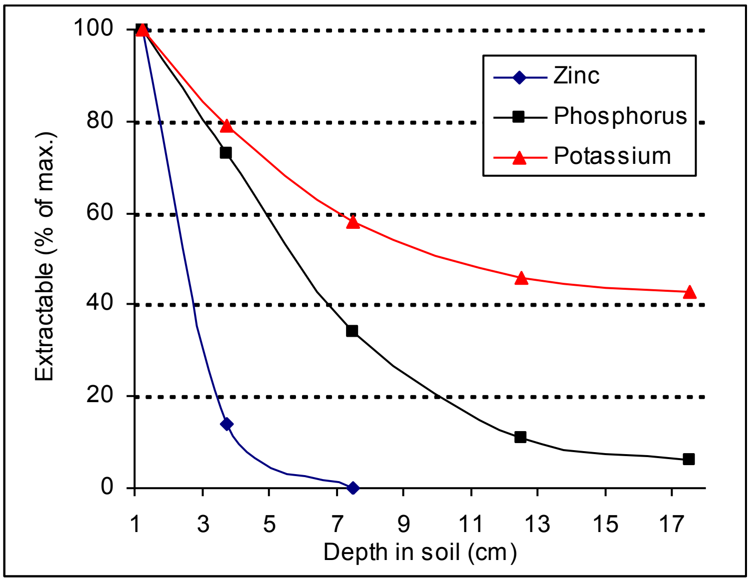


Figure 2.3.2: Distribution of DTPA extractable phosphorus and potassium with depth of soil after 4 years of direct drilling (from Drew and Saker 1978) and zinc after 1,400 mm of rain (from Brennan and McGrath 1988).

2.3.3.1 Phosphorus

Increasing the water content (to field capacity) of soil incubated with granules of superphosphate will increase the adsorption of phosphate onto soil (Sharpley and Ahuja 1982).

Barrow (1974) found that clover production in soil with phosphate incubated at 14% soil moisture was about one third of clover production on soil that was incubated at 1% soil moisture content. This unavailable phosphate has become firmly bound to the soil and has been described as phosphate that is fixed to the surface layers of the soil particles (Wiklander 1950), nonlabile (Larsen 1967), or in a form which is not in direct equilibrium with the soil solution (Barrow and Shaw 1975).

Phosphate becomes increasingly desorbed with incubation or leaching at increasing water quantity; this will occur in the absence of applied fertilizer (Weaver *et al.* 1988). Increasing soil water and time of contact with the soil increases the rate at which the new soil-solution equilibrium will be reached, whether the soil is losing or gaining phosphorus.

Phosphate that is mineralised from the organic pool is a small but important source of phosphate for plants, particularly if there are large amounts of organic material in the soil. Increasing soil temperature and moisture will increase the rate of microbial activity (Jenkinson 1988) which will increase the rate of mineralisation of organically held phosphorus.

2.3.3.2 Nitrogen

Organic nitrogen is constantly being cycled within soils and is mineralised to NH_4^+ and then nitrified to NO_3^-. Ammonium ions are adsorbed to clay minerals in the soil with similar strength as potassium (Wild 1988). In contrast, nitrate ions are not strongly adsorbed by most soils (Singh and Kanehiro 1969) and because they are held only in the soil solution they are easily leached. Nitrogen is taken up by plants as either NH_4^+ or NO_3^-, but since nitrogen is present in the soil solution mainly as nitrate it is this form that is mainly used by crop plants.

At field capacity, soil nitrogen is only present as nitrate but as a soil dries to wilting point the concentration of ammonium in the total soil fraction increases, such that the nitrate:ammonium ratio is about 1:1 at pF 4.2 (Harris 1988). Nitrogen transformations are mainly conducted by soil microorganisms. The microbes that nitrify nitrogen (ammonium to nitrate) are more adversely affected by dry soil than microbes that do the ammonification (organic nitrogen to ammonium). This gives a faster net production of ammonium than nitrate in the dryer soils.

The accumulated ammonium in dryer soils may be either lost by volatilization of NH_3 to the atmosphere – if the pH is high enough - or converted to nitrate once the soil wets. The resultant flush of nitrate that occurs after soil wetting may be either leached in a free draining soil, denitrified in a waterlogging soil, or taken up by plants.

2.3.3.3 Sulphur

Usually more than 90% of soil sulphur is held in the organic form (Syers *et al.* 1987). Organically held sulphur can mineralize to sulphate which will readily leach from soils (Williams 1969; McLay 1989), but can be adsorbed onto soil surfaces to some degree, particularly in acid soils (Jones 1968). Adsorbed sulphur may readily desorb in the presence of soil moisture, making it available for plant uptake and leaching.

Mineralisation of sulphur is highest when soil moisture is at 60% of water holding capacity (Chaudhry and Cornfield 1967), the rate declines at both higher and lower moisture contents. Sulphate flushes may result from wetting a dry soil. Soil conditions that are favourable to microbial growth will most likely increase the rate of mineralisation. Consequently, soil temperatures in the range of 20-40^{O}C have given the highest rate of mineralisation of sulphur (Williams 1967).

Sandy soils are most prone to sulphate leaching; 200 mm of water has been found to move most sulphate below 30 cm depth in soil columns (Chao *et al.* 1962). Sulphur is frequently applied in conjunction with phosphate and nitrogen in granular fertilizers and is mobilized when the granules are dissolved.

2.3.3.4 Manganese

Compared to many other metal ions, manganese is only weakly adsorbed onto clay minerals (Tiller 1983), organic material (Bloom and McBride 1979) and aluminium and iron oxides. However, manganese has been found to be more difficult to remove from the soil after several wetting and drying cycles (Reddy and Perkins 1976). Interlamellar entrapment or oxidation/precipitation upon drying are probably responsible for the increased retention.

Manganese (II) is the only oxidation state that has been identified in the soil solution and consequently is the only form of manganese available for plant uptake. There is a dynamic relationship between the (II) and (IV) oxidation states of manganese. Manganese (II) is oxidised to manganese (IV) in soils mainly via microbial pathways, whereas the reverse reaction, manganese reduction, is mainly chemically controlled (depending on conditions). The redox reactions of manganese are affected by environmental conditions, soil properties and microbial activity (Ritchie 1989). Factors that can affect microbial processes also may have exactly the opposite effect when the same process is chemically mediated.

Wet conditions allow anaerobic microorganisms to reduce manganese (Ponnamperuma 1972). This may lead to manganese toxicity in some cases. Dry or drying conditions will reduce manganese, giving an increase in plant available manganese (Jones 1957; Lopez and Graham 1972) due to suppressed microbial oxidation of manganese (Stahlberg *et al.* 1976) while the chemical reduction process continues.

Soil moisture and temperature have an interactive effect on manganese redox reactions. Reduction during a wet period would be greater than reduction during a drying period because both chemical and microbial reduction occur during wet periods but only chemical reduction occurs during a dry period. Increasing temperature during a dry period would increase the rate of chemical reduction to that attained by both chemical and microbial reduction during a colder, wet period. Microbial oxidation will also increase with increasing temperatures (up to 30°C) provided moisture is available (Ritchie 1989).

Manganese is resistant to leaching, particularly in alkaline and clay textured soils (Fahad 1987) and in aerobic conditions (Grass *et al.* 1973). On slightly acid, sandy soils, manganese is likely to be more leachable than copper but less leachable than potassium, depending on redox conditions.

2.3.3.5 Copper

Copper is strongly adsorbed onto soil constituents, making it resistant to leaching. This was illustrated by Gilkes *et al.* (1975) who applied copper-enriched superphosphate to the surface of a sandy soil and subjected it to 90 cm of leaching water. All the copper was retained in the surface 5 mm. Similar results have been found with the leaching of metal-contaminated sludge with 930 and 415 kg/ha of applied copper giving only slight increases in subsoil (15-30 and 25-35 cm) copper levels (Ellis *et al.* 1981 and Payne *et al.* 1988).

Soil applied copper becomes more strongly adsorbed when incubated with increasing soil water content (Khan and Banwart 1979; Williams and McLaren 1982), time (Brennan *et al.* 1980) and temperature (Brennan *et al.* 1984). Conversely, copper is also more easily extracted from soils at higher temperatures (Williams and McLaren 1982) and at higher soil water contents.

2.3.3.6 Zinc

Zinc is also strongly adsorbed onto soil constituents but not as strongly as copper (Forbes *et al.* 1976). Leaching studies have consistently shown more movement of zinc than copper (Gilkes *et al.* 1975; Ellis *et al.* 1981; Payne *et al.* 1988), although compared to other nutrients the movement is small. A field leaching study on sandy Western Australian soils of pH 5.5 (1:5; soil:water) showed that after 1438 mm of rain, 95% of zinc, applied as $ZnSO_4$, was in the top 4 cm of the soil (Brennan and McGrath 1988). On neutral, silty clay soils, very high levels of zinc were applied (897 kg/ha) with only small amounts of zinc leaching below 25 cm depth (Payne *et al.* 1988).

2.3.4 Dissolution of fertilizers

Applied granular fertilizers require moisture for dissolution of the nutrients to occur. Although the amount of water required for dissolution to commence may be small, the amount of moisture required will vary depending on fertiliser type. The poorly soluble rock phosphate fertilizer still slightly dissolved (4%) when incubated with air dry soil, for 280 days at 25°C (Kanabo and Gilkes 1988). Superphosphate fertilizer granules imbibe water and the resulting solution is acidic which aids in the dissolution of nutrients, particularly copper and zinc (Gilkes 1977). Diffusion and leaching then release the copper and zinc from within the granules to the soil solution.

Nutrients from fertilisers that are adsorbed onto soil particles will be desorbed into the soil solution as this solution is depleted, provided moisture is not limiting.

2.3.5 Movement to roots

Nutrients move to plant roots by mass flow, diffusion, or both of these modes. Nutrients that are held in soil solution will be carried by movement of the solution in a process called mass flow. The random movement of ions in solution will ensure that ions move to areas of ion depletion in the solution. This is known as diffusion.

Soil moisture directly affects mass flow and diffusion of ions in the soil. Increasing the soil moisture content will make the path of diffusion less tortuous and hence increase the rate of diffusion

(Porter *et al.* 1960). Similarly, increasing soil moisture increases mass flow and nutrients will consequently move to zones of depletion. This will benefit plant growth provided the nutrient is not tightly bound to the soil upon dissolution from the fertiliser granule.

When nutrients are mobilized from a nutrient rich source, like a fertilizer granule, to a less fertile area, the nutrient may be adsorbed onto this soil (Gilkes *et al.* 1975; Ellis *et al.* 1983) and not reach the zone of plant uptake. This commonly occurs with the strongly adsorbed cationic micronutrients, like copper, zinc and manganese, particularly in sandy soils of south western Australia. High rates of copper have been required to over-come initial copper deficiencies in these soils (Brennan *et al.* 1986). Mass flow and diffusion movement of these strongly adsorbable nutrients may be only for short distances and root extension may be a more important mechanism for ensuring plant uptake (Gilkes *et al.* 1975).

The mobile anions and cations can move freely with the soil solution and are consequently more available for plant uptake and leaching (Ellis *et al.* 1983).

2.3.6 Impact of water repellence on nutrients

Fertilizer granules and organic matter located in dry water-repellent soil may remain mainly chemically inert while the soil is dry. Consequently the applied fertilizers may not be dissolved or adsorbed onto the soil and mineralisation or microbial activity may not commence until the soil wets. If part of the soil wets later in the growing season (mid-winter), this inert soil fraction will then release nutrients making them available for plant uptake. As the soil is colder during winter it will result in slower adsorption of the fertilizers onto the soil surfaces (Barrow 1974, Brennan *et al.* 1983), making them more available for plant uptake. However, heavy rains are also more likely in mid-winter and anions and cations may be leached (particularly in free draining soils) but since plant root systems would be large at this time the plant may be able to take up a lot of the nutrients that may otherwise be lost due to leaching.

At the break of the season, wettable sandy soils can experience a wetting front that washes leachable nutrients from the topsoil beyond the plant root zone. However, on water repellent soils, nutrients located in the columns of topsoil that wet early in the season may undergo mineralisation and leaching at a rate exceeding that of wettable soils because more water would be channelled into these preferred pathways from the surface water repellent topsoil. The wettable subsoil would wet evenly spreading from sites of water flow through the topsoil. At these sites in the subsoil there may be some adsorption of nutrients or deposition of fine organic particles since the exchange sites in the subsoils may have more affinity for adsorption than the more fertile topsoil, due to a lower ionic strength of the subsoil.

It is doubtful that roots can grow into dry soil to extract nutrients to any major extent. There may be some potential for a symbiotic relationships with vesicular-arbuscular mycorrhizal fungi in such soil. Here, the fungi may be able to grow into the dry soil and extract nutrients and exchange these for an energy supply.

2.4 Effect of management on the uptake of applied nutrients in water repellent soils

Plant available nutrients are either held in or released from mineral complexes and organic material, as dealt with the previous sections or, in an applied granule placed on, or in, the topsoil. Techniques that minimize the effect of water repellence on the uptake of applied nutrients, in crop situations, are discussed in this chapter. In pasture situations, granules applied to the surface usually become deposited in the low lying areas which is where plant emergence mostly initially occurs.

Applied fertiliser in cropping situations can be placed either above (topdressed) or within (drilled or banded) the soil. Placing fertilisers in the soil is more common that topdressed fertilisers. To overcome the impact of water repellence on applied fertilizers they could be placed in a band of soil that is not affected by water repellence, by applying fertilizers in a foliar form, or by ameliorating water repellence. This section will discuss these options in relation to water repellence.

2.4.1 Fertilizer placement

Many studies have been done on agricultural crops comparing the effects of various placements of phosphorus fertilizer in a range of soil types, but few other nutrients have been studied. There appear to be no field studies comparing the effects of placement of micro-nutrient fertilizers on nutrient uptake. Research on fertilizer placement has usually compared fertilizer drilled with the seed, below the seed, at different row spacings and topdressed. Most studies report that drilling the fertilizer with the seed is the most cost effective treatment but under certain conditions deep placement is better.

2.4.1.1 Banded or drilled verses topdressed

Phosphorus fertilizers banded in the topsoil usually give better plant nutrient uptake than topdressed fertilizers with results being dependent on the fertility of the soil and rainfall. Plants grown on soils that are low in phosphorus will benefit most from phosphorus being drilled with the seed as opposed to it being topdressed (Paterson *et al.* 1981). On infertile soils, wheat drilled with phosphorus has responded up to three times better than wheat topdressed with phosphorus (Paterson *et al.* 1981). On soils with a high phosphorus status, plants generally respond similarly to either drilled or topdressed phosphorus (Welch *et al.* 1966, Schultz 1975).

Southern Australian sandy or calcareous soils commonly benefit most from drilled as opposed to broadcast phosphorus fertilizers (McDowell 1961, Rudd 1972, Jarvis and Bolland 1991). This is because these sandy soils are inherently infertile and require early phosphorus uptake that can come from fertiliser being drilled near the seed. The closer the phosphorus is to the plant roots the more quickly the fertilizer will be taken up. Calcareous and high fixing soils readily adsorb phosphorus and make it unavailable to plant roots. Phosphorus placed in a concentrated band in a calcareous or high fixing soil will decrease the contact surface area of the phosphorus with the soil. This will slow the rate of phosphorus fixation (Prummel 1957) and consequently result in improved phosphorus uptake by plants.

High rates of phosphorus (Smith 1958, Jarvis and Bolland 1991) and nitrogen (Cooke 1962) fertilizers may inhibit emergence and plant growth if drilled in close proximity to the seed. Phosphorus drilled at 40 and 80 kg/ha decreased wheat plant numbers at 3 weeks by 17 and 40 % compared with no phosphorus (Baker *et al.* 1970). Topdressed phosphorus had no effect on establishment.

Increasing soil moisture stress may exacerbate the toxic effects of both phosphorus (Baker *et al.* 1970) and nitrogen (Mason 1971) fertilizers when in close contact with the seed. Banding of urea or ammonium nitrate on sandy soils with wheat has adversely affected emergence, although grain yield was decreased only with the urea banding treatment (Mason 1971).

In potentially toxic situations, such fertilizers would be more appropriately topdressed than drilled with the seed. Topdressing fertilizers has some benefits for farmers compared to drilling fertilizers with the seed, as it is both more economical and convenient to manage.

With micronutrients, placement may be more critical since such small amounts are involved. On virgin sandy soils of Western Australia, copper placed near the seed (or thoroughly mixed with the soil) is likely to be more effectively utilized than topdressed copper. Since wheat plants at 45 days old were unable to utilize copper that was located more than 2 cm from the seed (Gilkes and Sadleir 1979), plants would benefit from close proximity to the copper. With manganese and lupin production, drilled manganese has been shown to be twice as effective as topdressed manganese (Gartrell and Walton 1984).

On water repellent soils, drilled fertilizers are more effectively utilized by crop plants than are topdressed fertilizers. This is because drilled fertilizer will be located near the crop seeds. If seeds are located in wet soil, then the fertilizer is also likely to be in the wet soil and will dissolve being available for plant uptake as the plant grows. If, on the other hand, the soil remains dry then neither seed imbibition or extensive fertilizer dissolution will occur and the fertilizer will not be available for weed growth. Broadcast fertiliser may be located in dry patches of soil that are inaccessible to crop plants or in wet soil which, in the absence of crop seeds, may improve weed growth.

2.4.1.2 At depth

Numerous studies have been conducted comparing plant growth with phosphorus and nitrogen fertilizer placement at varying depths. It appears that no studies have been done on deep placement of micronutrients. These depth of placement studies have been done on the premise that surface-applied fertilizers will not be as available for plant uptake as fertilizers placed in deeper, more moist soil. It is ironic, then, that few published deep placement studies contain rainfall or soil moisture data. This makes it impossible to compare the effectiveness of depth of fertilizer placement with varying soil moisture levels, across sites.

Improvements in grain yield from deep placement of phosphorus usually vary from 0 to 10 % over grain yields from drilled phosphorus. Apparently spectacular benefits (49 %) have been obtained in lupin crops in Western Australia (Jarvis and Bolland 1991). This work did not isolate the benefits of deep cultivation from those of phosphorus placement. Henderson (1991) in a similar environment showed a 20 % grain yield response to deep cultivation for lupins. Contrary to their paper, Jarvis and Bolland (1991) rarely, if at all, found significant yield benefits from placing phosphorus 4-5 cm below the seed at typical farmer use rates of 9 kg/ha of phosphorus. However, there appears to be a slight (3-9 %) and consistent benefit to placing phosphorus 4-5 cm below lupin seeds.

Increasing phosphorus placement depth to 12-13 cm appears to give further grain yield benefits (Jarvis and Bolland 1991), but again at commercial rates of fertiliser application these benefits are small. Nebraskan work compared phosphorus either drilled or placed at 0, 5, 10, and 15 cm depths (McConnell *et al.* 1986). Here wheat grain yields improved with increasing depth of placement to about 11 cm on average, over the 9 sites in 2 seasons. Phosphorus that was drilled with the seed gave grain yields equal to the 11 cm placement. These workers suggested that shallow applied phosphorus may have an advantage over deeper placed phosphorus when frequent showers wet the soil surface.

In glasshouse conditions deep fertilizer placement has demonstrated dry matter yield increases over values for shallow placement. Phosphorus and nitrogen placed at 25 cm depth in a reconstructed soil profile showed a 7 % increase in wheat grain yield relative to 5 cm placement (Alston 1976). In this experiment soil drying from ear emergence onwards did not increase grain yield of the deep placed fertilizer over the shallow placed fertilizer treatment. This is not surprising, as the plants would probably have already accumulated sufficient nitrogen and phosphorus from this fertile soil. The fertility of the site is demonstrated by the lack of response to 50 kg/ha equivalent of applied phosphorus.

On soils that are inherently more fertile deep placement of phosphorus (Schultz 1975) and phosphorus and nitrogen (Westerman and Edlund 1985) may only give marginal benefits over conventional placement techniques. In contrast sandy soils of southern Australia show a sharp decrease in plant available nutrients with depth and are prone to surface soil drying particularly during anthesis and grain fill. Simpson and Lipsett (1973) found that under dry topsoil conditions placement of phosphorus at 55 cm depth improved the growth of lucerne by 34% but decreased growth by 16% compared to surface applied phosphorus when the topsoil was kept moist. However, a basal dressing of 40 kg/ha of phosphorus was applied to the top 3 cm of virgin soil and this resulted in preferential root development in the very top layer.

On newly cleared infertile soils, deep placement of phosphorus is of great advantage over surface applied phosphorus (Scott 1973, Jarvis and Bolland 1991). Field experiments have demonstrated this with dry matter production of barrel medic (*Medicago truncatula*) doubling with placement of phosphorus at either 5 or 10 cm depth compared to surface applied phosphorus (Scott 1973). Similarly, but in pots, surface applied phosphorus yielded either 36 or 24 % less dry matter of subterranean clover compared to 8 cm placement and was dependent on whether the surface soil was moist for 4 or 12 days in 30 days (Cornish and Myers 1977).

Deep placement of phosphorus on sandy dryland soils in India has shown a 10 % increase in grain yield over conventional placement (Singh *et al.* 1986). Wheat yields were consistently better when phosphorus was placed at 12 or 18 cm as opposed to 6 cm placement over 3 years of field experiments. Similarly, 10 cm placement of 45 kg/ha of phosphorus increased grain yield of peas by 13 % over topdressed phosphorus (Singh 1970).

