FACTORS AFFECTING THE GROWTH OF WHEAT ROOTS IN THE SUBSOILS OF UPPER EYRE PENINSULA, SOUTH AUSTRALIA

A thesis submitted
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To - K.G. Wetherby
for believing that it was possible

CONTENTS

SUMMARY

The Upper Eyre Peninsula of South Australia constitutes about 20% of the State's wheat growing area and is characterised by alkaline, calcareous soils, a Mediterranean climate and low annual rainfall (<350 mm). Wheat yields are often much lower than would be expected from the growing season rainfall. This may be due, in part, to the inability of wheat to utilise subsoil water since roots are rarely seen to proliferate below 0.5 m, even in the presence of apparently available water. Excessive soil strength and soil chemical factors such as high extractable boron and high salinity were thought to be implicated and experiments were conducted to examine the effects of these factors on the growth of wheat. The boron and salt characteristics of some of the agronomically important land units of Upper Eyre Peninsula were studied in a survey in which samples were taken from five locations.

A field experiment was conducted to test the hypothesis that wheat roots would not grow into the subsoil in the presence of available water at the beginning of the season. Before sowing the wheat, irrigation was used to bring the water content of the soil close to field capacity in some plots, while other plots received rainfall only.

At sowing, the irrigated soil was weaker than the control soil. The soil at anthesis was too strong to permit penetrometer resistance to be measured below 0.18 m in both treatments. Water loss from the soil to anthesis was significantly greater from the irrigated soil than from the control soil. For the 0.7-1.1 m depth interval, the irrigated soil (EC_e 1.9 dS m^{-1}) was less saline than the control soil (5.9 dS m^{-1}). Soil boron increased with depth and was not significantly different between the two treatments. $CaCl_2$ extractable boron exceeded 15 mg kg^{-1} soil below 0.5 m.

There were significantly more roots in the irrigated than the control soil. Maximum rooting depth in the irrigated soil was 1.15 m and in the control soil 0.70 m ($P \leq 0.05$). Grain yields were not different between treatments. It is hypothesised that the rapid early growth and withdrawal of water from the irrigated soil led to a critical water deficit in the wheat between anthesis and maturity. Mean boron concentration in the grain from irrigated plots (10.3 mg kg^{-1}) was significantly higher than that from control plots (5.8 mg kg^{-1}). The data indicate a greater uptake of boron from the irrigated soil coincident with higher water use and deeper rooting. While roots were able to penetrate the subsoil in the presence of available water, the application of irrigation water modified the subsoil by leaching a large amount of salt.

A survey was conducted with the principal objectives of studying the extent of the potential hazard to cereals presented by boron and salt and the variability of their distribution in some of the agronomically important land units of Upper Eyre Peninsula . Samples were taken from five localities. Two of these, Nunjikompita and Cungena, represented a single mapping unit because of its size. The other localities were Minnipa-Wudinna, Penong, and Buckleboo. A hierarchical sampling design was adopted, with each land unit represented by two randomly located 10 km x 10 km areas, each containing two 1 km x 1 km areas. Samples were taken from each of 32 pits in each 1 km x 1 km area, the closest of which were 5 m apart.

It was concluded that the mapping unit comprising Cungena and Nunjikompita contained quantities of boron likely to present a low hazard to wheat production. Conversely, the Minnipa-Wudinna and Buckleboo units contained consistently high concentrations varying from the nutritionally adequate to >100 mg kg^{-1}. The Penong unit was very variable with respect to the distribution of boron. Salt was more variable than boron, and only the Buckleboo unit contained uniformly saline subsoils. Otherwise, saline and non-saline subsoils occurred to some extent in all units, with some very high EC_e s (>10 dS m^{-1}) recorded at Nunjikompita, Minnipa-Wudinna and Penong. Estimates of variance components from the survey data from each land unit are used to show how more precise estimates of mean boron and salt values may be obtained by modified survey designs, with greater survey effort concentrated at the sampling level where the highest proportions of the total variance occurred.

Within individual land units, some easily recognised subsoil features such as the presence of Blanchetown Clay at Buckleboo or the reddish phase of the Wiabuna Formation could be useful in indicating where high concentrations of boron are likely to occur within a profile. In the Buckleboo, Minnipa - Wudinna and Penong land units, high boron may be associated with elevated portions of the landscape.

The effects of salt and boron in the subsoil at high concentrations typical of the subsoils of a large area of Upper Eyre Peninsula were examined in a glasshouse experiment. Wheat was grown in deep pots of solonised brown soil comprising 0.2 m sandy loam topsoil above 0.6 m treated calcareous sandy loam subsoil and a base layer of light clay 0.26 m thick. The subsoil was treated with mixed salt (0, 13, 39, 75 $mmol_c$ kg^{-1}) and boron (0, 20, 38, and 73 mg kg^{-1}) in factorial combination. The basic hypothesis of this experiment was that the added salt and boron would not affect the root growth, water use efficiency, dry matter production or grain yield of the wheat. The soil was initially watered to field capacity and water use was determined by regularly weighing the pots. The soil was allowed to dry gradually during the season, but the weights of the pots were not permitted to fall below that corresponding to 17% of the available water holding capacity of the soil.

Tillering, dry weight of shoots and grain, and root length density were determined. Water-use efficiency was calculated with respect to total dry weight and grain production.