Deep placement of urea has also been shown to be beneficial under very dry surface soil conditions. Placement of urea at 10 cm depth almost doubled barley grain yield over conventional topdressed urea in dry growing conditions (Hartman and Nyborg 1989). Application of 25 mm of water per week throughout the growth of the barley resulted in grain yields of both urea placement treatments being similar. In another experiment (Varvel *et al.* 1989) placement of ammonium nitrate at about 15 cm did not improve the uptake of nitrogen in wheat over the conventional placement.

From this review, it seems that, if subsoil macronutrients are limiting, and the topsoil experiences drying during grain fill, then plants would benefit from deep placement of such nutrients. If a plant is able to accumulate sufficient amounts of a nutrient prior to surface drying and the plant is able to remobilize the nutrient to actively growing tissue when required then it may not suffer from deficiency.

2.4.1.3 Laterally placed

Improvements in grain yield from fertilizer placed either below or to the side (laterally) have not been demonstrated. In a review of fertilizer placement, Cooke and Widdowson (1955) suggest that fertilizer placed in a band to the side and below potatoes is the best method and a similar result was obtained for cereals nearly 30 years later (Klepper *et al.* 1983). With potato and other horticultural production, application rates of between 1000 and 2000 kg/ha of compound fertilizers are commonly used. Such high rates often have toxic effects on seedling growth and may decrease plant emergence if the fertilizer is located too close to the seed.

Work with other horticultural crops has shown similar benefits to deep placement of phosphorus over laterally placed fertiliser. After 8 years of field studies with swedes and turnips, Reith (1959) concluded that the best placement for superphosphate was directly below the seed at a depth of 7 to 9 cm. This being superior to both topdressed and placed in a band at the side of the seed.

2.4.2 Foliar applications

Foliar applied fertilizers are usually more expensive, more difficult and inconvenient to apply than soil applied fertilizers and are consequently used sparingly. Foliar applied fertilizers are usually reserved for situations where soil applied fertilizers cannot be extracted from the soil by plants in sufficient quantities to sustain a plants requirements. Such situations are likely to occur on peat and muck soils (Pizer *et al.* 1966), alkaline soils (Hannam *et al.* 1984), soils experiencing severe surface soil drying (Gartrell and Walton 1984, Grundon 1980, Hannam *et al.* 1985) and on soils that did not received the initial level of recommended soil applied fertilizers.

Soils experiencing severe surface soil drying will only induce detrimental effects on plants if the plants are unable to accumulate sufficient quantities of the nutrient prior to, or at, the time of requirement. With the mobile nutrients, accumulation of these nutrients prior to anthesis, before topsoil drying during flowering, is unlikely to decrease plant growth (Alston 1976, Kasper *et al.* 1989). With the less mobile nutrients, large amounts of these may need to accumulate prior to flowering, in order for grain yield to be unaffected (Hannam *et al.* 1985) by drying of the more fertile topsoil.

2.4.3 Amelioration of water repellency

Any activity that wets dry, water repellent soil is likely to improve nutrient availability and plant uptake. Several techniques have been devised to improve soil wetting in a cropping phase and broadly these include; physical changes to the soil surface shape at appropriate times, controlling weeds prior to seeding, delayed seeding, addition of clay and the application of soil wetting agents. All of these methods can improve soil wetting at or before sowing but have not been investigated for their effects on plant uptake of nutrients alone.

2.4.3.1 Physical soil changes

Work done in southern Australia has demonstrated 4 possible ways that farmers can make physical changes to the soil for improved soil wetting. These include; furrow sowing, surface compaction, cultivating in the rain and deep ploughing.

2.4.3.1.1 Furrow sowing

Furrow sowing places the seed below where water will pond. This improves the chances of the seed becoming wet compared to the seed being placed on the crest (conventional sowing). Furrow sowing improved barley emergence and grain yield in an experiment by 3.3 times over conventional sowing (Bond 1972). However, not enough information is given in this report for a critical review of the work.

Recently, Blackwell *et al.* (1994) has demonstrated improved crop emergence and grain yield by using wide (>200 mm) furrows in water repellent Western Australian soils. This work shows up to 50 % yield benefits from wide and deep (>60 mm) furrows. However, the benefits were less in southern agricultural areas and, throughout the agricultural regions of Western Australia, wind erosion and weed control problems occur at many sites and this may limit farmer adoption of wide furrows.

2.4.3.1.2 Surface compaction

Improved cereal emergence due to surface compaction has been demonstrated on sandy wettable soils (Crabtree 1990). Improvements ranged from 5-20 % and when weeds were controlled grain yield was also improved. Other studies have shown that compaction increases cereal emergence in a range of soil types both in Australia (Radford and Wildermuth 1987) and elsewhere, including sandy soils (Pathak *et al* 1976). Emergence improvements are always attributed to better seed-soil contact.

Step pack rollers have also been suggested as being effective in improving emergence on water repellent soils in

South Australia. These rollers create about 10 small catchments per square metre in which water ponds, creating water pressure which aids the penetration of water into the water repellent soil.

2.4.3.1.3 Cultivating in the rain

Physical mixing of the water repellent topsoil during or soon after rain has been adopted by many farmers in South Australia to improve soil wetting on water repellent soils. Harrowing, combining, cultivating and ploughing all incorporate the rainfall to the depth of working and result in the more uniform surface soil wetting (King 1985). However, such sandy soils are very prone to wind erosion and any extra cultivations may increase the potential for wind erosion on sandy soils (Crabtree 1986).

2.4.3.1.4 Deep ploughing

Inverting the top 30 cm of soil buries the top 10 cm of water repellent soil and puts about 20 cm of wettable subsoil on the surface. This enables good plant establishment and vigour (King 1985) and is likely to offer the benefits of deep placement (as discussed in section 4.1.2) as the more fertile topsoil is placed deeper in the soil profile. However, this technique leaves the soil very prone to wind erosion. Once this new wettable surface becomes water repellent then the layer of water repellent soil is extended to 30 cm depth.

2.4.3.2 Early weed control and delayed sowing

Herbicides control young weeds, which establish after autumn rains. Removing these weeds early in the season restricts soil moisture losses from transpiration and results in the slow accumulation of topsoil moisture, which may eventually result in more even soil wetting. Where a clay subsoil exists, water can be stored in this layer, allowing the soil profile to wet from below more easily with subsequent rains.

Many farmers delay sowing by 2-6 weeks on these soils to ensure some pre-crop weed control (King 1985). The effectiveness of soil applied herbicides is limited by poor soil wetting. The onset of herbicide resistance makes delayed sowing on water repellent soils an important technique. However, delaying sowing is costly with potential yield losses.

2.4.3.3 Fine particle additions

Application of clay to water repellent sandy soils has improved soil wetting in southern Australia (Ma'shum *et al.* 1989). The application of dispersive koalinitic based sub-soil at 100-200 t/ha (usually containing 30-38% clay) has given marked improvements to soil wetting, thereby improving crop and pasture emergence and growth (Obst 1994). This clay has been shown to coat the hydrophobic organic material in a way that masks the effects of water repellence (Ward and Oades 1993). Kaolinite clay was more effective than other clay minerals at reducing water repellence in these sandy soils in the laboratory.

The most economical rate of applied subsoil clayey soil is still being determined. It seems that there is no replicated experimental work been done by South Australian researchers on clay rates in the field. The field work done by the Western Australian Department of Agriculture in the mid 1990’s, north of Albany (Carter and Summers – Figure 2.4.3.3.1), shows that of the four rates of clay based subsoil tested (0, 25, 50 and 100 t/ha) the highest rate gave the greatest grain yield response. Their work did not determine the shape of the grain yield response curve.

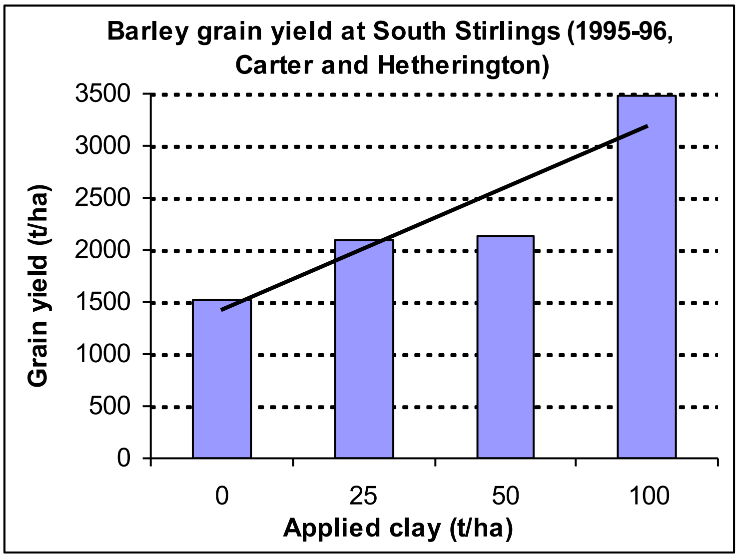


Figure 2.4.3.3.1: Barley grain yield response to applied subsoil at South Stirlings in 1995-96.

A clear message presented to local farmers by the Albany based workers was that low rates of clay (100 t/ha) were adequate for overcoming water repellence. They also concluded, from their one trial, that the clay should be broken down into small pieces before being mixed into the top 5 cm of soil. This view contrasted with claying pioneer Mr Clem Obst, from Mundulla in South Australia. Clem believes that 200-300 t/ha of subsoil (with 30-38% clay) needs to be thoroughly mixed into the water repellent soil to 10-15 cm depth with numerous cultivation passes (WANTFA newsletter, 1998). Clem believes that this is the most economical rate and way to apply clay.

More recent work by Crabtree (Figure 2.4.3.3.2 and Figure 2.4.3.3.3) has shown that clay rates higher than 100 t/ha of subsoil give useful grain yield improvements. This local work confers with the experience of claying pioneer Mr Clem Obst.

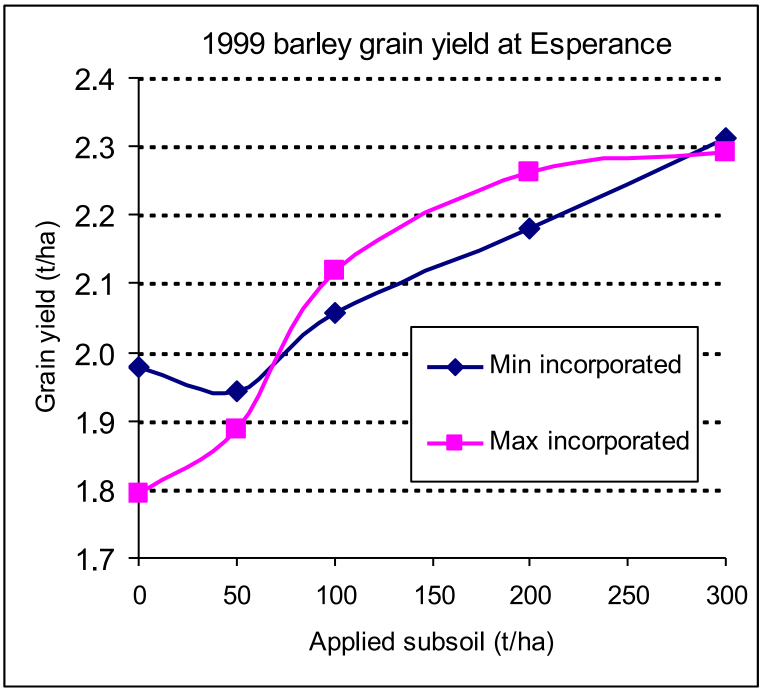


Figure 2.4.3.3.2: Barley grain yield response to applied subsoil at Dalyup, Esperance in 1999.

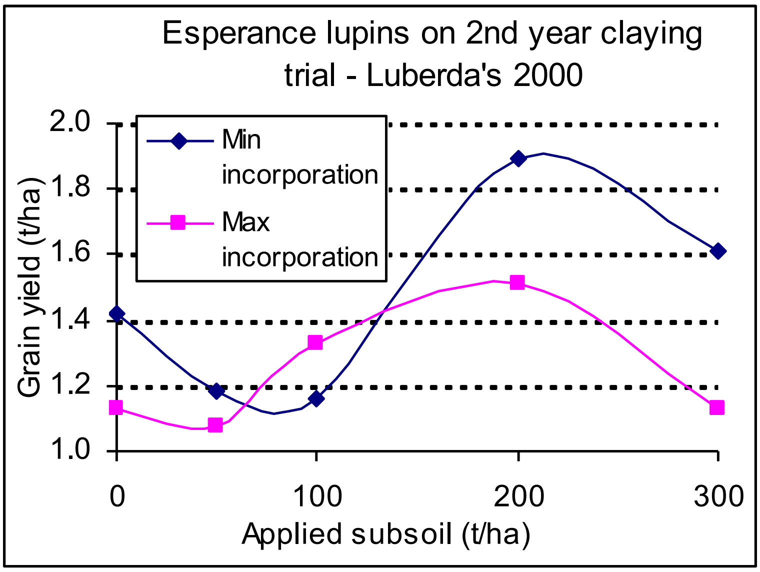


Figure 2.4.3.3.3: Lupin grain yield response to applied subsoil at Dalyup, Esperance in 2000 (lsd of 0.29 t/ha, P<0.05).

The addition of 2.5 t/ha of lime has given better field soil wetting on a water repellent soil on the south coast of Western

Australia and at higher rates in a laboratory (Ma'shum *et al.* 1989). This observation was the reason for follow up work which did not demonstrate improvements in soil wettability (Carter and Hetherington 1994). The reasons for the initial observed improvement in soil wettability from lime use is unknown. It is doubtful that it could be a surface area effect, as the rates are too low. The lime may have had a positive effect on the activity of microorganisms which break down the hydrophobic organic materials.

2.4.3.4 Wetting agents

Wetting agents have been experimented with for over 30 years, but have only recently been demonstrated to have potential benefit to broad acre agriculture. Wetting agents do increase the rate of water infiltration even on wettable soils (Pelishek *et al.* 1962). However, the earlier type of wetting agents used were too expensive to be considered for large scale application. Two more recently developed wetting agents (McGhie and Tipping 1983) have been shown to be superior to wetting agents previous used in the United States. The chemical structure of improved wetting agents required to give good soil wetting capabilities is discussed by Carnell (1984).

The new wetting agents (Wetta Soil® and Aquasoil®) performed similarly and much better than Aqua Gro® or a water control. Application of water, Aqua Gro and the new products resulted in a 3, 5 and 15 mm depth of water penetration into a water repellent soil (McGhie and Tipping 1983). Wallis *et al.* (1990) have shown that Wetta Soil was 6 times more effective at increasing ryegrass growth at 15 days after sowing than Aqua Gro at similar rates. A study of 10 soil wetters for soil potting mixes found Wetta Soil and Aquasoil gave superior soil wetting qualities to other tested products (Handreck, unpublished data).

Blanket rates of Wetta Soil and Aquasoil of 50 L/ha have consistently given improved crop and pasture emergence on severely water repellent sands (McGhie 1983). Banding of these wetting agents at 5-10 L/ha has also given improved crop growth (McGhie 1983) but at this rate routine adoption of this technique for broad acre agriculture is still too expensive. Rates lower than this have not been tested in field situations.

3. Summary

The causes of water repellence and the impact of water repellence on plant emergence are known. The impact of this poor emergence and continuing soil dryness on plant growth and response to applied and organically bound nutrients is less well understood. The water repellence problem, in broad acre farming, currently has no simple and economically viable measures available for farmers to adopt to improve their crop and pasture establishment.

Application of 200 t/ha of clay to water repellent topsoil does solve water repellence for perhaps 50-100 years or more. However, this is only an option where a source of clay exists near water repellent soil, spreading of the clay is expensive (but tax deductible), but is only likely to be profitable where clay is near the soil surface and within one kilometre of the site of application. Where claying is not practical furrow sowing improves emergence, but farmers are still commonly forced to delay sowing to ensure good pre-crop weed control.

Cultivating in the rain is too restrictive as rainfall events often do not extend long enough to enable large enough hectares of cultivation to occur while it is raining. Soon after rain stops this technique becomes much less effective and makes sandy water repellent soil prone to wind erosion. Applying blanket wetting agent at 20-50 L/ha has demonstrated large potential benefits, but is too expensive. Banding wetting agent at 5-10 L/ha, but not in a furrow, has shown some potential, but again was considered to be too expensive.

Plants are mostly unable to take up nutrients from dry soil. Most plants, except stolonic species, are unable to penetrate dry soil, and therefore their uptake of nutrients is minimal in dry soils. Nutrient uptake, may occur from dry soil, for some nutrients, with some plant species, but this is likely to be limited. Applied granular fertiliser, which is located in dry water repellent soil, is likely to be unavailable to plants. Organically bound nutrients are also likely to be mostly unavailable for plant uptake.

Farmers who crop water repellent soils have several major problems to deal with. Obtaining uniform crop establishment without weeds, wind erosion or insect problems, is made almost impossible without the adoption of some ameliorative technique(s). Farmers are currently forced to cultivate in the rain - where possible, sow later than desired, apply larger quantities of pesticides or use some form of reduced tillage, to improve crop establishment on water repellent soils. Staggered weed emergence in crops make post seeding weed control difficult and soil applied herbicides are often ineffective or can cause damage to the crop.

It is evident from this review that there is a major deficiency of knowledge of sustainable land management for water repellent soils that promote efficient use of rainfall and fertilisers. The purpose of the research described in this thesis is to explore the hypotheses that i) plant emergence can be improved by a combination of furrow sowing, press wheel use and low rates of banded wetting agent, and ii) dry surface soil can impede manganese uptake of lupins.

4. Improved pasture establishment and production on water repellent soils

Abstract

Pasture establishment and production is reduced by water repellent soils. Ameliorative techniques are explored with this study. Two field experiments were conducted on water repellent soils to investigate (i) the improvement in emergence of pasture species with furrow sowing and the use of a press wheel and banded wetting agent and (ii) the residual effectiveness (applied 2 years previously) of a wetting agent on pasture growth and composition.

In the first experiment, conventional level sowing (flat planting) was compared with furrow sowing using press wheels. Five pasture species were included and the furrow-sown treatments involved a banded wetting agent applied at four rates. Furrow sowing with a planter having press wheels increased the average emergence at 14 days after sowing by 133% relative to the conventional treatment and emergence was further increased 44% by banding 4 L ha^{-1} of wetting agent in the furrows. There was a large (up to a six-fold) increase in early pasture production (330 to 2,010 kg ha^{-1}) and a large effect on pasture composition due to the residual effect of a wetting agent applied 2 years previously. The proportion of subterranean clover (*Trifolium subterraneum*) in the pasture increased from 6 to 33% due to the use of a wetting agent.

Hypotheses

The hypotheses tested here for water repellent soils are that: (i) furrow sowing with press wheels and banded wetting agents will improve emergence of five pasture species and (ii) the residual effect of wetting agent will improve early pasture growth and composition compared with that observed on untreated water repellent soils.

Materials and Methods

Sites

The pasture establishment site was at north Gibson, 40 km north of Esperance, Western Australia in 1988. The soil was a grey sand overlaying lateritic gravelly loamy sand at 25-35 cm and a heavy textured horizon starting at 80-90 cm (duplex soil: Dy 4.82, Northcote, 1979). The topsoil (0-10 cm) had a pH of 4.8 (1:5 0.01 M $CaCl_2$), contained 10 g kg^{-1} clay and 11 g kg^{-1} organic carbon. The measured water repellence was 3.6 MED (molarity of ethanol drop test, King, 1981). The site has an average annual rainfall of 425 mm, most of which falls during the winter growing season from May to October.

The site chosen to investigate the residual effect of a wetting agent was at Wellstead, 80 km north east of Albany, Western Australia, and is a red/brown gravelly sand overlying clay at 45 cm (a yellow duplex soil, sand over clay, given as Dy 4.83 in the Australian classification, of Northcote, 1979). The topsoil had a pH of 5.0 (1:5 0.01 M $CaCl_2$), with a gravel content of 220 g kg^{-1}, a clay content of 40 g kg^{-1}, organic carbon of 12 g kg^{-1}, and a water repellence value of 3.9 MED. This site had been sown to barley 2 years earlier (in 1987) (Crabtree and Gilkes, 1999a) with various rates of a wetting agent (0-75 L ha^{-1}) applied at the time of sowing.

The site receives an average 440 mm annual rainfall but received 600 mm in 1988, which probably leached some of the 1987 applied wetting agent to below the surface soil.

The design for the 1987 experiment was a completely randomised block with three replicates. The wetting agent (Aquasoil®) applied in

1987 at 0, 5, 10, 20, 50, or 75 L ha^{-1} in a 2 cm wide band while sowing barley with press wheels trailing. A boom was mounted behind the press wheels with nozzles at 18 cm spacings and adjusted to spray water and wetting agent in the bottom of the furrows directly above the seed. Two years after these treatments, when pasture measurements were taken (1989) for this paper, the site had been levelled out by sheep traffic.

A Duncan multiple range test with controlled errors was conducted on the data. The least significant difference (LSD) was calculated at the $P = 0.05$ level.

Pasture establishment experiment

Plots for the pasture establishment experiment were 20 m long and 1.4 m wide. Weeds were sprayed with a 1:1 mix of paraquat [1,1-dimethyl-4,4-bypyridinium ion] and diquat at 2 L ha^{-1} seven days before cultivating the plots and seeding on 9 June 1988. Cultivation was done with a full-cut cultivator at 8 km hr^{-1} and at 8-cm deep across the plots. Species in all plots were sown with a cone seeder at 4 km hr^{-1}, except for the conventional treatment plots, which were sown at 8 km hr^{-1}. There were five pasture species tested for each of the five cultural techniques tested. This made five species by five techniques by three replicates, equaling 75 plots conducted in a randomised complete block design. The species included; subterranean clover, dryland lucerne (*Medicago sativa*), tagasaste (*Chamaecytisus palmensis*), phalaris (*Phalaris sp.*), and perennial ryegrass (*Lolium perenne*) and they were sown at 18 cm row spacings either in the furrow with wetting agent applied (at 0, 0.5, 1, and 4 L ha^{-1}) or into level soil without wetting agent (control). Heavy (33 kg) press wheels were trailed behind the seeder in all but the control treatments, and this improved furrow definition (Crabtree and Gilkes, 1999b).

The seeder had four rows of tines; the front row for cultivating, the middle two for sowing and the rear row for seed covering. Each row of tines was spaced at 36 cm and had 12 cm wide points attached. Sowing at the bottom of the furrow was achieved by lifting the rear covering tines and trailing press wheels. The control treatment plots were level sown with trailing harrows.

Wetta Soil® wetting agent was applied in the bottom of the furrows through solid stream nozzles, which were mounted to the rear of the press wheels. A 3 mm solid stream of wetting agent (at various concentrations) was applied, with the mix making a total spray volume of 30 L ha^{-1} for all treatments at a spraying pressure of 150 kPa. Because of the low volumes of water applied, a water only control treatment was not considered necessary. The wetting agent is a nonyl-phenyl-ethoxeate, a molecule with a hydrophobic and a hydrophilic end and has been specifically developed as a soil wetting agent (Carnell, 1984).

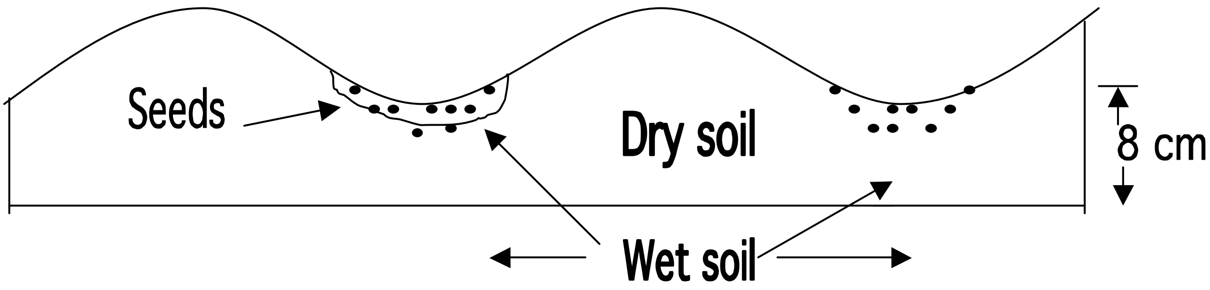


Figure 4.1: Random seed placement zone and wetting pattern observed after rain without wetting agent (left) and with 0.5 L ha^{-1} of wetting agent (right).

Seeds were sown at 5 kg ha^{-1}, 0-10 mm deep (Figure 4.1) and with 13 kg ha^{-1} of phosphorus as superphosphate. Plant counts were made in each plot at six 1-m row sections at 14 and 28 days after sowing. Since this pasture site already contained sub-clover and ryegrass, which germinated at the same time as the experimental plant species, we did background plant counts on neighbouring plots not sown to these species. This helped us calculate the treatment effect for only the seeds sown. However, the background plants probably contributed to increase variability in data for these two species.

Insects attacked the plants between 14 and 28 days after seeding, reducing plant populations of some species. This was despite chlorpyrifos insecticide being applied at 2 L ha^{-1} 9 and 22 days after seeding to kill redlegged earth mite (*Halotydeus destructor*), cutworm (*Agrotis* spp.) and vegetable weevil (*Listroderes difficilis*) larvae.

Effect of residual wetting agent on pasture

The residual effects of Aquasoil® wetting agent were determined by measuring effects on volunteer pasture growth and composition. This was 2 years after barley was sown in the furrow with a planter having press wheels and with wetting agent applied at six rates (from 0-75 L ha^{-1}) in June 1987 (see Chapter 4). The subterranean clover-rich annual-pasture had regenerated the previous year providing an adequate seedbank for regeneration in 1989.

Three plant samples for determining pasture dry matter (DM) production were cut from 0.25 m^2 of each plot on 3 July 1989, 2 years after the wetting agent had been applied. The samples were oven dried at 50°C for 48 hours, weighed and separated into subterranean clover, grasses (*Bromus diandrus* and *Hordeum leporinum*), and capeweed (*Arctotheca calendula*) components.

Results

Pasture establishment experiment

Furrow sowing with press wheels treatment resulted in increased emergence (plants m^{-2}) of all five species with an overall average increase of 133% at 14 DAS (days after seeding) relative to the value for the level sowing treatment (Table 4.1). By 28 DAS the increase in emergence was much less (41%) but still represented a significant and agronomically important improvement in emergence. Based on 14 DAS data there was a further 44% average improvement in emergence by applying 4 L ha^{-1} of wetting agent compared with the furrow sown with press wheels and no wetting agent treatments. The lowest rate of wetting agent (0.5 L ha^{-1}) decreased plant emergence for three species at 14 DAS by an average of 15%, but not significantly.

Table 4.1: Pasture species emergence (plant m^{-2}) at 14 and 28 days after seeding.

	Clover		Lucerne		Tagasaste		Phalaris		Ryegrass	
	------Days After Seeding------									
Treatment[†]	14	28	14	28	14	28	14	28	14	28
Level	39a[‡]	63	18a	na[§]	6a	44a	63a	78a	70a	117
F, 0.0	107b	77	50bc	na	14ab	63b	111a	128ab	141bc	156
F, 0.5	99b	91	40ab	na	23bc	68b	134b	126ab	119ab	139
F, 1.0	110b	98	46bc	na	21bc	72b	125b	142b	144bc	160
F, 4.0	127b	95	67c	na	24c	73b	197c	157b	189cd	156

[†] Treatment, where Level is level sown, F is furrow sown, and values are the rate of banded wetting agent in (L ha^{-1}).

[‡] Different letters in a column indicate results were significantly different at the P = 0.05 level. Absence of letters indicates there were no significant differences.

[§] na is not assessed (as plants were eaten by insects and affected by disease).

Continued insect attack and damage affected responses at 28 DAS compared with 14 DAS, and was particularly severe for the broad-leaved species (clover, lucerne and tagasaste). The insecticide was applied twice, although with limited success, because the trial area was surrounded by older pasture that resulted in re-invasion by insects. Lucerne was completely absent from the trial by 28 DAS.

Residual effect of wetting agent on pasture growth

Dry matter yields in July were increased six-fold in pastures where the wetting agent was applied 2 years earlier to a barley crop (Table 4.2). Production of subterranean clover was increased by 1.7 t ha^{-1} for the highest rate of applied wetting agent. The pasture composition improved with proportionally more subterranean clover and less grass and capeweed in the sward. Visual inspection of the plots at the end of the season (early October), showed that the plots treated with wetting agent maintained their superior pasture production.

Table 4.2. Dry matter (DM) yields in pasture on 3 July 1989, 2 years after application of banded wetting agent.

Wetting Agent (L ha^{-1})	Total DM (kg ha^{-1})	Partitioned DM (% of total)		
		Clover	Capeweed	Grasses
0	330	6	4	90

5	520	10	22	67
10	840	25	18	57
20	1490	44	7	50
50	1810	42	25	33
70	2010	52	12	36
LSD (P = 0.05)	120			

Discussion

Furrow sowing with a planter having press wheels doubled plant emergence for all species, compared with the conventional level sowing practice. The benefits were most evident during early plant establishment. These improvements due to use of press wheels are much greater than those measured for barley on similar water repellent soils (Bond, 1972; Crabtree and Gilkes, 1999a).

The application of a banded wetting agent gave further improvements in pasture emergence (47%) over the use of press wheels alone. A similar, although less spectacular, response was observed for barley (Crabtree and Gilkes, 1999a). Interestingly the larger sized seeds responded better to these ameliorative measures. This work clearly indicates that pasture establishment on water repellent soils in southern Australia is likely to benefit from furrow sowing, press wheel use, and low rates of banded wetting agent. The use of low rates of banded wetting agents is likely to be economical. However, this study is limited and cannot adequately answer economic questions.

An important observation is that at 0.5 L ha^{-1} of applied wetting agent the rain water was channelled into a narrow band (typically 10 mm wide) at the bottom of the furrow (Figure 4.1). Without wetting agent the water repellent soils usually wet to a 10-mm depth evenly across the flat part of the furrow (perhaps 60 mm wide). The wider spread of water that occurred in the soil without the banded wetting agent therefore ensured that more of the shallow placed seeds came in contact with water and emerged compared to the seeds from the 0.5 L ha^{-1} rate of banded wetting agent where a thinner and deeper soil volume was wetted. However, as a result of deep drainage, through preferred pathways, and surface drying of the water repellent soil, the emergence was not translated to more pasture growth and more seedlings died in the furrow for the treatment without wetting agent than when the wetting agent was used. The 4 L ha^{-1} of wetting agent wet to about 30 mm wide and subsequently ensured more reliable emergence. More precise seeders may allow lower rates of banded wetting agent to be used and they should be tested.

In the second experiment the residual effect of wetting agent greatly improved pasture quantity and quality. One year after application, in 1988, which was a very wet year, there were no visible differences in pasture regeneration across treatments, indicating even wetting of all plots. However, in 1989 even with the early rainfall being 50% higher than the average value, differences in early (July) pasture production between treatments were marked.

There was up to a six-fold increase in early pasture production where a wetting agent had been applied 2 years earlier. At a cost of about $A800 ha^{-1} for the 75 L ha^{-1} of wetting agent used in this experiment it is clearly uneconomical. However, these data demonstrate that amelioration of repellent soils can dramatically improve early pasture production and composition. In Mediterranean climates this limited early winter production occurs at a critical time for stock management and is of much greater value to farmers than pasture produced later in the season.

This work also clearly demonstrates that water repellence reduces pasture quality and quantity. These effects have major implications for subsequent pasture dynamics, including effects of insects, and soil nitrogen accumulated for following crops and pastures.

5. Banded wetting agent and compaction improve barley production on a water repellent sand

Abstract

Large areas of crop-land in Western Australia exhibit severe annual water repellency. Crop establishment is frustrated by the staggered emergence of plants, despite significant amounts of rain falling prior to the desired time of seeding. Three techniques were used to investigate improvements in barley (*Hordeum vulgare* L.) establishment on a water repellent sand: (i) spraying various rates of banded (2 cm wide) wetting agent while furrow seeding with press wheels, (ii) seed placement either in a furrow or in the side of a ridge, and (iii) compaction with press wheels or a Flexi-Coil® land packer. The application of wetting agent increased seedling emergence from 110 to 170 plants m^{-2}, dry matter production from 4.2 to 6.0 t ha^{-1} and grain yield from 1.96 to 2.60 t ha^{-1}, despite more weeds occurring with increasing rate of banded wetting agent. Use of press wheels, which also resulted in a furrow sowing condition, increased seedling emergence from 72 to 101 plants m^{-2} and grain yield from 1.70 to 2.13 t ha^{-1}. Furrow sowing, at 18 cm row spacings with full soil disturbance, in the absence of heavy press wheel compaction, had no effect on seedling emergence or grain yield. The application of wetting agent increased topsoil wetting and decreased spatial variability of emergence. Increased soil wetting may have increased plant nutrient availability (from fertiliser and soil), reduced

evaporation and possibly reduced water loss to subsoil on this duplex soil. The optimum degree of compaction required on water repellent soils is not known and needs further research.

Hypothesis

This study, with barley grown on a water repellent sand, examines the effects of (i) spraying various rates of banded (2 cm wide) wetting agent while furrow seeding with press wheels, (ii) seed placement either in a furrow or in the side of a ridge, and (iii) compaction with press wheels or a Flexi-Coil® land packer.

Materials and Methods

Two experiments were conducted at Beaumont, South Stirlings, near the south coast of Western Australia (33°S, 118°E). The soil was a red/brown gravelly sand overlying clay at 45 cm (a yellow duplex soil, sand over clay, given as Dy 4.83 in the Australian classification of Northcote, 1979). The topsoil (10 cm) had a pH of 5.0 (1:5 0.01 M $CaCl_2$), with a gravel content of 225 g kg^{-1}, a clay content of 30-60 g kg^{-1}, organic carbon of 10-12 g kg^{-1} and a water repellence value of 3.3 to 4.5 MED (molarity of ethanol drop test, as per King, 1981).

The soil was cultivated with a tined implement in April 1987 in a dry state to a depth of 10 cm. Plots were 1.44 m (8 rows) wide and 20 m long. All treatments were replicated four times. Barley (*Hordeum vulgare* L. cv. Stirling) was sown at a 2-3 cm depth on 29 June 1987 into dry soil at 80 kg ha^{-1} with 21 kg ha^{-1} nitrogen and 9.1 kg ha^{-1} phosphorus using a cone seeder with four rows of tines.

Banded Wetting Agent Experiment

The experimental design was a completely randomised block with banded wetting agent (Aquasoil®; a non-ionic surfactant), which was applied behind trailing press wheels at 0, 5, 10, 20, 50, and 75 L ha^{-1}, and concentrated in a 2-cm-wide band while sowing. The cast iron press wheels were in a gang of eight. Each wheel weighed 28 kg, was 10.3 cm wide, was 38.2 cm in diameter and was 'V' shaped with an internal apex angle of 120°. Each wheel had a total loading of 31 kg (the extra 3 kg are for axle, frame, and bearings), which applied an average vertical force of 3.0 N mm^{-1}. The apices of the press wheels were placed directly over the seed.

A boom was mounted behind the press wheels with nozzles at 18 cm spacings and adjusted to spray water and wetting agent in the bottom of the furrows, directly (vertically) above the seed. The spraying pressure was 150 kPa and a total of 300 L ha^{-1} of water plus wetting agent was applied for all treatments. The amount of wetting agent and water applied is equivalent to 0.03 mm (or 0.27 mm in the 2 cm strip) of rainfall. This water evaporated within an hour of application on a dry, warm (18-21°C) and windy (10-20 km h^{-1}) day.

Seed Placement and Compaction Experiment

This experiment was a split plot design with seed placement treatments as main-plots and compaction treatments as the subplots with 4 replicates. The seeds were placed either half-way up the ridge (conventionally) or in the bottom of the furrow (Figure 5.1).

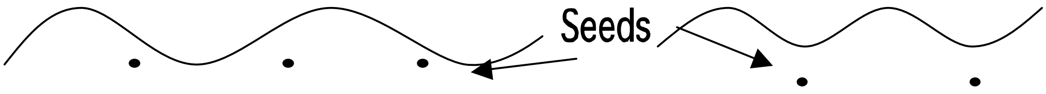


Figure 5.1: Conventional or side of the ridge sowing (left), versus furrow sowing for seeding in the bottom of the furrow (right).

Conventional seed placement was achieved by using all four ranks of the cone seeders tines with 10 cm wide points; the front rank of tines for cultivating, the middle two ranks for sowing, and the rear rank for seed covering (which destroys furrow sowing). Furrow sowing was achieved similarly, but with the middle two ranks of tines having 5 cm wide points and the rear rank removed. The dry cultivation provided a fine structured seedbed prior to seeding.

Compaction treatments were achieved using a gang of eight press wheels or a Flexi-Coil® land packer, with no compaction as a control. The Flexi-Coil® land packer was rolled over the plots immediately after seeding. It weighed 493 kg, was 1.83 m wide, and randomly covered 58% of the soil surface with an average force of 4.5 N mm^{-1}.

Measurements

Seventy-two soil core samples (0-10 cm) were taken on 16 October 1987 (109 days after seeding) on a 4 m square grid within the plots. The soil was then air dried for 72 hours, gently sieved with a screen having 2 mm openings and water repellence of the soil was measured. The MED test was used, which is the 'Molarity of an Ethanol Drop' that takes 10 seconds to be completely absorbed into the soil (King, 1981). The experimental soils had MED values ranging from 3.3 to 4.5 (severe repellence being >3.2; King, 1981) and the average MED for the sites of the two experiments being 4.0 (s.d. = 0.22) and 3.8 (s.d. = 0.22), for the compaction/placement and wetting agent experiments respectively.

Emergence was measured using ten 0.25 m^2 squares (quadrats) per plot, at 14 and 28 days after seeding (DAS). As a measure of spatial variability of plants, the lowest three quadrat counts in each plot were averaged, which demonstrate how poor emergence was on parts of some plots. Plants were cut from six random 0.25 m^2 squares per plot on 16 October to determine dry matter. Grain yields were measured by machine harvesting the crop from all eight rows of each plot on 20 November 1987. A Duncan multiple range test with controlled errors was conducted on the data with discrimination at the $P = 0.05$ level.

Results

The average annual rainfall for the experimental site is 415 mm, with 270 mm during the growing season of May to October. At an adjacent site in 1987, the year of the experiments, only 240 mm of rain fell with 157 mm falling during the growing season. Rain falling after October was too late to influence grain yield (Table 5.1). In the 2 years before the experiments, the site supported a subterranean clover (*Trifolium subterraneum* L. cv. Dinninup) dominant pasture.

Table 5.1: 1987 rainfall (mm) at a neighbouring site (Swain's farm).

Jan to April	May[A]			June			July			Aug	Sep	Oct
	E	M	L	E	M	L	E	M	L			
23	31	2	2	3	11	9	5	10	18	30	21	15

[A] all, E, M and L is the whole month or early, middle and late third of the month.

Applied Banded Wetting Agent

Increasing the rate of applied wetting agent increased emergence, decreased plant spatial variability, and increased DM production and grain yield (Table 5.2). The following equation gives the best fit for the grain yield data ($P < 0.001$, $n=4$, $r^2 = 0.98$)

$$\text{Grain yield (t ha}^{-1}\text{)} = 1.96 + 0.31\ [\text{wetting agent rate (L ha}^{-1}\text{)}]^{\ 0.16}$$

Table 5.2: Barley emergence, dry matter production at anthesis and grain yield, with applied wetting agent.

Banded wetting agent rate (L/ha)	Emergence 28 DAS (plants/m^2)		Top DW at anthesis (t/ha)	Grain yield (t/ha)
	weak areas[A]	average		
0	69	110	4.29	1.96
5	97	134	5.31	2.36
10	108	145	5.62	2.44
25	119	149	5.49	2.44
50	122	161	6.01	2.54
75	132	170	6.02	2.60
LSD at %5	11	16	0.54	0.24

A = as an indication of spatial variability.

There was vigorous growth of the subterranean clover (*Trifolium subterraneum*) weed in plots where the wetting agent, was applied at the higher rates, while the clover was sparse in the control plots. It is estimated that this amount of clover would have decreased barley grain yield by at least 25% (M. Ewing, *pers comm*).

Soil wetting was improved by addition of the wetting agent. On 16 October 1987, 7 hours after 9 mm of rain, the untreated soil was mostly wet to a depth of only 1 cm. Where 50 L ha^{-1} of wetting agent had been applied, the topsoil was wet evenly along the furrow to a depth of 10 cm. This topsoil had 10-50% of this soil volume wet, and the water had moved out from the furrow to an increasing distance with increasing rates of banded wetting agent. For the control treatment, the soil was mostly dry at depth in the furrow and usually only wet in the top 1 cm.

Placement and Compaction Experiment

Placement of the seed in the side of the ridge (conventional sowing), but with the use of a press wheel, increased emergence ($P<0.05$) by 40% and grain yield by 25% and greatly reduced spatial variability. The squares with least plants in each plot, which provide an indication of spatial variability, had three times more plants where the seed was conventionally sown with press wheels compared to sowing without compaction (56 versus 19 plants m^{-2} at 28 DAS).

No other treatment significantly increased emergence or grain yield (Table 2.3). There was no relationship between the severity of repellence and DM production in this experiment. However, water repellence in these experiments was above 3.2 MED in all cases, which indicates severe repellence.

Table 5.3: Emergence, dry matter at anthesis and grain yield, for barley sown either conventionally or in a furrow with different compaction treatments.

Seed placement	Type of compaction	Emergence [A] (plants/m^2) 28 DAS	Anthesis dry wt (t/ha)	Grain yield (t/ha)
Conventional	Nil - control	72	4.44	1.70
Conventional	Flexicoil	73	4.99	1.82
Conventional	Press wheel	101	5.04	2.13
Furrow	Nil	62	4.68	1.69
Furrow	Flexicoil	57	4.27	1.70
Furrow	Press wheel	74	4.09	1.79
LSD at 5% level =		17	0.75	0.19

[A] 200 plants/m^2 would be equivalent to 100% emergence.

Unintentionally, the conventional seed placement (seed located in the side of the ridge) was lost when press wheels were applied and became a furrow sowing treatment (Table 5.3). The soil near the seed with this treatment received more than the intended 3.0 N mm^{-1} compaction. Furthermore, for the furrow sown treatment, soil around the seed was compressed to a lesser extent than intended, as the sides of the press wheels compressed the sides of the 'already furrowed' soil surface. It is therefore likely that the only treatment that resulted in effective compaction and furrow placement was the conventional plus press wheel treatment, which resulted in the greatest yield.

Discussion

The application of a banded wetting agent in this experiment proved effective and is likely to be profitable for southern Australian farmers. By using the curve of best fit, and the costs and prices for Australian farmers, a rate of 1 L/ha of banded wetting agent (at A$5-10/L) would have returned about 200% on monies invested for most years since 1987. Benefits of the wetting agent in this study would have been greater if subterranean clover had been killed. Changing the row spacing, degree of tillage, and furrow shape and size are now considered important refinements to this system.

This narrow band of wetting agent, in conjunction with furrow sowing, ensured good soil wetting in the immediate vicinity of the seed. Both Bond (1972) and McGhie (1983) speculated that economic returns might occur with banded wetting agents and these results show that increased soil wetting has improved emergence, growth, and grain yield of barley.

The better soil wetting with applied wetting agent was both along and across the width of the furrow, thus decreasing spatial variability of plant growth. Once wet, the soil remained wettable throughout the growing season. Some topsoil in the plots without applied wetting agent remained dry and unimbibed, and viable seed was excavated from these patches at harvest time.

Wetting agents give several benefits to the plant-soil system. Better soil wetting releases applied fertilisers to the soil solution and increases mineralisation of organic matter. Uniform wetting along the furrows improved water infiltration and decreased surface ponding, as observed, and thereby it is likely to have decreased evaporation and increased water use efficiency of the crop.

Use of the press wheel increased emergence and grain yield with conventional sowing (which effectively became a form of furrow sowing) but not with the designated furrow sowing. This is thought to be due to better compaction of soil around the seed. The improvements are not due to furrow sowing alone as furrow sowing, even with press wheels, gave no improvements. Hence a combination of compaction plus furrow sowing increased emergence and grain yield. In contrast, Bond (1972) found that furrow sowing alone gave better emergence and grain yield. Perhaps the extremely low rainfall for this experiment is the reason for the difference. Flexi-Coil® land packing was of no benefit, possibly because it did not create a furrow-sowing-effect and compaction was random.

Compaction requirements of water repellent soils need defining. Dry sand does not compact well and water repellent soils are usually mostly dry at the desired time of sowing. In this work an average pressure of 3 N mm^{-1} was not adequate to provide optimal barley emergence. Other studies have shown that compaction increases cereal emergence for a range of soil types both in Australia and elsewhere (Radford and Wildermuth, 1987), including sandy soils (Pathak et al., 1976). Increased emergence is usually attributed to better seed-soil contact, which was not directly measured in this study. Because of the dry nature of water repellent soils, the compaction mechanics may be different than in wettable soils.

Press wheels had not previously been used in Western Australia, mostly because they had not been tested and proved beneficial and their rolling motion is hindered by tree stumps. However, this experiment demonstrates that increased grain yields can be obtained with press wheel use. The Flexi-Coil® land packer has given increased grain yields on a wettable soil (Crabtree, 1990) although that did not occur in this experiment.

More testing of these systems is needed. Variables such as furrow shape and size, compaction requirements, and rates and types of banded wetting agent need to be further researched in a range of conditions. Attention should also be given to the wind erosion risk and herbicide techniques due to the staggered emergence of weeds and because herbicides require uniform soil-water conditions. Numerous farmers in southern Australia have adopted elements of this management package with considerable success.

6. Furrows, press wheels and wetting agents improve crop emergence and yield on water repellent soils

Abstract

The rates of emergence of wheat and lupin were measured in 13 field experiments on water repellent sands. Conventional sowing was compared with furrow sowing either with or without the use of a press wheel and several rates of banded wetting agent. Measurements included severity of water repellence, plant emergence, rainfall, soil temperature at sowing and, at one site, the area of wet soil after sowing.

All ameliorative techniques improved emergence, with responses being greatest when seeds were sown into dry soil. Compared with conventional sowing, furrow sowing increased wheat and lupin emergence by an overall average of 16 and 41% respectively. The benefits were greater at the drier sites. Increases in emergence due to the use of a press wheel were sometimes small, although they always occurred (1-19%). It was visually observed that press wheel use gave more uniform seeding depth, reduced clods and ensured more accurate placement of banded wetting agent.

Banded wetting agent consistently improved wheat and lupin emergence, particularly where early rains were light and press wheels were used. The wetting agent increased the cross-sectional area of wet topsoil (0-10 cm) which was positively related with increased wheat emergence ($R^2 = 0.91$). At 0.5 L ha^{-1} of banded wetting agent, the soil along the furrow was four times wetter than without wetting agent. Wetting agent at 0.5 and 1 L ha^{-1} (with press wheels) increased wheat emergence by 6 and 11% and lupin emergence by 13 and 11%,

respectively. The high rates of banded wetting agent gave highest plant densities.

Grain yield was only measured at three sites. Furrow sowing did not increase grain yield, however, press wheels use with furrow sowing increased grain yield by 30%. Banded wetting agent increased grain yield. The highest rate increased grain yields by a further 9% above press wheels and furrow sowing.

Hypothesis

The hypotheses tested here is that furrow sowing, either alone or in combination with press wheels and banded wetting agents, will improve emergence of cereals and lupins on water repellent soils. Benefits from these techniques are difficult to predict as they relate to (i) the amount of early season rainfall, (ii) the severity of soil water repellence, and (iii) the temperature of the soil at sowing.

Materials and methods

Sites

Twelve experiments were conducted in the southern and northern agricultural regions of south Western Australia in 1988-89 (Table 6.1). Three sites were sown to lupins (*Lupinus angustifolius* - cv Danja) and nine to wheat (*Triticum aestivum* - cv Spear and Aroona [south] and Gutha [north]), with an additional site in 1987 (site 13) being sown to barley (*Hordeum vulgare* - Crabtree and Gilkes 1999a).

Table 6.1. Site details for the lupin (1-3) and wheat (4-12) experiments.

Site	Locality in southwestern Australia	Water repellence MED sd	Date Sown	Applied fertiliser (kg ha^{-1})	
				P	N
1	Dalyup	4.0 0.2	11 May '88	13	0
2	Gibson	3.0 0.2	9 June '88	13	0
3	Yerangutup	3.2 0.3	29 May '88	15	0
4	Condingup	3.4 0.3	30 May '88	13	25
5	Isseka	2.0 0.6	31 May '88	20	18
6	Neridup	3.6 0.3	7 June '88	10	22
7	Badgingarra	2.6 0.6	8 June '88	20	18
8	Badgingarra	1.9 0.5	16 June '89	20	18
9	Eneabba	1.5 0.8	15 June '89	20	18
10	Isseka	2.7 0.5	14 June '89	20	18
11	Kojaneerup	3.8 0.2	5 May '89	13	25
12	Moonyoonooka	3.7 0.5	14 June '89	20	18

The experimental soils were acidic, sandy-surfaced, duplex soils being either Dy 4.82 or Dy 4.42 (Northcote 1979). The surface sands were either grey or red-brown and overlay a heavier textured horizon at 35-95 cm depth. The topsoil (top 10 cm) had a pH of 4.5-5.3 (1:5 0.01 M $CaCl_2$), contained 1-5% clay, had 0.8-1.3 % organic carbon and had water repellence values of 1.5-4.0 MED (molarity of ethanol drop test, as per King (1981), n = 3). Average annual rainfall for the sites is 375-425 mm, most of which falls during the growing season from May to October.

Experimental design and treatments

The experiments followed either a complete (1988) or incomplete (1989) randomised factorial design. Seven rates of banded wetting agent were applied (0, 0.5, 1, 2, 4, 8 and 16 L ha^{-1}) at sowing. Seeding in the side of a ridge (conventional) was compared with furrow sowing, either with or without press wheels, and banded wetting agent at most sites (1-7 and 11). The treatments of wetting agents without press wheels was not included in the remaining 5 sites. All treatments were replicated 3 times.

The press wheels used were cast iron, in a gang of 8, each weighed 28 kg, was 10.3 cm wide and 38.2 cm in diameter; they were 'V' shaped with an internal apex angle of 120°. They had a total loading of 31 kg (an extra 3 kg for each wheel, for axle, frame and bearings) on each wheel, which applied an average vertical force of 3.0 N mm^{-1}. The apices of the press wheels were placed directly over the seed.

Experimental procedure and measurements

Sites were sprayed with standard rates of herbicides (either glyphosate or a diquat:paraquat mix) before sowing. The lupin sites were sprayed with 2 L ha^{-1} of simazine before cultivating. Pre-sowing cultivation was done at 8 km h^{-1} to a depth of 6-8 cm deep across sites 1, 2, 5, 6, and 9-12 to ensure weed control and to make the site conditions more uniform.

Seeding rates varied from 68-80 kg ha^{-1} for lupins and 50-80 kg ha^{-1} for wheat, with the lower rates being used at the more northern sites. Plots were either 20 or 40 m long, 1.44 m wide and seeds were sown at 2-4 cm depth with 10-20 kg ha^{-1} of applied P in the seed furrow (Table 6.1). The seeder had 4 rows of tines; the front row for cultivating, the middle 2 rows for sowing and the rear row for seed covering (with conventional seed placement only). The rows of tines were spaced 36 cm apart with 12 cm wide points attached to 3 of the rows of tines and 5 cm wide points attached to the third row of tines. All treatments were sown at 4 km h^{-1}, except for the conventional treatment which was sown at 8 km h^{-1} to ensure ridge sowing.

Wetta Soil® wetting agent was applied accurately to the lowest part of the furrow through solid stream nozzles. The nozzles were mounted on a boom attached behind either a gang of mounted press wheels or the combine frame. The wetting agent was mixed with water at different concentrations to obtain the range of application rates. These water plus wetting agent solutions were applied at a constant 30 L ha^{-1}; spraying was at 150 kPa pressure and in a 3-5 mm wide band. Because of the low volumes of water applied, a water only control treatment was not considered necessary. Insecticide (chlorpyrifos) was applied at 2 L ha^{-1} at site 2 only.

Six plant counts per plot, using a one metre length randomly located along a row, were measured 14 and 21-28 days after sowing (DAS) for lupins and wheat. For comparing emergence between sites, the plant counts were adjusted to percent of the conventional treatment.

Soil was collected from each site in a grid pattern before sowing, in order to measure the severity of water repellence (King 1981). This was done using the molarity of ethanol drop (MED) test on air dried topsoil (10 cm). Daily rainfall was measured at each site and the daily temperature was obtained from the Bureau of Meteorology's recording stations located near the sites.

At one site (11), 6 measurements of topsoil wetness, were taken at random, across a seeded row of topsoil (18 cm wide by 10 cm deep). This was done 8 DAS which was 10 hours after 16 mm of rain.

Curve fitting and analyses of data

Emergence response curves to banded wetting agent, both with and without press wheels, were fitted by eye. The highest plant emergence value achieved at each site, was designated as maximum emergence (or 100%). This value was used to determine the percentage of plants that did not emerge for the less successful treatments at each site.

The percentages of plants that did not emerge with conventional, furrow sowing (with and without press wheels) and 1 L ha^{-1} rate of banded wetting agent (with and without press wheels) were calculated for each site. The 1 L ha^{-1} rate was used as this is a rate farmers might consider to be economically viable.

Rainfall that might affect plant emergence was deemed to be that rain which fell between 1 April and the date of sowing (subsequently referred to as 'early rains'). The percentage of plants that did not emerge was then compared with the amount of early rains.

Results

All amelioration techniques used (furrow sowing, press wheel use and banded wetting agent) improved the emergence of both lupins and wheat compared to conventional seeding (Tables 6.2 and 6.3). Furrow sowing increased lupin and cereal emergence by an average of 41% and 16% across all sites respectively.

Press wheels

Applying press wheels usually improved emergence of furrow sown lupins and wheat at all rates of banded wetting agent (Figure 6.1). Press wheels increased lupin and wheat emergence by an additional 6 and 2%. Press wheel use was most beneficial with lupins at the low rates of banded wetting agent. Lupins were more responsive to press wheel use than wheat.

Banded wetting agent

Increasing banded wetting agent increased plant emergence and reduced spatial variation in emergence (data not presented) for both lupins and cereals. The lupins showed larger emergence increases to banded wetting agent than wheat.

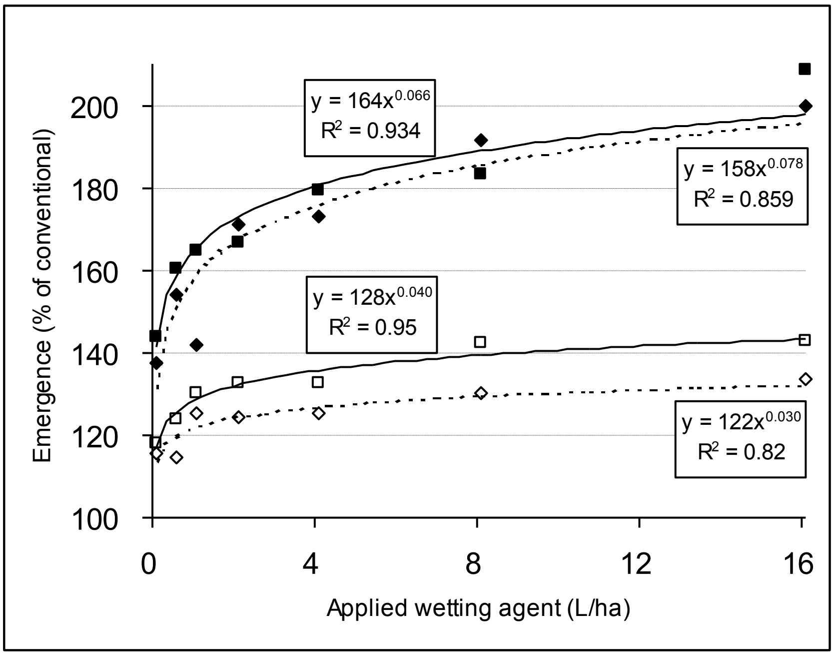


Figure 6.1: Effect of banded wetting agent, from all sites where comparisons existed, for with press wheels (■) and without press wheels (◆), on emergence of lupins (black shading, n = 3 sites) and wheat (outline of symbol, n = 5 sites {4,5,6,7 and 11}) on water repellent soils. (Power curves are fitted to x axis data plus 0.1 L/ha)

Table 6.2: Lupin emergence for conventional and furrow sown with and without press wheels and with rates of banded wetting agent (means, n=3).

	Conv.A	Percent plant counts at 14 DAS, with press wheels at the following rate of banded wetting agent (L/ha)							logrth respB
Site	(pl/m2)	0	½	1	2	4	8	16	(R2)
1	36	197	236	244	242	267	275	278	0.84
2	46	135	163	161	185	152	163	217	0.51
3	63	116	114	117	110	146	143	159	0.77
Avg	48	144	160	165	167	179	183	208	0.95
Without press wheels									
1	36	183	256	236	258	269	275	286	0.69
2	46	111	104	102	143	139	154	174	0.87

3	63	132	132	116	140	138	168	167	0.72
Avg	48	138	154	142	171	173	192	200	0.91

[A] = Conventional seed placement. [B] = Logarithmic correlation between banded wetting agent and lupin emergence.

Table 6.3: Cereal emergence for conventional and furrow sown with and without press wheels and with rates of banded wetting agent (means, n=3).

	Conv.[A]	Percent plant counts at 21-28 DAS, with press wheels at the following rate of banded wetting agent (L/ha)							Logrth Resp[B]
Site	(pl/m^2)	0	½	1	2	4	8	16	(R^2)
4	68	159	176	187	174	186	192	194	0.67
5	95	115	85	100	132	102	126	100	0.02
6	78	105	127	137	124	135	135	159	0.70
7	103	112	130	116	115	106	106	118	0.10
8	70	123	124	150	116	137	140	140	0.18
9	72	125	136	140	124	146	136	124	0.00
10	70	129	133	129	133	141	141	120	0.00
11	72	100	100	110	118	136	153		0.96
12	66	117	135	129	139	132	142	141	0.60
13	99	104	117	120	123	127	132	139	0.94
Avg	80	116	124	129	128	131	136	135	0.85
		Without press wheels							
4	68	163	149	179	156	171	179	175	0.31
5	95	96	94	100	114	127	127	126	0.83
6	78	115	117	138	123	129	133	137	0.50
7	103	109	111	109	109	94	95	96	0.72
11	72	103	110	117	132	121	136		0.78
Avg	83	116	114	125	124	125	130	134	0.85

[A] = Conventional seed placement.

[B] = Logarithmic correlation between banded wetting agent and cereal emergence.

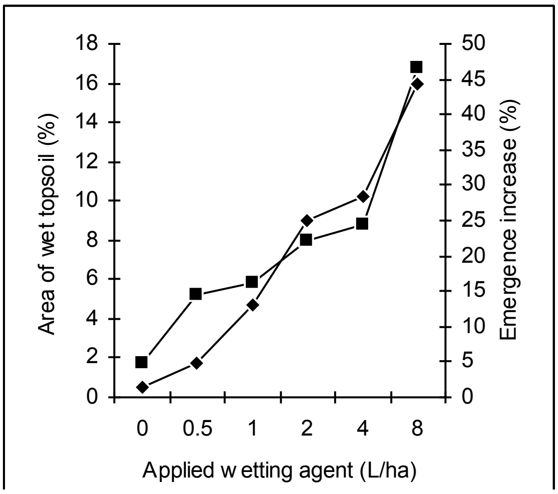
Low rates of wetting agent further increased plant emergence when press wheels were used. The 0.5 and 1 L ha^{-1} rate of banded wetting agent, with press wheels, increased lupin emergence by 13 and 15% and wheat emergence by 6 and 11%. Without press wheels, the emergence improvements were smaller and less consistent with banded wetting agent.

At the 8 and 16 L ha^{-1} of banded wetting agent (plus press wheels), lupin emergence was increased by 28 and 45% and wheat emergence by 19 and 18% compared with no banded wetting agent. The emergence response was greatest and usually more reliable with less early rain: wheat emergence increased by 34% at 8 L ha^{-1} of banded wetting agent (sites 4, 6 and 11, with press wheels).

Soil wetting

At site 11, increasing the rate of banded wetting agent, with press wheels, from 0 to 8 L ha^{-1} linearly increased the cross-sectional area of wet soil at 8 days after sowing by a factor of ten-fold from 300 to 3,170 mm^2 (with $R^2 = 0.91$). Better wetting of the soil with increasing banded wetting agent was also related to better cereal emergence (Figure 6.2).

Applying press wheels improved the relationship between increasing banded wetting agent and wet soil. The banded wetting agent greatly increased soil wetting, with the press wheels, even at the lowest rate of



wetting agent. However, without banded wetting agent the press wheels did not increase soil wetting.

Figure 6.2: Effect of banded wetting agent, with and without press wheels at site 11, on percentage of wet topsoil in a 10 cm by 18 cm cross-sectional area (■) of soil (n=6) and wheat emergence increase over conventional placement (◆).

Climate and site effects on cereal emergence

Increasing early rainfall improved cereal emergence for all treatments except the conventional seeding technique (Table 6.4). The conventional treatment had 31% less plants emerged at 21-28 DAS compared with the estimated maximum emergence. Grouping the data on the basis of (a) severity of water repellence, (b) soil water evaporative losses and (c) air temperature at the time of sowing, did not improve the relationships between emergence and early rainfall.

Grain yield responses

Insects and rabbits were attracted to the quickest and best emerging treatments which were selectively damaged after emergence. Better weed emergence in the ameliorated treatments, which were often not checked, complicated potential grain yield benefits from the ameliorative treatments.

However, 3 sites were harvested (2, 4 and 6; one lupin and two wheat) and showed that furrow sowing alone, did not increase yield (Figure 6.3). Addition of press wheels increased yield by 30%. Applying wetting agent increased grain yield, with a strong positive relationship between grain yields and rate of banded wetting agent, both with press wheels (R^2 = 90) and without press wheels (R^2 = 94).

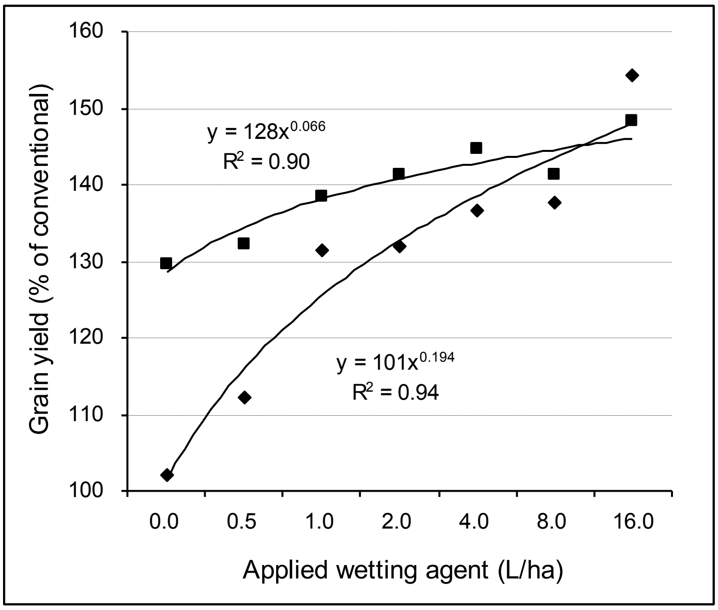


Figure 6.3: Effect of rates of banded wetting agent on crop yield, with (■) and without press wheels(◆), at sites 2, 4 and 6 (n=9).

Table 6.4: Estimated maximum emergence (% from maximum) for cereals: a measure of treatments not reaching the possible maximum and this measure compared to early rains.

Site	Estimated maximum emergence (pl/m^2)	Percentage of plants not emerged compared to the estimated maximum possible emergence at 21-28 DAS					April to sowing rains (mm)
		Control	furrow	furrow + PW^A	furrow + PW^A + WA^B	furrow - PW^A + WA^B	
4	131	40	19	16	10	15	183
5	122	22	20	20	16	11	181
6	114	53	18	15	11	16	177
7	120	14	11	4	3	12	225
8	98	29	11	12	8	-	150
9	99	27	14	8	4	-	176
10	96	26	7	6	3	-	199
11	111	35	33	36	29	23	56
12	99	33	7	17	12	-	202
13	155	36	36	34	26	-	68
	Average	31	18	17	12	15	
Early rainfall regressions against treatments							
R^2		0.11	0.78	0.80	0.78	0.84	
a		41.6	43.1	44.7	35.4	26.6	
b		-0.06	-0.16	-0.17	-0.14	-0.07	
Significance		ns	$P<0.05$	$P<0.05$	$P<0.05$	$P<0.05$	

^{A} = Press wheels, ^{B} = Wetting agent at 1 L/ha

Discussion

Furrow sowing, using press wheels and wetting agents, either singularly or in combination improved lupin and wheat emergence on these water repellent soils. Conventional sowing on water repellent soils gave about 30% less plants compared to the best treatment, even when there were good early rains (200 mm). Therefore the adoption of furrow sowing, press wheel use and/or banded wetting agents, even in wet years, is likely to improve crop emergence on water repellent soils.

Furrow sowing has previously been shown to improve cereal emergence in Southern Australia by up to 100% (Bond, 1972; King, 1985; Crabtree, 1996a). Furrow sowing allows water to flow into furrows where it ponds, which enables much water to bypass the topsoil. Then the water can penetrate to the subsoil through preferential flow down wettable zones (Ritsema and Dekker, 1994; Crabtree and Gilkes, 1999a). Consequently, some seeds that are planted in the furrow may remain in dry soil. Furrow sowing alone does not ensure even wetting and optimum emergence along the furrow as seen in Figure 6.2. Poor soil wetting and reduced emergence occurred in the furrow sowing only treatment compared to treatments where even low rates of banded wetting agent had been applied.

The addition of press wheels to furrow sowing improved lupin and cereal emergence. The press wheels improved furrow definition and may have compacted some of the dry soil around the seeds. Compaction of wettable soils increases seed:soil contact, when soils are moist (Hyder et al., 1955), which improves movement of water to seeds (Stout et al., 1961) but this may not occur for dry water repellent soils. Dry water repellent soils are difficult to pack as water is not present between sand grains to act as a lubricant and therefore press wheels may not improve the seed:soil contact to the same extent as on wettable sands. High press wheel pressure (>3 N mm^{-2}) on water repellent soils has been shown to improve barley emergence and grain yield (Crabtree and Gilkes, 1996a) which was presumably due to increased packing achieved at high pressures.

More work is needed to define press wheel pressure requirements for these soils and the modes of action of press wheels. The press wheels used in this work gave several benefits including better break-down of soil clods in the furrow, a more uniform sowing depth and increased precision and accuracy of the banded wetting agent.

Banding wetting agent in the furrows ensured more uniform wetting along the length of, and across the furrows. This better soil wetting further increased crop emergence, even at 0.5 L ha^{-1} of banded wetting agent. This low rate gave 4-times more wet topsoil than the soil without wetting agent.

All three amelioration techniques gave the largest wheat emergence responses for drier starts to the season. It is therefore in the driest seasons that these techniques may offer the greatest benefits in improved plant emergence. In wet environments or years farmers may find furrow sowing disadvantageous on shallow duplex (texture contrasting) soils due to the increased risk of water-logging in the furrows.

Increases in grain yield resulting from these ameliorative techniques were often restricted by wet growing seasons and more weed, insect and rabbit damage which was most common on the first emerging treatments. Most sites also subsequently wet uniformly soon after emergence and the beneficial amelioration effects increased, the sometimes, unchecked weeds which masked potential yield benefits from amelioration.

More recent work from sandy soils in Western Australia has shown that the banded wetting agents used in this work may encourage nutrient leaching from the topsoil (P. Blackwell pers comm) and this could influence grain yield. However, earlier work has shown that economic grain yield responses from banding low rates of wetting agents can occur with these wetting agents in dry seasons (Crabtree and Gilkes, 1999a).

In the last 5 years, widespread adoption of no-tillage sowing techniques on the south coast of Western Australia has ensured the use of furrow sowing and press wheels; most recently clay is being successfully used as a long-term ameliorant. Some farmers in this area, with the most water repellent soils are banding wetting agents at low rates (0.5-2.0 L/ha) and usually at wider row spacings of 25-36 cm, particularly with *Lupinus angustifolius*. The residual effect of better soil wetting that occurs in the previous years furrows has affected crop and weed emergence in the following year.

This work demonstrates that farmers would do well to immediately adopt furrow sowing and press wheel use in southern Australia for water repellent soils. In fact, since this work, local and widespread adoption of these techniques has occurred. Banding low rates of wetting agents has shown positive emergence and grain yields, enough so to encourage further experimentational refinement of the system.

7. Deep placement of Mn fertiliser on a sandy soil increased grain yield and reduced split seed in *Lupinus angustifolius*.

Abstract

Experiments were conducted over two years with *Lupinus angustifolius* L. on a site with acid sandy soil near Esperance, Western Australia to determine if deep placed manganese fertiliser increases lupin grain yield. Manganese at 4 and 8 kg ha^{-1} was placed below the surface immediately before sowing at 4, 20 and 30 cm and at 4, 8, 12, 16 and 20 cm in 1987 and 1988 respectively. Foliar Mn applied at 1 kg ha^{-1} when the first order laterals were in mid-flowering stage, was also compared.

Increasing the depth of Mn placement increased grain yield in both years. The deepest placed Mn increased grain yields by 255 kg ha^{-1} (10%) and 430 kg ha^{-1} (106%) in year 1 and year 2 over the shallow (4 cm) placed Mn. The higher responses to deep placed Mn occurred in year 2, the year with the driest spring and most intense aphid infestations. Foliar applied Mn was as effective as most deep placed Mn treatments, except for the highest rate (8 kg ha^{-1}) at the greatest depth (20 cm) in year 2. The higher rate of applied Mn gave the best grain yields.

Introduction

The hypothesis tested here is that deep placement of Mn into the wettable subsoil below drying of water repellent topsoils will increase the effectiveness of Mn fertilisers for lupins. I conducted two experiments in consecutive seasons (1987-88) to examine deep placement of Mn on lupin dry matter and grain yield and seed quality.

Materials and methods

Climate and Soils

The two experiments were conducted on the Esperance Downs Research Station, 30 km north of Esperance, Western Australia. The annual average rainfall is 494 mm, with an average of 335 mm falling in the May-October growing season.

Both experiments were on the same soil type at sites 200 m apart but in consecutive years. The soil was uniform white sand, with organic staining in the surface 10 cm, over ironstone gravel which ranged in depth from 25-40 cm over clay which started at 55-70 cm depth (duplex; Dy 4.56, Northcote 1979). For both sites the topsoil (top 10 cm) had 1-1.2% organic carbon, 1% clay, had a severe water repellence value of 2.6 using the molarity of ethanol drop test (MED; King, 1981) and a pH of 5.0 (1:5 0.01 M $CaCl_2$).

The experimental sites were cleared of native vegetation in 1951 and had not previously been sown to lupins or received Mn fertilisers. The sites had been cropped 6-7 times with cereals in rotation with annual pastures. In the previous 4 years, pasture was grown and was composed mainly of subterranean clover (*Trifolium subterraneum*), annual ryegrass (*Lolium rigidum*) and capeweed (*Arctotheca calendula*).

Experimental procedures

Both experiments were complete randomised blocks with 4 and 3 replicates for experiment 1 and 2 respectively. Plots were 38 m by 1.44 m (8 rows) wide with buffers. Paraquat (100 g L^{-1}) and diquat (100 g L^{-1} plus surfactant) were sprayed at 2.0 and 0.75 L ha^{-1} across the sites on 20 May 1987 and 18 May 1988. Glyphosate (360 g L^{-1}) was applied at 1.5 L ha^{-1} on 26 May 1987 to control capeweed.

The 1987 experiment was complicated by the occurrence of the disease rhizoctonia bare patch. Consequently, in the 1988 experiment, all plots were ripped to 30 cm with an Agrowplow® immediately before sowing. Deep ripping on these soils is known to decrease rhizoctonia bare patch in wheat and lupins (Jarvis and Brennan 1986, Brennan and Crabtree 1989). Experiment 2 was ripped again to 20 cm before sowing with a modified cultivator at 18 cm spacings. All plots were sown with a standard combine drill.

Danja and Gungurru lupins (*Lupinus angustifolius*) were inoculated with commercial rhizobium culture and sown at 75 kg ha^{-1} of viable seed on 2 June 1987 and 26 May 1988 into moist soil. Post emergent grasses were controlled with 1.25 L ha^{-1} of Hoegrass® (375 g L^{-1} diclofop-methyl) and 0.5 L ha^{-1} of Fusilade® (212 g L^{-1} Fluazifop plus surfactant) in July 1987 and 30 June 1988. High aphid numbers in 1988 were treated with two misted applications of 300 and 750 g ha^{-1} of Pirimor® (500 g L^{-1} Pirimicarb) and one misted application of 1.0 L ha^{-1} dimethoate (400 g L^{-1}) on 23 August, 6 September and 14 September, all these treatments were mixed with 0.2 % light spraying oil before spraying. However, crop damage from aphids still occurred.

Superphosphate (9.1% P) was drilled with the lupin seed at 120 kg ha^{-1}. Soil applied Mn was applied as either granular $MnSO_4$ (27% Mn) or liquid Mangasol® (17.3 % Mn) at 4 or 8 kg Mn ha^{-1}. The soil applied Mangasol® was sprayed into tubes mounted behind the tines of an Agrowplow at 33 cm intervals in 1987 and behind the modified cultivator at 18 cm intervals in 1988. Manganese was placed at 4, 20 and 30 cm depths for the 1987 experiment and at 4, 8, 12, 16 and 20 cm depths for the 1988 experiment. For some treatments foliar Mn was misted at 1 kg ha^{-1} as Mangasol® when the flowers on the first order laterals were in mid-flowering.

Measurements

Six plant counts were taken from 1 m of rows 14 days after sowing. Dry matter (DM) production was measured and youngest open leaflets (YOLS) were taken 67 and 106, and 87 and 113 days after sowing in 1987 and 1988 respectively by randomly selecting 20 plants per plot from areas not affected by Rhizoctonia. Plant samples were oven dried at 70°C for at least 48 hours, crushed and digested and analysed for Mn using atomic absorption spectrophotometry. Grain yield was measured by harvesting a 1.3 m strip from the centre of each plot on 18 and 23 November in 1987 and 1988, respectively.

Split seed and seed numbers were measured by randomly selecting (except from Rhizoctonia patches in 1987) 20 plants per plot prior to harvest. The pods from these lupins were divided into main stems and laterals. The pods were then thrashed and the seeds were divided into 5 categories; normal seeds, normal seeds but split, normal seeds incipiently split, shrivelled seeds and shrivelled split seeds, as used by Walton (1976). Each category of seed was weighed, counted and then digested and analysed for Mn content. Some of these categories have been subsequently grouped.

Results

Emergence was not affected by any treatment in either experiment with an average of 40 and 38 plants m^{-2} for experiments 1 and 2, respectively. These densities were considered adequate for optimal plant growth (Walton 1982), although recent work with modern varieties shows that a higher grain yield occurs with higher plant densities (W. Cowling *pers comm*).

Spring rainfall (1 September to 6 November) was 67 % more for experiment 1 (1987, see Table 7.1) than for experiment 2 (1988). Pan evaporation readings, for the adjacent Esperance town site (35 km south) during spring, were 4.4 and 4.8 mm day^{-1} for 1987 and 1988. Both factors thus make 1988 a drier spring than 1987.

Table 7.1. Esperance Downs Research Station monthly and weekly rainfall (mm).

Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
1987	19	2	24	49	94	53	41	53	49	20	44	13	463
1988	20	2	25	38	97	77	61	46	31	16	24	27	465
Avg †	21	2	25	38	55	61	63	63	53	40	32	19	494

Spring rainfall (mm)

	September				October				November		Total
Date	1	2	3	4	1	2	3	4	1	2	-
1987	15	0	5	29	0	7	13	0	16	2	87
1988	2	7	4	7	15	5	0	8	0	8	52

† Long term average (35 years)

Experiment 1

Applying Mn doubled average grain yield, doubled seed size, greatly increased the percentage of normal seeds, and decreased the area of rhizoctonia by 10% for all depths of Mn placement (Table 7.2). Applied Mn at 0, 4 and 8 kg ha^{-1} gave grain yields of 1362, 2647 and 2819 kg ha^{-1}, seed size of 85, 146 and 165 mg, the amount of healthy seeds were 7, 89 and 92 % and rhizoctonia was decreased from 10.6 to 9.7 and 9.5 %.

Shallow (4 cm deep placed) Mn, either as a liquid drilled at 33 cm spacings or as granules at 18 cm spacings gave equal plant responses.

Table 7.2. Effects of Mn placement and soil ripping in 1987 on lupin DM production, grain yield, grain quality and area of rhizoctonia.

Treat-ment No.	Mn applied (kg ha^{-1}) as:			Rip depth (cm)	Dry matter (kg ha^{-1})		Grain Yield (kg ha^{-1})	Area of Rhizo-ctonia (%)	Seed size (mg)	Seed number per ½ m^2	Percentage of Seeds that are:		
	granules†	liquid§	foliar‡		28 Aug	23 Sep					normal	shriveled	split+l#split
1	0	0	0	5	2390	4472	1251	23	88	711	7	21	50
2	0	0	4	5	2362	4427	2310	20	115	1007	83	6	6
3	0	0	8	5	2265	4499	2439	22	159	768	85	3	9
4	0	0	0	20	2631	5301	1295	7	68	948	6	19	56
5	0	0	4	20	2778	5343	2697	8	188	719	94	1	4
6	0	0	8	20	2788	5332	3011	5	173	869	96	1	3
7	0	0	0	30	3078	5814	1540	2	98	784	7	18	57
8	0	0	4	30	3056	5659	2933	2	136	1080	90	3	4
9	0	0	8	30	3227	5774	3007	1	162	928	96	0	3
10	4	0	0	30	3117	5694	2678	3	144	930	88	4	3
11	4	0	8	30	3103	5780	3060	2	191	801	98	0	2
12	0	1	0	5	2305	4423	2492	17	135	923	92	2	4
13	4	1	0	5	2420	4590	2544	19	159	801	95	1	3
14	4	0	0	5	2410	4523	2421	22	108	1124	86	3	7

15	8	0	0	5	2422	4624	2509	22	133	944	93	2	4
LSD (0.05)					234	446	212	3.3	27	166	2.5	2.6	2.6

†, ‡ and § = Mn applied as granules, foliar or liquid (drilled at the rip depth, at 36 cm spacings).

Incipient (or nearly) split.

Ripping to 30 cm decreased rhizoctonia bare patch, and increased early and late DM, grain yield, number of seeds and percent of normal seeds. Increasing ripping depth through 5, 20 and 30 cm increased yields with early DM values of 2339, 2732 and 3120 kg ha^{-1}, late DM of 4466, 5325 and 5749 kg ha^{-1}, grain yield of 2000, 2334 and 2493 kg ha^{-1}, the number of seeds being 829, 845 and 930 per 0.5 m^2 and the percentage of normal seed being 58, 65 and 64 %.

Increasing ripping depth decreased the area of rhizoctonia patch from 21 % without ripping to 7 to 2 % for ripping at 20 and 30 cm depth. Higher rates of applied Mn (8 versus 4 kg ha^{-1}) decreased the area of rhizoctonia patch by 30 % ($P < 0.10$) for 20 cm ripping and by 39 % (ns) for 30 cm ripping. For a detailed discussion on the effects of ripping on rhizoctonia at this site see Brennan and Crabtree (1989).

Foliar applied Mn gave similar grain yields to surface applied Mn, although it can not be directly compared to deeper placed Mn due to an additional response to cultivation which accompanied the deep placement of Mn.

Experiment 2

Applying 8 kg ha^{-1} of granular Mn fertiliser, at 4 cm depth, increased grain yield three-fold, seed size two-fold and the percentage of normal seeds eleven-fold (Table 7.3). Increasing the rate of applied

Mn from 0 to 4 and 8 kg ha^{-1} increased grain yield from 182 to 396 and 567 kg ha^{-1}, average seed size from 34 to 48 and 68 mg (being half of typical seed size - perhaps due to the bad aphid infestation) and the amount of healthy seeds from 3 to 13 and 34 %, respectively. Foliar applied Mn gave less grain yield, a lower incidence of normal seeds and a smaller seed size than did the deep placed (20 cm) Mn treatment.

These improvements were further increased by deeper placement. Increasing Mn placement depth from 4 to 20 cm doubled grain yield and percent normal seeds, increased seed size by 50 %, and decreased shrivelled seeds to one-seventh. Increasing depth of Mn placement from 4 to 20 cm increased grain yield from 466 to 945 kg ha^{-1}, amount of normal seeds from 29 to 71 % and seed size from 60 to 92 mg, while shrivelled seeds were reduced from 36 to 7 %.

The formulation of Mn drilled at seeding as granules or liquid had no effect on any plant measurement at either 4 or 8 kg ha^{-1} of Mn. Foliar applied Mn gave better grain yields, more normal seeds and larger seed size than surface applied Mn (P<0.001), but 8 kg ha^{-1} Mn placed at 20 cm depth was even better than foliar applied Mn (P<0.001). Foliar applied Mn plus drilled Mn granules gave a similar, but slightly better grain yield and other seed effects compared to foliar applied Mn alone.

Table 7.3. Manganese placement effects in 1988 on lupin DM production and grain yield and quality.

Treat-ment No.	Mn applied (kg ha^{-1}) as:			Mn depth (cm)	Dry matter (kg ha^{-1}) taken		Grain Yield (kg ha^{-1})	Seed size (mg)	Seed number per ½ m^2	Percentage of Seeds that are:			Main stem seeds (%)
	granules†	liquid§	foliar‡		1 Aug	9 Sep				normal	shriveled	split+l$^{\#}$split	
1	0	0	4	4	1177	7230	330	58	728	30	30	40	34

2	0	0	8	4	1177	7187	587	63	608	29	40	31	63
3	0	0	4	8	1184	7128	461	51	535	25	36	39	21
4	0	0	8	8	1239	7153	574	66	526	32	37	31	46
5	0	0	4	12	1176	7112	601	55	560	16	49	35	47
6	0	0	8	12	1223	7239	802	81	506	50	36	14	74
7	0	0	4	16	1178	7159	766	76	649	47	42	11	39
8	0	0	8	16	1186	7011	967	76	622	61	32	7	60
9	0	0	4	20	1256	7203	844	83	581	66	29	6	42
10	0	0	8	20	1229	7245	1045	101	542	77	15	8	67
11	0	0	0	-	1094	6814	182	34	568	3	24	73	63
12	0	1	0	-	-	-	797	71	594	29	29	41	21
13	4	0	0	4	1274	7178	410	48	411	14	38	49	65
14	4	1	0	4	-	-	876	75	505	48	31	21	45
15	8	0	0	4	1206	6879	567	68	623	42	30	28	42
LSD (0.05)					ns	ns	144	27	ns	29	14	12	ns

†, ‡ and § = Mn applied as granules, foliar or liquid (drilled at the rip depth, at 36 cm spacings).

Incipient (nearly) split.

Discussion

Grain yield increased progressively with increasing depth of Mn placement over two seasons. This is the first recorded field study, we know of, where a deep-placed micronutrient has increased grain yield relative to a shallow placed micronutrient. Glasshouse work in South Australia (Nable and Webb 1993) has shown that deeper placed zinc has improved Zn uptake with better grain yields. This is despite Zn being available in surface soil that was kept moist.

Benefits have been shown with many plant species from deep placement of macro-nutrients, in particular, deep placed phosphorus in Mediterranean climates. The increased grain yield in this study is considered mostly due to better Mn availability during spring. Surface soil drying has often been shown to restrict root uptake of surface applied nutrients. This has been found for phosphorus in wheat (Piper and de Vries, 1964), lucerne (Simpson and Lipsett, 1973), annual medic (Scott, 1973) and lupins (Jarvis and Bolland, 1991).

Crabtree et al. (1998) showed in a pot experiment that Mn uptake by lupins was reduced as the surface soil containing the Mn dried. This probably also occurred in this study as larger responses occurred with the deep placed Mn in the drier of the two seasons (1988).

Laboratory studies often show that an increase in Mn extractability occurs as soils dry (Ritchie, 1989). However, this is not always the case, and is influenced by several factors including pH, the ability of Mn to complex with organic, sesquioxide and clay mineral particles, and the biological activity of the soil. Despite this complex set of possible interactions Mn uptake by lupins is probably more dependent on survival of the plant root cortex, as a soil dries, than on the solubility of Mn (Crabtree et al., 1996).

Deeper placed Mn requires increasing ripping depth, which involves increased cost, and may prohibit deep (>15 cm) placement of Mn. It is likely therefore, that farmers on these soils, may benefit from placing Mn at a 10-14 cm depth. Farmers may also want to cultivate to these depths to control rhizoctonia (Brennan and Crabtree, 1989), avoid fertiliser toxicity (especially with wider row spacings), increase early root growth by providing softer soil below the seed, and providing deep placement of phosphorus.

The deep placement of Mn with phosphorus should be investigated. Plant roots proliferate where phosphorus is placed (Baeumer and Bakermans 1973, Drew and Saker 1978) and if Mn was placed with phosphorus, the plant may have greater access to Mn, with the potential to further improve grain yield.

In this study twice the recommended rate of applied Mn increased grain yield for all placement depths over yields obtained for the recommended rate (4 kg ha^{-1}). Thus recommended rates of Mn fertilisers may be too low and more than 4 kg ha^{-1} of Mn should be applied where Mn has not previously been applied. However, a combination of drilling 4 kg ha^{-1} of Mn, then doing a tissue test at early pod set, followed by a foliar spray if necessary, may be a cheaper option, as this research has shown that foliar applications are successful.

Foliar applied Mn gave equal or better grain yields than all soil placement techniques except the 8 kg ha^{-1} rate at 16 and 20 cm depths. However, foliar applied Mn has little residual value for subsequent crops, can cause crop damage (when applied from the ground) and the crop has to be monitored for correct timing of spraying.

The wide row spacing (33 cm) of the applied Mn in the 1987 experiment did not decrease lupin grain yield compared to the 18 cm row spacing in 1988. This is perhaps a consequence of lupins having a high requirement for Mn during pod fill (Gartrell and Walton, 1984) which occurs when lupins have had the opportunity to grow roots into the deep subsoil where the Mn was placed. Manganese is more available in acid soils and the Esperance sandplain is acidic with the subsoil (100-150 mm depth) being about 0.3 pH units lower than the topsoil. In this more acidic subsoil Mn might remain more available.

Farmers are therefore encouraged to adopt an integrated approach to Mn application on acidic sandplain soils, using deep placed (~12 cm) Mn, monitoring Mn in foliage in spring and using foliar sprays if needed. More long-term field experiments would be beneficial to better define situations that will respond to deep placed Mn. However, enough benefits currently exist to make deep placement of Mn a desirable practice. Rhizoctonia is greatly reduced by deep working (10 cm) which is often a useful benefit for Western Australian farmers who adopt no-tillage sowing techniques.

Wider rows also enable farmers to seed through thick cereal stubbles and farmers may need to deep band their fertilisers to consistently avoid fertiliser toxicity (Jarvis and Bolland, 1991). There is a potential yield advantage to deep banding both Mn and phosphorus and farmers may benefit by modifying their seeders to deep band a proportion of both these nutrients. Also, there is more moisture available at depth during spring when Mn uptake is essential to plant development. This work indicates that deep placing other micronutrients in environments where topsoils are dry during part of the growing season may be advantageous.

8. Drying of surface soil decreased *Lupinus angustifolius* root length and Mn uptake in a split root experiment

Abstract

In a glasshouse experiment, a split root experiment was used to determine the ability of lupins (*Lupinus angustifolius L.*) to take up Mn from dry soil either when young or at mid-flowering of the primary branches. Three soil watering regimes (maintained at field capacity, maintained below wilting point and alternating from field capacity to well below wilting point) were imposed after taproots had grown through topsoil and into a nutrient solution below. Four sequential harvests (11, 22, 37 and 49 days after planting) were taken to determine the effect of soil drying on lupin growth, Mn uptake and soil extractable Mn.

Soil drying, early in the lupin plants life, stopped the growth of lateral roots in the soil and slowed the growth of roots grown in sub-soil solution and of lupin tops. Soil drying decreased uptake of Mn in the tops to 13% of what was taken up under continuous wet soil conditions. Of the 13%, most (11%) was taken up while the soil was drying. Soil re-wetting enabled the plants to resume uptake of Mn and soil re-drying (just before anthesis) decreased the Mn concentration in the lupin stems to 4.8 ug/g, whereas stems of lupins grown in the wet and dry soils contained 10.3 and 3.3 ug/g respectively. Easily reducible and plant available soil Mn were not affected by soil wetting and drying treatments.

This work confirms that the uptake of Mn by lupin may be severely restricted by drying of surface soil at both the beginning and end of the lupin plants life. The decrease in root length restricted Mn uptake rather than the chemical form of Mn.

Top cone rests
Water medium for subsoil
Hole for lupins to grow

Hypothesis

The hypothesis tested here is that surface soil drying will affect Mn uptake by lupins growing in a sandy acidic soil.

Materials and Methods

Pot design and plants

Lupins were grown in a horizontal split pot, where the roots were in a soil medium above a liquid medium. The plants grew through 1 kg of soil, in a upper pot, into a lower pot, containing 1.1 L of nutrient solution. Both pots were cylindrical and made of polythene. The upper pot was 86 mm in diameter and 94 mm high and the bottom pot was 107 mm in diameter and 250 mm high. The upper pot had an inverted cone attached to the bottom which had a 90 degree internal angle and the cone height was 35 mm. A 10 mm hole in the centre of the cone was sealed with Terrastat® putty and Vaseline® which allowed the lupin taproots to penetrate into the bottom pot without water being able to pass between the pots (technique developed by Loss et al 1993). The nutrient solution level was kept 5-15 mm below the seal.

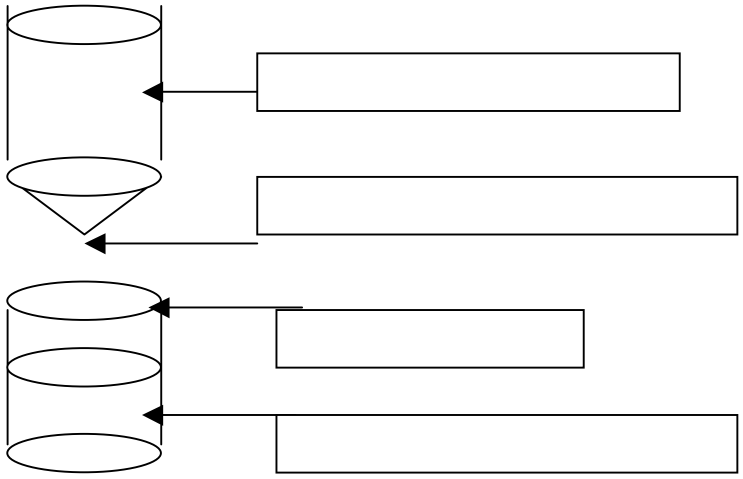


Figure 8.1: Pot design for Mn uptake study.

Seven lupin seeds were planted per pot and the plants were thinned to 3 plants per pot by 11 days after sowing (DAS). All plants were grown in soil kept near field capacity (12%; w/w) until 11 DAS when all of the lupin taproots had just passed through the seal (5-15 mm long) and into the nutrient solution below. The plants were watered twice daily and the upper pots were weighed once per day. Seed weight ranged from 120 to 130 mg and seed Mn levels ranged from 8 to 10 μg Mn/g of seed.

Experimental design

An incomplete factorial design was used which compared 3 soil watering regimes with 4 sequential plant harvests by 3 replicates. The pots were randomised and partly rotated within each replicate weekly. The watering regimes were; soil maintained near field capacity, soil dried after 11 DAS to below wilting point (1.4%; w/w), and soil dried from 11-22 DAS, re-wet to near field capacity from 22-37 DAS and re-dried to below wilting point from 37-49 DAS. Harvests were taken at days 11, 22, 37 and 49 DAS, the final harvest being when the primary inflorescences were at mid-flowering stage. The data were analysed using a one way analysis of variance.

Glasshouse conditions and nutrients added

The plants were grown in an evaporatively cooled glasshouse at the University of Western Australia from 9 November to 28 December 1990. The daily minimum and maximum air temperature ranged from 15-25 and 30-38°C. Pots were immersed in a root cooling bath at 18°C.

The soil used was topsoil sand from a virgin Lancelin brown sand site (Uc) with a pH of 5.3 (1:5 0.01 mol $CaCl_2$/L). This soil has been characterised by Brennan *et al.* (1980) as having 2% clay, 0.8% organic carbon and 0.7% free sesquioxides. The soil was dried for 36 hours then sieved to obtain the less than 2 mm fraction.

Basal nutrient solutions were pipetted onto the soil surface, dried and thoroughly mixed into the soil. The soil applied nutrients were (μg/g soil): H_3BO_3, 0.10; $CaCl_2.2H_2O$, 71.0; $CoSO_4.7H_2O$, 0.36; $CuSO_4.5H_2O$, 2.13; FeNaEDTA, 33.3; K_2SO_4, 71.0; $MgSO_4.7H_2O$, 19.9; $Na_2MoO_4.2H_2O$, 0.2; KH_2SO_4, 100 and $ZnSO_4.7H_2O$, 5.0. No Mn was applied to the soil as a preliminary experiment demonstrated this soil was able to supply sufficient Mn for adequate lupin growth.

The concentrations in the nutrient solution were (μM): H_3BO_3, 5.00; $CaSO_4$, 625; $CoSO_4.7H_2O$, 0.20; $CuSO_4.5H_2O$, 0.20; FeNaEDTA, 3.00; K_2SO_4, 600; $MgSO_4.7H_2O$, 20; $Na_2MoO_4.2H_2O$, 0.03; $NaNO_3$, 250; NaH_2PO_4, 20 and $ZnSO_4.7H_2O$, 0.75. The nutrient solution was changed once or twice weekly and the pH was kept between 5.8 and 6.2 with 5 mM of MES buffer used to stabilise pH changes (as developed by Ewing and Robson 1991). Air was bubbled through the solution at 1 bubble/second this being sufficient aeration to not cause damage to the lupin taproots.

Measurements

Fresh weight of whole shoots was recorded at each harvest after which the shoots were separated into youngest open leaflet (YOL), stem and rest of shoots. The soil roots were washed from the soil with deionised water and, along with the nutrient solution roots, were blotted dry, weighed and then measured for root length. Both shoots and roots were oven dried at 70^oC in paper bags for 72 h then re-weighed. After oven drying the soil-roots were separated into laterals and taproots.

The dry soil treatment resulted in sand granules being attached to the dead roots; consequently, estimates of sand mass mixed with the roots (by sub-sampling) were made for each sample and subtracted from the dry weight of the lateral roots grown in the soil.

During the course of the experiment the cotyledons and some leaves dropped from the plants, particularly the plants where the soil had dried. These leaves were collected, dried, weighed and their dry weights added to dry weights of the remainder of the plant.

An analysis of variance was done on the data. The root length and root weight in solution, at harvest on day 11 produced no data - as the roots had not grown through into the solution at this time. Therefore only 8 treatments were included in the statistical analysis for these parameters.

Plant shoot fractions from 2 replicates of each treatment were analysed for Mn content. The plant samples were digested in a nitric acid:perchloric acid mixture (Johnson and Ulrich 1959) and Mn determined using atomic absorption spectrophotometry.

Soil Mn was extracted using 2 extractants for each pot at each harvest and 3 samples were taken prior to commencement of the experiment The soil was teased from the roots and 2 lots of 5-g weights (dry weight equivalents) were sub-sampled from the soil from each pot and put into 25 mL vials. Extractant solution was then added to provide a 1:5 soil:solution ratio and shaken on an end over end shaker. As a measure of plant available Mn, a solution of $0.033M$ H_3PO_4 was added and shaken for 3 h (Salcedo and Warncke 1979) and as a measure of easily reducible Mn a solution of 1 M NH_4OAc containing 0.2% hydroquinone at pH 7 (Hammes and Berger 1960) was shaken for 10 minutes. The vials were then centrifuged at 894 G for 10 minutes, filtered with 0.45 μm Whatman No. 4 paper and solutions were then analysed for Mn using atomic absorption spectrophotometry.

Results

Plant growth

The split pot system separated the two media with the plug between the soil and solution effectively preventing transfer of solution to the soil and *vice versa*. The lupin plants constantly grew through time when watered to field capacity (Table 8.1). In contrast, topsoil drying slowed the growth of the shoots and roots in the topsoil and solution. Re-wetting the soil increased the rate of growth, and subsequent drying again slowed plant growth.

Table 8.1. Treatment, lupin age at each harvest, dry weights of tops and roots, root length and hydroquinone (Hq) and phosphoric acid (P) extractable Mn.

Har-Vest No.	Soil Water	Lupin age (days)	Root length (m)		Dry weight (g/pot)				Soil extr. Mn (ug/g)[B]	
			Soil	Solution	Shoots	Roots from Soil	Roots from Solution	Total	Hq	Phos
0	Dry	0	-	-	-	-	-	-	0.34	0.61
1	Wet	11	10.5	0.0	0.39	0.04	0.00	0.43	0.52	1.01
2	Wet	22	24.8	5.9	1.31	0.39	0.13	1.83	0.42	0.72
2	Dry	22	5.6[A]	1.3	0.71	0.05	0.05	0.81	0.45	0.80
3	Wet	37	30.2	17.9	2.74	0.75	0.47	3.96	0.35	0.77
3	Dry	37	5.6[A]	9.3	1.36	0.06	0.17	1.59	0.44	0.98
3	Dw[C]	37	15.7	7.3	1.49	0.28	0.19	1.96	0.30	0.65
4	Wet	49	25.7	22.1	4.17	0.99	0.68	5.85	0.46	0.83
4	Dry	49	6.5[A]	16.3	2.25	0.07	0.58	2.90	0.55	0.92
4	Dwd[C]	49	18.3	17.7	2.73	0.33	0.53	3.59	0.28	0.59
	l.s.d.	(P=0.05)	8.2	3.6	0.44	0.12	0.17	0.73	0.14	ns

	l.s.d.	(P=0.10)	6.7	3.0	0.36	0.11	0.14	0.61	0.11	ns

[A] Difficult to assess root length in dry soil, see text. [B] Extracted with Hq (0.2% hydroquinone in 1M NH_4OAc) or Phos (0.033M H_3PO_4). [C] Dw or Dwd refer to dry:wet or dry:wet:dry.

The roots in the solution grew well despite topsoil drying. Root growth was still occurring toward the end of the experiment although it was more due to the thickening of the roots rather than to elongation. The apparent root growth in the topsoil while drying was due to the taproot thickening and not to growth of lateral roots, as is demonstrated by the root length data. Sand particles adhered to the lateral roots which died soon after drying was imposed. The dry weight and length of lupin roots increased with soil re-wetting ($\underline{P}<0.05$) and soil re-drying stopped further growth of roots in the soil.

Mn uptake

Mn uptake for the wet soil increased with time (Table 8.2). However, soil drying from day 11 stopped Mn uptake, despite some (although not significant) uptake occurring as the soil dried from day 11-22. Mn movement into YOLs was slow for the plants that were grown in dry soil and the movement was from the stem, taproot and perishing lateral roots and not from the soil. Mn uptake from the drying soil treatments was 31% of Mn uptake from the wet soil during the same period (day 11-22). Re-wetting the soil tripled Mn uptake during the re-wet phase. However, once re-dried Mn uptake ceased again.

Table 8.2: Content (μgMn/pot) and concentration (μgMn/g) of Mn in lupin shoots, stem, rest, YOLs (youngest open leaflets) and seed in glasshouse experiment.

Har-Vest No.	Soil water	Lupin Age (days)	Mn content in plant shoots (μgMn pot^{-1})					Mn concentration in shoots (μgMn g^{-1} plant)				
			Total	Stem	Rest	YOLs	Seed	Total	Stem	Rest	YOLs	Seed
1	Wet	11	17	0.6	16	1.0	-	57	19	62	48	-
2	Wet	22	73	3.4	66	3.9	-	56	16	65	54	-
2	Dry	22	35	0.7	33	1.3	-	47	7	54	35	-
3	Wet	37	209	7.7	198	3.6	-	75	15	90	66	-
3	Dry	37	35	1.1	33	0.5	-	26	4	32	9	-
3	Dw^{A}	37	109	2.8	103	3.1	-	69	11	81	66	-
4	Wet	49	313	8.6	293	3.0	8.1	70	10	98	71	12
4	Dry	49	42	1.5	40	0.3	0.2	19	3	24	8	5
4	Dwd^{A}	49	147	2.8	141	1.4	0.9	53	5	69	40	9
l.s.d. (P=0.05)			36	1.6	37	1.6	2.9	15	2.7	17	22	1.5
l.s.d. (P=0.10)			30	1.3	30	1.3	2.5	13	2.2	14	18	1.2

[A] Dw or Dwd refer to dry:wet or dry:wet:dry.

Increasing Mn uptake was associated with increased length of the lateral roots in the soil ($P<0.05$). Also, increasing dry weight (DW) of lateral roots grown in the soil, increased with the uptake of Mn by shoots of lupins ($P<0.001$). The relationship being:

DW of lateral roots (g/pot) = {Mn in shoots (μg/pot) - 19.2}/263
$R^2 = 0.94$

Soil extractable Mn

Easily reducible (extractable) Mn did not alter with time for either dry soil or soil at field capacity (Table 8.1). However, two wetting and drying cycles did decrease the amount of easily reducible Mn. The phosphoric acid extractable Mn, which more closely reflects plant available Mn (Ritchie, 1989), showed no significant changes with soil moisture regime.

Discussion

Lupin lateral roots, grown in the soil, died as the soil dried to below wilting point. This decreased the growth of lupin shoots and the roots grown in the solution. The loss of lateral roots in the dried soil rendered the plants unable to extract Mn, and other nutrients, from the soil. During initial soil drying, the Mn content of shoots increased from 17 to 35 μgMn/pot. Much more Mn was taken up during the second drying (increased from 109 to 147 μgMn/pot). For both treatments the Mn content in lupin shoots was much less than for plants that had grown in permanently wet soil (313 μg/pot). Final Mn concentration in the whole shoots and seed was marginal for wet soil and severely deficient for the dry soil.

Root exudation can increase with soil moisture stress (Svenningsson *et al.,* 1990) and some plants are able to exude water from their roots into soil at night. Root exudates can reduce and complex Mn and make it more available for uptake (Godo and Reisenauer 1980). These exudates also provide microbial substrate which could aid microorganisms in reducing Mn. However, acid soils, as used here, inhibit Mn reducing microorganisms (Leeper and Swaby 1940).

In this study, plentiful moisture was available to the roots growing in the solution, but this water was not used by the lupins to improve their ability to extract Mn from the dry topsoil. This result is consistent with field responses on the Esperance sandplain where a usually sufficient Mn application in the topsoil resulted in severe Mn deficiency despite water being available at depth (Crabtree 1998, Gartrell and Walton 1984).

These results are also consistent with field observations where surface soil drying has inhibited the uptake of phosphorus by medics (Scott 1973) and copper by wheat (Grundon 1980). It also agrees with greenhouse experiments with phosphorus by corn (*Glycine max* L. Merr.) (Marais and Wiersma 1975) where uptake was limited by soil drying.

In contrast, Thorup (1969) found that roots of tomato plants (*Lycopersicon esculentum*) grew into dry soil, transporting some water into this dry soil which enabled uptake of phosphorus. Similarly, Nambiar (1977) found that ryegrass (*Lolium multiflorum* Lam.) roots grew in dry soil and may have absorbed Mn from dry soil.

It would appear that tomatoes have the ability to initiate roots in dry soil (Thorup 1969), whereas ryegrass roots may have the ability to persist in dry soil (Nambiar 1977). However, both of these observations were from studies where the roots were sealed or closed to evaporational loss. Lupins grown in this study were open to evaporative loss from the sandy soil, and perished rendering them unable to take up nutrients from the dry soil.

It is clear that different plant species differ in their ability to sustain root growth and function in dry soil. Work with stoloniferous bermudagrass (*Cynodon dactylon* L.) clearly demonstrates its ability to transfer moisture from wet to dry soil, even in an open system (VanBavel and Baker 1985). In this work, where there are high evaporative losses, *Lupinus angustifolius* did not demonstrate a capacity to transfer water into lateral roots in the dry soil layer. Such movement was not measured, but the roots did dehydrate quickly.

Under field conditions it is therefore likely that surface soil drying in spring will severely limit the uptake of Mn by lupins. Since soil drying caused the death of lupin roots in dry soil in this experiment it is likely that all nutrients in the dry topsoil, will be unavailable to lupins under these drying conditions.

9. General Discussion

This brief chapter identifies the major findings of the research and points out limitations and needs for further work. It also makes suggestions for best management practices for water repellent soils and considers the economics of management options.

Plant emergence was consistently improved by furrow sowing, applying press wheels and banding low rates of wetting agents on water repellent sandy soils from southern Western Australia. All eight plant species tested responded to these treatments. Emergence typically improved by 20-50 % by adopting furrow sowing with press wheel over conventional sowing techniques on these water repellent sands. As a result of this, and other work that was carried out more than ten years ago, many farmers on the south coast with water repellent soils, have adopted the furrow sowing technique and press wheels. The addition of banded wetting agent gave further emergence improvements of 10-50 %, depending on the rate used. Low rates of banded wetting agent (0.5 L/ha) usually increased plant emergence by 10-20 %. Banded wetting agent, applied at any rate, always increased plant emergence along the length of the furrow. Without banded wetting agent there was more plant spatial variability along the furrow, with patches where no plants emerged.

Banded wetting agents at low rates (<2 L/ha) gave narrow (8-13 mm) bands or columns of wet soil in the bottom of and below the furrow. Depending on the accuracy and consistency of seed and wetting agent placement, this narrow column of wet soil, may not always improve plant emergence, particularly at the lower rates. The pasture establishment experiments showed this problem where seeds were scattered across the base of the furrow. In this experiment the 0.5 L/ha of wetting agent sometimes gave less plant emergence than no banded wetting agent and the laboratory studies showed why.

In the laboratory studies artificial furrows were made with very low rates of banded wetting agent applied and demonstrated improved water infiltration but in a narrow band. At 0.10 L/ha of banded wetting agent, applied water ponded in a furrow for one-third of the time that control with no wetting agent did. Further work in this area could focus on precision seed placement and banded wetting agent at 0.10-0.5 L/ha.

Weed control was a consistent problem in field research and is one reason why grain yield was not consistently improved. It is possible that, soil wetting between furrows did not occur at some sites throughout the season where wetting agents were used and did occur where no preferred wetting path was created without wetting agent. Therefore some nutrient unavailability, in this inter-row area may have occurred, thereby penalising grain yield with wetting agent use. Furrow shape was not explored in this study and this is also likely to affect weed control, capacity of the inter-row area to wet up and the furrow's capacity to catch water.

Future technologies incorporating the findings of this work will have a positive outcome for lupin growing in water repellent soils. The genetic engineering of lupins to tolerate the broad spectrum herbicide Basta® may solve the staggered emergence problems with weeds. The low rates of banded wetting agent, as shown here, do improve lupin emergence, and in conjunction with more precise seed placing seeders (no-tillage seeders), and Basta applied perhaps 4-6 weeks after seeding, could make cropping these water repellent soils more economic.

The drier the soil conditions the better was the crop emergence response to these three ameliorative techniques. However, the procedures could not be advocated unless stubble cover is maintained and soil disturbance kept to a minimum, as these sandy soil types are easily eroded by wind.

Placing the manganese fertiliser below water repellent topsoil improved lupin grain yields markedly. It appears that this is the first recorded field study showing grain yield improvements, from any broad acre crop, due to deep placement of a micro-nutrient. More work should be done to determine the extent of these large lupin responses to deep placed manganese. This work now has new relevance, even on wettable topsoils with the current large scale adoption of liming throughout Western Australia. Placing Mn into more acidic subsoils is likely to improve Mn uptake by lupins compared to uptake from the surface soil onto which lime has been applied.

The glasshouse experiment demonstrated that lupin roots were unable to grow in dry soil or take up manganese from dry soil. This was consistent with the field work where the surface applied manganese was not taken up by the lupins during a dry period in spring. It is likely that banding manganese and other nutrients below the seed, also in a precise and narrow band, in conjunction with banded wetting agents could lead to further grain yield benefits.

The best management practice for farmers who need to crop water repellent soils will vary depending on their individual situation. Mixing clay into the surface soil is likely to be a long-term economic solution for most farmers. However, this ‘claying’ technique requires that clay is within 1.5 m of the soils surface and within about 1.0 km from the area requiring application of the clay.

For areas where claying is not possible, farmers should consider no-till sowing with press wheels. This technique ensures that crop seeds are placed in the bottom of furrows that will more readily wet than if randomly located through an uneven topsoil. Further economic improvements are likely if farmers band small rates of wetting agent into the bottom of the furrow – this will ensure more even crop germination along the furrow.

10. References

Adhikari, M., and Chakrabarti, G. (1976). Contribution of natural and microbial humic acids to water repellency in soil. *Journal of Indian Society of Soil Science.* 24;217-9.

Alexander, M. (1980). Effects of acidity on micro-organisms and microbial processes in soil. In *Effects of Acid Precipitation on Terrestrial Ecosystems.* Eds. T.C. Hutchinson and M. Havas. pp. 363-80. Plenum Press, New York.

Alston, A.M., (1976). Effects of depth of fertilizer placement on wheat grown under three water regimes. *Australian Journal of Agricultural Research.* **27**;1-10.

Aylmore, L.A.G., Karim, M.J., and Quirk, J.P. (1971). Dissolution of gypsum, monocalcium phosphate, and superphosphate fertilizers in relation to particle size and porous structure. *Australian Journal of Soil Research.* **9**;21-32.

Bache, B.W. (1980). The acidification of soils . In *Effects of Acid Precipitation on Terrerstrial Ecosystems.* Eds. T.C. Hutchinson and M. Havas. pp. 183-202. Plenum Press, New York.

Bahrani, B., Mansell, R.S., and Hammond L.C. (1973). Using infiltrations of heptane and water into soil columns to determine soil-water contact angles. *Journal of American Soil Science Society.* **37**;523-4.

Baker, J.M., Tucker, B.B. and Morrill, L.G. (1970). Effects of sources of phosphate under varying soil temperature and moisture regimes on the emergence of winter wheat. *Journal of American Soil Science Society.* **34**;694-7.

Barlow, E.W.R. (1986). Water relations of expanding leaves. p.45-58. *In* N.C. Turner and B. Passioura (*ed.*) Plant growth, drought and salinity. C.S.I.R.O. Melbourne, Australia.

Barrow, N.J., (1985). Reaction of anions and cations with variable-charge soils. *Advances in Agronomy.* **38**;183-230.

Barrow, N.J., (1974). The slow reactions between soil and anions: 1. Effects of time, temperature, and water content of a soil on the decrease in effectiveness of phosphate for plant growth. *Soil Science.* **118**;380-6.

Barrow, N.J., and Shaw, T.C. (1975). The slow reactions between soil and anions. 2. Effect of time and temperature on the decrease in phosphate concentration in the soil solution. *Soil Science.* **119**;167-77.

Bateman, D.F. (1961). The effect of soil moisture upon development of poinsettia root rots. *Phytopathology.* **51**;445-51.

Biddiscombe, E.F. (1975). Effect of moisture stress on flower drop and seed yield of narrow-leafed Lupin (*Lupinus angustifolius* L. *cv.* Unicrop). *Journal of Australian Institute of Agricultural Science.* **42**(2);70-2.

Blackwell, P., Morrow, G., Webster, A. and Nicholson, D. (1994). Improvement to crop production from wide furrow sowing in water repellent sand; a comparison to level sowing methods. Proceedings of the 2nd National "Water Repellency Workshop", Perth, Western Australia. Pages 106-13.

Bloom, P.R., and McBride, M.B. (1979). Metal ion binding and exchange with hydrogen ions in acid-washed peat. *Journal of American Soil Science Society* **43**;687-92.

Bond, R.D. (1964). The influence of microflora on the physical properties of soils. II. Field studies on water repellent sands. *Australian Journal of Soil Research.* **3**;123-31.

Bond, R.D. (1968). Water repellent sands. *Transgressional 9th International Congress of Soil Science.* **1**;339-47.

Bond, R.D., (1969). The occurrence of water repellent soils in Australia. Proc. of symposium on water repellent soils. May 6-10, 1968, Riverside, University of California.

Bond, R.E., and Harris, J.R. (1964). The influence of microflora on physical properties of soil. I. Effects associated with filamentous algae and fungi. *Australian Journal of Soil Research.* **2**;111-22.

Bond, R.D., (1972). Germination and yield of barley when grown in a water repellent sand. *Agronomy Journal*. **64**;402-3.

Bornemisza, E. (1964). Wettability of soils in relation to their physico-chemical properties. Diss. Abstract. 3771.

Bouaziz, A., and Buckler, L. (1989a). Modelling of wheat imbibition and germination as influenced by soil physical properties. *Journal of American Soil Science Society* **53**;219-27

Bouaziz, A. and Buckler, L. (1989b). Modeling wheat seedling growth and emergence: I. Seedling growth affected by soil water potential. *Journal of American Soil Science Society.* **53**;1832-8.

Brennan, R.F., Gartrell, J.W., and Robson, A.D. (1980). Reaction of copper with soil affecting its availability to plants. I. Effect of soil type and time. *Australian Journal of Soil Research.* **18**;447-59.

Brennan, R.F., Robson, A.D., and Gartrell, J.W. (1983). Reactions of copper with soil affecting its availability to plants. II. Effects of soil pH, soil sterilization and organic matter on the availability of applied copper. *Australian Journal of Soil Research.* **21**;155-63.

Brennan, R.F., Gartrell, J.W. and Robson, A.D. (1984). Reactions of copper with soil affecting its availability to plants. III. Effect of Incubation temperature. *Australian Journal of Soil Research.* **22**;165-72.

Brennan, R.F., Gartrell, J.W., and Robson, A.D. (1986). The decline in the availability to plants of applied copper fertilizer. *Australian Journal of Agricultural Research.* **37**;107-13.

Brennan, R.F. and McGrath, J.F. (1988). The vertical movement of zinc on sandy soils in southern Western Australia. *Australian Journal of Soil Research.* **26**;211-216.

Buxton, E.W., (1957). Some effects of pea root exudates on physiologic races of *Fusarium oxysporum* Fr. F. *pisi* (Linf.) Snyder and Hansen, *Trans. British Mycological Society.* **40**;145-54.

Carnell, W.J. (1984). Investigation of soil wetting agents. West. Aust. Govt. Chem. Laboratories. Report No. 28.

Carter, D.J., and Hetherington, R.E. (1994). Claying of water repellent soils in the Albany district of the south coast of Western Australia. Proceedings of the 2nd National "Water Repellency Workshop", Perth, Western Australia. Pages 140-44.

Chao, T.T., Harward, M.E. and Fang, F.C. (1962). Movement of S35 tagged sulphate through soil columns. *Journal of American Soil Science Society.* **26**;27-32.

Chaudhry, I.A., and Cornfield, A.H. (1967). Effect of moisture content during incubation of soil treated with organic materials on changes in sulphate and sulphide levels. *Journal of Science Food and Agriculture.* **18**;38-40.

Chaudhry, F.M., and Loneragan, J.F. (1970). Effect of nitrogen, copper, and zinc fertilizers on the copper and zinc nutrition of wheat plants. *Australian Journal of Agricultural Research.* **21**;865-79.

Chen, A.W.C., and Griffin, D.M. (1966). Soil physical factors and the ecology of fungi. V. Further studies in relatively dry soils. *Transactions of the British Mycological Society.* **49**;419-26.

Chen, Y., and Schnitzer, M. (1978). The surface tension of aqueous solutions of soil humic substances. *Soil Science.* **125**;7-15.

Cooke, G.W., and Widdowson, F.V. (1955). Fertilizer placement for arable and herbage crops. *Field Crop Abstracts.* **8**;233-7.

Cooke, I.J. (1962). Damage to plant roots caused by urea and anhydrous ammonia. *Nature* (London). **194**;1262.

Cornish, P.S. and Myers, L.F. (1977). Low pasture productivity of a sedimentary soil in relation to phosphate and water supply. *Australian Journal of Experimental Agriculture.* **17**;776-83.

Crabtree, W.L. (1983). The effect of cultivation on soil chemical and physical properties. Honours Thesis, Univ. of West. Aust.

Crabtree, W. L., and McGhie D.A. (1990). Managing water repellence in sandy soils. West. Aust. Dept. of Agric. Farmnote 55/90. Agdex 511.

Crabtree, W.L. (1986). The role of minimum tillage on the south coast sandplain soil - a literature review. West. Aust. Dept. of Agric. DRM Tech. Report 45.

Crabtree, W.L., (1990). Toward better minimum tillage for south-coastal sandplain soils. Western Australian Department of Agriculture, DRM Technical Report No. 111.

Currie, J.A. (1961). Gaseous diffusion in porous media. Part 3. Wet granular materials. *British Journal of Applied Physics.* **12**;275-81.

Darbyshire, J.F. (1975). Soil Protozoa-animalcules of the subterranean microenvironment. In soil Microbiology. Ed N. Walker, Butterworths.

Deacon, J.W. and Henry, C.M. (1980). Age of wheat and barley roots and infection by *Gaeumunnomyces graminis* var *tritici. Soil Biology and Biochemistry.* **12**;113-18.

DeBano, L.F., (1981). Water repellent soil: a state of the art. USDA For. Serv. PSW-46 p1-22.

DeBano, L.F. (1969). The relationship between heat treatment and water repellency in soils. In Proc. symposium on water repellent soils. May 6-10, 1968, 265-277, Univ. of California.

DeBano, L.F., and Rice, R.M. (1973). Water repellent soils: Their implications in forestry. *Journal of Forestry.* **71**;220-23.

DeBano, L.F., Mann, L.D., and Hamilton, D.A. (1970). Translocation of hydrophobic substances into soil by burning organic litter. *Journal of American Soil Science Society.* **34**;130-3.

Drew, M.C. and Saker, L.R. (1978). Effects of direct drilling and ploughing on root distribution in spring barley, and on the concentration of extractable phosphate and potassium in the upper horizons of a clay soil. *Journal of Science in Food and Agriculture.* **29**;201-6.

Ellis, B.G., Erickson, A.E., Jacobs, L.W., Hook, J.E., and Knezek, B.D. (1981). Cropping systems for treatment and utilization of municipal wastewater and sludge. NTIS PB81-187254.

Ellis, B.G. Knezek, B.D. and Jacobs, L.W. (1983). The movement of micronutrients in soils. In "Chemical Mobility and Reactivity in Soil Systems." ASA, SSSA.

Emerson, W.R., and Bond, R.D., (1963). The rate of water entry into dry sand and calculation of the advancing contact angle. *Australian Journal of Soil Research.* **1**;9-16.

Ewing, M. A., Robson, A. D. (1991). The use of MES buffer in early nodulation studies with annual medicago species. *Plant and Soil* **131**, 199-206.

Fahad, A.A. (1987). Movement of manganese-54 in calcareous soils as affected by leaching solution, lime content, salinization, and sterilization. *Journal of American Soil Science Society.* **51**;1487-92.

Fehl, A.J., and Lange, W., (1965). Soil stabilization induced by growth of microorganisms on high-calorie mold nutrients. *Soil Science.* **100**;368-74.

Forbes, E.A., Posner, A.M., and Quirk, J.P. (1976). The specific adsorption of divalent Cd, Co, Cu, Pb, and Zn on goethite. *Journal of Soil Science.* **27**;154-66.

French, R.J. and Schultz, J.E. (1984). Water use efficiency of wheat in a mediterranean-type environment. I. The relation between yield, water use and climate. *Australian Journal of Agricultural Research.* **35**;743-63.

Gartrell, J.W. and Walton, G. (1984). Manganese deficiency (Split seed) in sweet narrow-leafed lupins. West. Aust. Dept. Agric. Farmnote 89/84, Agdex 161/632.

Gilkes, R.J. (1977). Factors influencing the release of copper and zinc additives from granulated superphosphate. *Journal of Soil Science.* **28**;103-11.

Gilkes, R.J., Young, R.C., and Quirk, J.P. (1975). Leaching of copper and zinc from trace element superphosphate. *Australian Journal of Soil Research.* **13**;33-41.

Gilkes, R.J. and Sadleir, S.B. (1979). The influence of placement geometry on the effectiveness of copper superphosphate. *Australian Journal of Soil Research.* **17**,121-8.

Godo, G.H., and Reisenauer, H.M. (1980). Plant effects on soil manganese availability. *Journal of American Soil Science Society.* **44**;993-5.

Grass, L.B., MacKenzie A.J., Meek B.D. and Spencer, W.F. (1973). Manganese and iron solubility changes as a factor in tile drain clogging: I. Observations during flooding and drying. *Journal of American Soil Science Society.* **37**;14-17.

Gregory, P.J., McGowan, P.V., Biscoe, P.V., and Hunter B. (1978). Water relations of winter wheat. I. Growth of the root system. *Journal of Agricultural Science Camb.* **91**;91-102.

Greig-Smith, R. (1910). Contributions to our knowledge of soil fertility. (I). Proc. Linn. Soc. NSW p808-22.

Griffin, D.M. (1972). In "The Ecology of Soil Fungi." Ed Chapman and Hall.

Grundon, N.J. (1980). Effectiveness of soil dressings and foliar sprays of copper sulphate in correcting copper deficiency of wheat (*Triticum aestivum*) in Queensland. *Australian Journal of Experimental Agriculture.* **20**;717-23.

Hale, M.G., Moore, L.D., and Griffin, G.J. (1978). Root exudates and exudation. In *Interactions Between Non-Pathogenic Soil Microorganisms and Plants* (eds Y.R. Dommergues and S.V. Krupa) pp 163-203. Elsevier Scientific Publication Company Amsterdam.

Hannam, R.J., Graham, R.D., and Riggs, J.L. (1985). Redistribution of manganese in maturing *Lupinus Angustifolius* cv. Illyarrie in relation to levels of previous accumulation. *Annals of Botany.* **56**;821-34.

Hannam, R.J., Davies, W.J., Graham, R.D., and Riggs, J.L. (1984). The effect of soil and foliar applied manganese in preventing the onset of manganese deficiency in *Lupinus angustifolius*. *Australian Journal of Agricultural Research.* **35**;529-38.

Harper, R.J., and Gilkes, R., (1994). Soil attributes related to water repellency and the utility of soil survey in predicting its occurrance. *Australian Journal of Soil Research..* **32:**1109-24.

Harter H D and McLean E D 1965 The effect of moisture level and incubation time on chemical equilibria of a Toledo clay loam soil. *Agronomy Journal* 57,583-588.

Harris, P.J. (1988). Microbial Transformations of nitrogen. In "Russell's Soil Conditions and Plant Growth". Published Longman Scientific and Technical. Ed. A. Wild.

Hartman, M.D., and Nyborg M. (1989). Effect of early growing season moisture stress on barley utilization of broadcast-incorporated and deep-banded urea. *Canadian Journal of Soil Science.* **69**;381-9.

Haynes, R.J. and Swift, R.S. (1986). Effects of soil acidification and subsequent leaching on levels of extractable nutrients in a soil. *Plant and Soil.* **95**;327-36.

Heenan, D.P., and Campbell, L.C. (1980). Growth, yield components and seed composition of two soybean cultivars as affected by manganese supply. *Australian Journal of Agricultural Research.* **31**;471-6.

Henderson, C.W.L. (1991). Sensitivity of eight cereal and legume species to the compaction status of deep, sandy soils. *Australian Journal of Experimental Agriculture.* **31:**347-55.

Hendrickson, A.H., and Veihmeyer, F.J., (1931). Influence of dry soil on root extension. *Plant Physiology.* **6**;567-76.

Henry, C.M., and Deacon, J.W. (1981). Natural (non-pathogenic) death of the cortex of wheat and barley seminal roots, as evidenced by nuclear staining with acridine orange. *Plant and Soil.* **60**;255-74.

Hill, J., Robson, A.D., and Loneragan, J.F. (1978). The effects of copper and nitrogen supply on the retranslocation of copper in four cultivars of wheat. *Australian Journal of Agricultural Research.* **29**;925-39.

Hingston, F.J., and Gailitis, V. (1976). The geographic variation of salt precipitation over Western Australia. *Australian Journal of Soil Research.* **14**;319-35.

Hocking, P.J. (1982). Effect of water stress on redistribution of nutrients from leaflets of narrow-leaved lupin (*Lupinus angustifolius* L.) *Annals of Botany.* **49**;541-3.

Hocking, P.J., and Pate J.S. (1977). Mobilization of minerals to developing seeds of legumes. *Annals of Botany.* **41**;1259-78.

Hocking, P.J., and Pate J.S. (1978). Accumulation and distribution of mineral elements in the annual lupins *Lupinus albus* L. and *Lupinus angustifolius* L. *Australian Journal of Experimental Agriculture.* **29**;267-80.

Holzhey, C.S. (1969). Soil morphological relationships and water repellence. In Proc. symposium on water repellent soils. May 6-10, 1968, Riverside, Univ. California.

Huber, O.M., and Wilhelm, N.S. (1988). The role of manganese in resistance to plant diseases. Chapter 11 of *Manganese in Plants and soils* Ed R.D. Graham, R.J. Hannam and J.L. Riggs.

Hunter, A.S., and Kelley, O.J. (1946). The extension of plant roots into dry soil. *Plant Physiology.* **21**;445-51.

Hunter, J.R. and Erickson, A.E. (1952). Relation of seed germination to soil moisture tension. *Agronomy Journal.* **44**;107-9.

Hutchinson, K.J., and King, K.L (1982). Microbial respiration in a temperate sown grassland grazed by sheep. *Journal of Applied Ecology.* **19**;821-33.

Islam, A.K.M.S., Edwards, D.G. and Asher, C.J. (1980). pH optima for crop growth: Results of flowing solution culture experiment with six species. *Plant and Soil* **54**;339-57.

Jamison, V.C. (1942). The slow reversible drying of sandy soils beneath citrus trees in central Florida. *Journal of American Soil Science Society.* **7**;36-41.

Jarvis, R.J., and Bolland, M.D.A. (1991). Lupin grain yields and fertiliser effectiveness are increased by banding superphosphate below the seed. *Australian Journal of Experimental Agriculture.* **31:**357-66.

Jasper, D.A., Abbott, L.K., and Robson, A.D. (1989). Hyphae of a vesicular-arbuscular mycorrhizal fungus maintain infectivity in dry soil, except when the soil is disturbed. *New Phytol.* **112**;101-7.

Jenkinson, D.S. (1988). Microbial transformations of nitrogen. In "Russell's Soil Conditions and Plant Growth". Ed. A. Wild. Longman Scientific and Technical.

Jones, L.H.P. (1957). The effect of liming a neutral soil on the cycle of manganese. *Plant and Soil.* **8**;315-27.

Jones, M.B., Martin, W.E. and Williams, W.A. (1968). Behaviour of sulphate-sulphur and elemental sulphur in three California soils in lysimeters. *Journal of American Soil Science Society.* **32**;535-39.

Kanabo I.A.K. and Gilkes, R.J. (1988). The effects of moisture regime and incubation period on the dissolution of North Carolina phosphate rock in soil. *Australian Journal of Soil Research.* **26**;153-63.

Kaspar, T.C., Zahler, J.B., and Timmons, D.R. (1989). Soybean response to phosphorus and potassium fertilizers as affected by soil drying. *Journal of American Soil Science Society* **53**;1448-54.

Khan, A. and Banwart, W.L. (1979). Effect of incubation and microbial inhibition of field moisture capacity on changes in DTPA-extractable Fe, Zn, and Cu in soils of varying pH. *Commications in Soil Science and Plant Analysis.* **10**(3);613-22.

King, P.M., (1981). Comparisons of methods for measuring severity of water repellence on sandy soils and assessment of some factors that affect its measurement. *Australian Journal of Soil Research*. **19**;275-85.

King, P.M. (1985). Water-repellent sands. South Aust. Dept. Agric. Fact Sheet no 12/85 Agdex 503.

Klepper, B., Rasmussen, P.E., and Rickman, R.W. (1983). Fertilizer placement for cereal root access. *Journal of Soil Water Conservation.* **38:**250-52.

Larsen, S. (1967). Soil phosphorus. *Advances in Agronomy.* **19**;151-210.

Letey, J. (1969). Measurement of contact angle, water drop penetration time and critical surface tension. Proc. Symp. on water repellent soils, Univ. Calif. Riverside, pp43-8.

Letey, J., Osborn, J., and Pelishek, R.E. (1962). The influence of the water-solid contact angle on water movement in soil. *Bull Int. Assoc. Science. Hydrol.* **3**;75-81.

Lindstrom, M.J.,Papendick, R.I., and Koehler, F.E. (1976). A model to predict winter wheat emergence as affected by soil temperature, water potential and depth of planting. *Agronomy Journal.* **68**;138-40.

Loneragan, J.F., Snowball, K., and Robson, A.D. (1976). Remobilization of nutrients and its significance in plant nutrition. In *Transport and Transfer Processes in Plants,* eds. J.J. Wardlaw and J.B. Passioura, pp. 463-9. Academic Press, London and New York.

Loomis, W.E., and Ewan, L.M. (1936). Hydrotropic responses of roots in soil. *Botanical Gazette.* **97**;728-43.

Lopez, P.L. and Graham, E.R. (1972). Labile pool and plant uptake of micronutrients. I. Determination of labile pool of Mn, Re, Zn, Co and cu in deficient soils by isotopic exchange. *Soil Science* **114**;295-9.

Loss, S. P., Robson, A. D., and Ritchie, G. S. P. (1993). H^+/OH^- exudation and nutrient uptake in upper and lower parts of lupin (*Lupin angustifolius* L.) root systems. *Annals of Botany* **72**, 315-20.

Ma'shum, M., and Farmer, V.C. (1985). Origin and assessment of water repellency of a sandy South Australian soil. *Australian Journal of Soil Research.* **23**;623-6.

Ma'shum, M., Tate, M.E., Jones, G.P., and Oades, J.M. (1988). Extraction and characterization of water-repellent materials from Australian soils. *Journal of Soil Science.* **39**;99-110.

Ma'shum, M., Oades, J.M., and Tate, M.E. (1989). The use of dispersible clays to reduce water repellency of sandy soils. *Australian Journal of Soil Research.* **27**;797-806.

Mahler, R.L., Hammel, J.E., and Harder, R.W. (1985). The influence of crop rotation and tillage methods on the DTPA-extractable copper, iron, manganese, and zinc in northern Idaho soils. *Soil Science*. **139**;279-86.

Marais, J.N., Wiersma, D. (1975). Phosphorus uptake by soybeans as influenced by moisture stress in the fertilized zone. *Agronomy Journal.* **67**;777-81.

Martin, J.K. (1977). Factors influencing the loss of organic carbon from wheat roots. *Soil Biol. Biochem.* **9**;1-7.

Mason, M.G. (1971). Effects of urea, ammonium nitrate and superphosphate on establishment of cereals, linseed and rape. *Austalain Journal of Experimental Agriculture.* **11**;662-9.

McConnell, S.G., Sander, D.H., and Peterson, G.A. (1986). Effect of fertilizer phosphorus placement depth on winter wheat yield. *Journal of American Soil Science Society.* **50**;148-153.

McDowell, T.E., Smith, J.A.C., Toms, W.J., and Carroll, M.D. (1961). "Spread Super" for cereal crops. *Western Australian Journal of Agriculture.* **2**;869-70.

McGhie, D.A., and Posner, A.M. (1980). Water repellence of a heavy-textured Western Australian surface soil. *Australian Journal of Soil Research.* **18**;309-23.

McGhie, D.A., and Posner, A.M. (1981). The effect of plant top material on the water repellence of fired sands and water repellent soils. *Australian Journal of Soil Research.* **33**;906-20.

McGhie, D.A. and Tipping, P.I. (1983). Beating the non-wetting soil problem. *Western Australian Journal of Agriculture.* **3**;84-6.

McGhie, D.A. (1983). Water repellent soils on farms. West. Aust. Dept. Agric. Farmnote 117/83. Agdex 511.

McGinnies, W.J. (1960). Effects of moisture stress and temperature on germination of six range grasses. *Agronomy Journal.* **52**;159-62.

McLay, C.D.A. (1989). Sulphate leaching under field conditions. PhD Thesis, Lincoln College, New Zealand.

Mengel, D.B., and Barber, S.A. (1974). Development and distribution of the corn root system under field conditions. *Agronomy Journal.* **66**;341-4.

Nable, R.O., and Loneragan, J.F. (1984). Translocation of manganese in subterranean clover (*Trifolium subterraneum* L. cv. Seaton Park). II. Effects of leaf senescence and of restricting supply of manganese to part of a split root system. *Australian Journal of Plant Physiol.* **11**;101-11.

Nambiar, E.K.S. (1977). The effects of drying of the topsoil and of micronutrients in the subsoil on micronutrient uptake by an intermittently defoliated ryegrass. *Plant and Soil.* **46**;185-93.

Nambiar, E.K.S. (1976b). The uptake of zinc-65 by oats in relation to soil water content and root growth. *Australian Journal of Soil Research.* **14**;67-74.

Nelson, P. and Delane, R. (1990). Producing lupins in Western Australia. Western Aust. Dept. of Agric. Bulletin 4179. Agdex 161/10.

Netzly, D.H., and Butler, L.G. (1986). Roots of sorghum exude hydrophobic droplets containing biologically active components. *Crop Science.* **26**;775-78.

Obst, C. (1994). Non-wetting soils: management problems and solutions at "Pineview", Mundulla. Proceedings of the 2nd National "Water Repellency Workshop", Perth, Western Australia. Pages 137-39.

Olsen, S.R., Watanabe, F.S., and Danielson, R.E. (1961). Phosphorus absorption by corn roots as affected by moisture and phosphorus concentration. *Journal of American Soil Science Society.* **25**;289-94.

Olsen, R.A., Clark, R.B., and Bennett, J.H. (1981). The enhancement of soil fertility by plant roots. *American Science.* **69**;378-84.

Owen, P.C. (1952). The relation of germination of wheat to water potential. *Journal of Experimental Botany.* **3**;188-203.

Pate, J.S., Gunning, B.E.S., and Briarty, L.G. (1969). Ultrastructure and functioning of the leguminous root nodule. *Planta.* **85**;11-34.

Paterson, G.A., Sander, D.H., Grabouski, P.H. and Hooker, M.L. (1981). A new look at row and broadcast phosphate recommendations for winter wheat. *Agronomy Journal.* **73**;13-17.

Pathak, B.S., Gupta, P.K., and Mahajan V., (1976). Effect of Soil compaction on seedling emergence. Punjab Agic. Univ. Ludhiana. *Journal of Research.* **13**(1): 35-47.

Payne, G.G., Martens, D.C., Winarko, D. and Perera N.F. (1988). Form and availability of copper and zinc following long-term copper sulfate and zinc sulfate applications. *Journal of Environmental Quality.* **17**;707-11.

Pelishek, R.E., Osborn, J., Letey, J., (1962). The effect of wetting agents on infiltration. *Journal of American Soil Science Society.* **26**;595-8.

Perry, M.W., and Gartrell, J.W. (1976). Lupin "split seed";A disorder of seed production in sweet, narrow-leafed lupins. *Western Australian Journal of Agriculture.* **17**, No. 1 (4th series).

Pizer, N.H., Caldwell, T.H., Burgess, G.R. and Jones, J.L.O. (1966). Investigations into copper deficiency in crops in East Anglia. *Journal of Agricultural Science.* (Cambridge) **66**;303-14.

Ponnamperuma, F.N. (1972). The chemistry of submerged soils. *Advances in Agronomy.* **24**;29-96.

Porter, L.K., Kemper, W.D., Jackson, R.D. and Stewart, B.A. (1960). Chloride diffusion in soils as influenced by moisture content. *Journal of American Soil Science Society.* **24**;460-63.

Prescott, J.A., and Piper, C.S. (1932). The soils of the South Australian mallee. *Trans. R. Soc. South Aust.* **56**;118-36.

Prummel, J. (1957). Fertilizer placement experiments. *Plant and Soil* **8**(3);231-53.

Radford, B.J., and Wildermuth, G.B., (1987). Effects of sowing depth, seed dressings, a press wheel, cultivars and trifluralin on the establishment of barley. *Australian Journal of Experimental Agriculture.* **27**: 579-84.

Radjagukguk, B. (1980). Manganese nutrition in lupins. Plant response and the relationship of manganese supply to its distribution. Ph.D. Thesis. University of Western Australia, Perth.

Reddy, M.R. and Perkins, H.F. (1976). Fixation of manganese by clay minerals. *Soil Science.* **121**;21-4.

Reith, J.W.S. (1959). Fertilizer placement for swedes and turnips. *Empire Journal of Experimental Agriculture.* **27**;300-12.

Ritchie, G.S.P. (1989). The chemical behaviour of aluminium, hydrogen and manganese in acid soils. In "Soil Acidity and Plant Growth." Ed. A.D. Robson. Academic Press Australia.

Roberts, F.J., and Carbon, B.A. (1971). Water repellence in sandy soils of south Western Australia. I. Some studies related to field occurrence. CSIRO. Div. Plant Ind. Field Stn Rec. 10;13-20.

Roberts, F.J., and Carbon, B.A. (1972). Water repellence in sandy soils of Western Australia. II. Some chemical characteristics of the hydrophobic skins. *Australian Journal of Soil Research.* **10**;35-42.

Roth, L.F., and Riker, A.J. (1943). Influencing of temperature moisture, and soil reaction on damping-off of red pine seedlings by *pythium* and *rhizoctonia. Journal of Agricultural Research.* **67**;273-93.

Roper, M. (1998). Microbes reduce repellence in February edition of Western Australian No-Tillage Farmers Association newsletter', page 146-7, Edited by W.L. Crabtree.

Rovira, A.D. (1969). Plant root exudates. *Botanical Review.* **35**;35-57.

Rowell, D.L. (1988). Soil Acidity and alkalinity. In "Russell's Soil Conditions and Plant Growth". Ed. A. Wild. Longman Scientific and Technical. England.

Rudd, C.L. (1972). The effect of method of application of superphosphate on wheat yield. *Experimental Record* (South Australia) **7**;4-9.

Russell, E.W. (1973). Soil Conditions and plant growth. 10th Edition.

Salim, M.H., Todd, G.W., and Schlehuber, A.M. (1965). Root development of wheat, oats and barley under conditions of soil moisture stress. *Agronomy Journal.* **57**;603-7.

Savage, S.M., Martin, J.P., and Letey,J. (1969a). Contribution of humic acids and a polysaccharide to water-repellency in sand and soils. *Journal of American Soil Science Society.* **33**;149-51.

Savage, S.M., Martin, J.P., and Letey, J., (1969b). Contribution of some soil fungi to natural and heat induced water-repellency in sand. *Journal of American Soil Science Society.* **33**;405-9.

Scholl, D.G. (1971). Soil wettability in Utah juniper sands. *Journal of American Soil Science Society.* **35**;356-61.

Schreiner, O., and Shorey, E.C. (1910). Chemical nature of soil organic matter. *USDA Bur. Soils Bull.* **74**;2-48.

Schultz, J.E. (1975). Effect on wheat yield and grain phosphorus content of deep placement and foliar application of phosphate. *Agricultural Record* **2**;51-3.

Scott, B.J. (1990). Diagnosis of magnesium deficiency by plant analysis. Ph.D. Thesis. University of Western Australia.

Scott, B.J. (1973). The response of barrel medic pasture to topdressed and placed superphosphate in central western New South Wales. *Australian Journal of Experimental Agriculture.* **13**;705-10.

Shackel, K.A., and Hall, A.E., (1983). Comparison of water relations and osmotic adjustment in sorghum and cowpea under field conditions. *Australian Journal of Plant Physiology.* **10**;423-35.

Shantz, H.L., (1927). *Ecology.* **8**;145.

Sharpley, A.N. and Ahuja, L.R. (1982). Effects of temperature and soil-water content during incubation on the desorption of phosphorus from Soil. *Soil Science.* **133**;350-5.

Shaw, R.H., and Laing, D.R. (1966). In *Plant Environment and Efficient Water Use*, eds. W.H. Pierre *et al. American Society of Agronomy*: Madison, Wisconsin.

Simpson, J.R., and Lipsett, J. (1973). Effects of surface moisture supply on the subsoil nutritional requirements of lucerne (*Medicago sativa* L.). *Australian Journal of Agricultural Research.* **24**;199-209.

Singer, M.J., and Ugolini, F.C. (1976). Hydrophobicity in the soils of Findley Lake, Washington. *For Science.* **22**;54-60.

Singh, B.R., and Kanehiro, Y. (1969). Adsorption of nitrate in amorphous and kaolinitic Hawaiian soils. *Journal of American Soil Science Society.* **33**;681-3.

Singh, H.M. (1970). Effect of placement of phosphatic fertilizer (single superphosphate) on yield of peas (*Pisum sativum*). *Science and Culture.* **36**;659-60.

Singh, R.K., De, R., and Turkhede, B.B., (1986). Effect of fertilizer placement and row arrangements on the yield of two varieties of wheat grown under dryland conditions. *Journal of Agricultural Science.* **107**(1);113-8.

Smith, D.F. (1958). The effect of lime in pasture establishment on leached sands - southeast of south Australia. Australian Agrostology Conference 1: Part 1, paper No. 26.

Sprent, J.I. (1971). The effects of water stress on nitrogen-fixing root nodules. I. Effects on the physiology of detached soybean nodules. *New Phytol.* **70**;9-17.

Stahlberg, S., Sombatpanit, S. and Stahlberg, J. (1976). Manganese relationships of soil and plant. II. Studies on manganese fixation. *Acta Agriculturae Scandinavica.* **26**;65-81.

Stelwaag, A. (1882). Forsch. Geb. Agrikult. Cited by Tschapek (1984).

Summers, R.N. (1987). The induction and severity of non-wetting in soils of the south coastal sandplain of Western Australia. Masters Thesis. University of West. Aust.

Svenningsson, H., Sundin, P., and Litjenberg C. (1990). Lipids, carbohydrates and amino acids exuded from the axenic roots of rape seedlings exposed to water-deficit stress. *Plant, Cell and Environment.* **13**;155-62.

Syers, J.K., Curtin,D. and Skinner, R.J. (1987). Soil and fertilizer sulphur in U.K. agriculture. Fertilizer Society of London. p43.

Teakle, L.J.H, and Southern, B.L. (1937). The peat soils and related soils of Western Australia. A survey of Herdsman lake. *Western Australian Department of Agriculture Journal.* **14**;404-24.

Thorup, R.M. (1969). Root development and phosphorus uptake by tomato plants under controlled soil moisture conditions. *Agronomy Journal.* **61**;808-11.

Tiller, K.G. (1983). Micronutrients. In "Soils, An Australian Viewpoint." Div. of soils, CSIRO pp365-387, CSIRO Melbourne/Academic Press London.

Tschapek, M., Pozzo Ardizzi, J., and De Bussetti, S.G. (1973). Wettability of humic acid and its salts. *Zeitschrift fur Pflanzenernahrung und Bodenkunde.* **135**;16-31.

Turner, N.C., Stern, W.R., and Evans, P. (1987). Water relations of osmotic adjustment of leaves and roots of lupins in response to water deficits. *Crop Science.* **27**;977-83.

Uehara, G., and Gillam, G. (1981). The mineralogy, chemistry and physics of tropical soils with variable charge clays. Westview Tropical Agric. Ser. No. 4.

Ulrich, B. (1980). Production and consumption of hydrogen ions in the ecosphere. In "Effects of Acid Precipitation on Terrestrial Ecosystems." Eds. T.C. Hutchinson and M. Havas. pp 255-282. Plenum Press. New York.

VanBavel, C.H.M., and Baker, J.M. (1985). Water transfer by plant roots from wet to dry soil. *Naturwissenschaften.* **72**;606-7.

Van't Woudt, B.K. (1959). Particle coatings affection the wettability of soils. *Journal of Geophysics Research.* **64**;263-7.

Varvel, G.E., Havlin, J.L. and Peterson, T.A. (1989). Nitrogen placement evaluation for winter wheat in three fallow tillage systems. *Journal of American Soil Science Society.* **53**;288-92.

Volk, G.M., (1947). Significance of moisture translocation from soil zones of low moisture tension to zones of high moisture tension by plant roots. *Journal of American Society of Agronomy.* **39**;93-106.

Vose, P.B. (1963). The translocation and redistribution of manganese in *Avena*. *Journal of Experimental Botany.* Vol. **14**, No. 42;448-57.

Wallis, M.G., Horne, D.J. and McAuliffe, K.W. (1990). 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. *New Zealand Journal of Agricultural Research.* **33**;145-50.

Ward, P.R., and Oades, J.M. (1993). Effect of clay mineralogy and exchangeable cations on water repellency in clay-amended sandy soils. *Australian Journal of Soil Research.* **31**;351-64.

Watson, C.L., and Letey, J. (1970). Indices for characterising soil-water repellence based upon contact angle-surface tension relationships. *Journal of American Soil Science Society.* **34**;841-4.

Weaver, D.M., Ritchie, G.S.P., Anderson,G.C. and Deeley, D.M. (1988). Phosphorus leaching in sandy soils. I. Short-term effects of fertilizer applications and environmental conditions. *Australian Journal of Soil Research.* **26**;177-90.

Weaver, J.E. (1926). Root development of field crops. McGraw-Hill, New York.

Welch, L.F., Mulvaney, D.L., Boone, L.V., McKibben, G.E. and Pendleton, J.W. (1966). Relative efficiency of broadcast versus bonded phosphorus for corn. *Agronomy Journal*. **58**;283-7.

Westerman, R.L., and Edlund, M.G. (1985). Deep placement effects of nitrogen and phosphorus on grain yield, nutrient uptake, and forage quality of winter wheat. *Agronomy Journal.* 77;803-9.

Western Australian No-Tillage Farmers Association Newsletter (1998). Edited by W. L. Crabtree. “Claying overcomes water repellence in south Australia.”

Wetherby, K.G., (1984). The extent and significance of water repellent sands on Eyre Peninsula. Dept. of Agric. South Australia Technical Report 47, Agdex 520.

Wiklander, L. (1950). Kinetics of phosphate exchange in soils. Ann R. Agric. Coll. (Sweden). **17**;407-23.

Wild, A. (1988). Plant nutrients in soil: Nitrogen .In "Russell's Soil Conditions and Plant Growth". Ed. A. Wild. Published;Longman Scientific and Technical.

Williams, C.H. (1967). Some factors affecting the mineralization of organic sulphur in soils. *Plant and Soil.* **26**;205-33.

Williams, C.H. (1969). Moisture uptake by surface-applied superphosphate and movement of the phosphate and sulphate into the soil. *Australian Journal of Soil Research.* **7**;307-16.

Williams, C.H. (1971). Reaction of surface-applied superphosphate with soil. II. Movement of the phosphorus and sulfur into the soil. *Australian Journal of Soil Research.* **9**;95-106.

Williams, J.G. and McLaren, R.G. (1982). Effects of dry and moist incubation of soils on the extractability of native and applied soil copper. *Plant and Soil.* **64**;215-24.

Wilson, J.K. (1931). The shedding of nodules by beans. *Journal of American Society of Agronomy.* **23**;670.

Withers, N.J., and Forde, B.J. (1979). Effects of water stress on *Lupinus albus* III. Response of seed yield and vegetative growth to water stress imposed during two or three growth stages. *New Zealand Journal of Agricultural Research.* **22**;463-74.

Wladitchensky, S.A. (1966). Moisture content and hydrophobicity as related to the water capillary rise in soils. *Symposium of International Association Science in Hydrology.* **82**;360-5.

11. Appendix of list of published papers

Crabtree, W. L. (1999a). Deep placement of Mn fertiliser on sandy soil increased grain yield and reduced split seed in *Lupinus angustifolius*. *Plant and Soil.* **214**:9-14.

Crabtree, W. L. (1999b). Furrows, press wheels and wetting agents improve crop emergence and yield on water repellent soils. *Plant and Soil.* **214**:1-8.

Crabtree, W. L. Robson, A. D., and Ritchie, G. S. P. (1998). Drying of a surface soil decreased Lupinus angustifolius root length and Mn uptake in a split pot experiment. *Australian Journal of Agricultural Research* 49 (7).

Crabtree, W. L., and Gilkes, R. J. (1999a). Banded wetting agent and compaction improves barley production on a water repellent sand. *Agronomy Journal* 91:463-467.

Crabtree, W. L. and Gilkes, R. J. (1999b). Improved pasture establishment and production on water repellent sandy soils'. *Agronomy Journal* 91:467-470.