Salt decreased tillering, dry matter production, grain yield, root length and water-use efficiency (total dry weight): it increased sodium and decreased boron concentrations in the plants. Boron decreased dry matter production (but not tillering), grain yield, root length and water-use efficiency (total dry weight and grain yield): it increased the concentrations of boron and decreased the concentration of sodium in the plants. At the concentrations of salt and boron used, boron had more deleterious effects on wheat than did salt. Yield was depressed by salt at concentrations of sodium in the tissue commonly found in field-grown plants.

A penetrometer study was conducted to test the hypothesis that mechanised agriculture could be implicated in increasing soil compaction on agricultural soils typical of Upper Eyre Peninsula. Penetrometer resistance measured on virgin soil was increased by wheel traffic and agricultural operations in all cases. The increase in soil strength was significant down to 0.30 m, which is considerably greater than the normal depth of tillage in the area (0.05 m). Reduction in the coefficient of variation of penetrometer strengths after the passage of wheels was taken as evidence for associated losses of soil structure. Virgin soils provide important reference states for assessing the impact of agriculture in an area.

A study of the amounts and types of field traffic was done with the objective of quantifying some of the factors causing soil compaction. Fields are cropped typically in only 50% of years with the other 50% of years being self-sown pastures involving negligible field traffic. In a cropping year, the total area of wheel tracks of farm vehicles is equal to 165% of the area of the field,but only 47.5% of the actual area is covered by wheels. The total amount of traffic is 62.6 t km ha^{-1}. The mechanisms which are important in maintaining a good soil structure in humid, temperate regions of the northern hemisphere are either absent or of negligible effect in the semi-arid, Mediterranean-type climatic region considered. Therefore, in spite of the relatively low levels of field traffic, there is a perpetual, insidious increase in soil compaction and associated problems.

Experiments were carried out to evaluate the efects of tillage in ameliorating a perceived soil compaction problem at two sites (Minnipa and Cungena). The experiments were done in 1987 and 1988 which unfortunately were both drought years. The experimental hypothesis was that deeper than conventional tillage would reduce soil strength, improve the root growth of wheat and alter the soil water regime in the root zone in comparison with conventionally tilled soil, resulting in yield increases.

Tillage deeper than the conventional depth (0.05 m) with a chisel plough at Minnipa had no measurable effect on water use or root growth in the period of measurement, or on grain yield. Soil strength was reduced by tillage to 0.30 m, but tillage to 0.15 m did not remove a hard pan below normal tillage depth. The loosening effect of deeper tillage was not measurable in dry soils by anthesis.

At Cungena, tillage to 0.3 m resulted in some enhancement of root growth and soil water extraction. Grain yields were increased by tillage to 0.3 m in both seasons. Soil strength was considerably reduced by deeper than normal tillage.

At Cungena, a further series of (recompaction) experiments was conducted in which tilled soil was recompacted by four passes of a large (11,800 kg) tractor before sowing. It was hypothesised that soil tilled below normal tillage depth would, after relatively few passes of a tractor, assume a soil strength equal to or greater than soil tilled to normal depth. As a result, root growth, soil strength, soil water contents and grain yields would not differ between treatments. Changes in soil water content at anthesis similar to those produced by deeper tillage in the tillage experiment at Cungena occurred in the recompaction experiment in 1987. Otherwise, differences evident in the tillage experiments (e.g.in rooting density and grain yields) were not reproduced in the recompaction experiments. Deeper tilled soil appeared to be more susceptible to the effects of recompaction (in terms of increasing soil strength) than control soil. The effect of four passes of wheels of a large (11,800 kg) tractor was to remove in both years the yield benefits induced by tillage to 0.3 m. The effects of deeper tillage in this environment are not likely to be lasting under the current tillage systems operating.

The amount and intensity of wheel traffic on Eyre Peninsula is much lower than in Europe, but there is evidence that cultivated soils in the area are more compact than comparable virgin soils. Compaction is more likely to be due to the absence of mechanisms which undo compaction than to high values of traffic intensity. While deeper tillage had some beneficial effects at one site, other less expensive and more cost effective methods of enhancing root growth in these strong soils need to be investigated.

It was concluded that the presence of high concentrations of salt and boron and a steadily increasing soil compaction problem present serious impediments to the growth and penetration of the roots and ultimately the yield of wheat over much of Upper Eyre Peninsula.

STATEMENT

This thesis contains no material that has been accepted for the award of any other degree or diploma in any University, and, to the best of my knowledge and belief, it contains no material previously published or written by another person, except when due reference is made in the text.

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I give consent to this copy of my thesis, when deposited in the University Library, being available for loan and photocopying.

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SOUTH AUSTRALIAN DEPARTMENT OF AGRICULTURE
CLEVE RESEARCH LABORATORIES

MAP LEGEND

Soil units

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3 - Jumbled siliceous sands (sands up to 2 m deep) over clays and tertiary sediments.

4 - Parallel sand ridges with shallow loamy soils in the swales.

5 - Parallel siliceous sand ridges with sandy loams over class II or IIIC calcrete in the flats.

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Compiled by: K.G. Wetherby from data of Crocker (1946a), Davies (1975), Elliot (1965), Firman (1978), French (1958), King and Alston (1975), Northcote (1961), Smith (1960) Stephens (1943), Wetherby (1980, 1984, 1985a,b,c,) Wetherby and Hughes (1990), Wetherby and Kew (1990), Wetherby *et al.* (1982, 1983) Wood (1974), Wood and Davies (1975) and Wright (1985).

Drawn by: Des R. Elliott PROFESSIONAL DRAFTING AND COMPUTER SERVICE, ADELAIDE, SOUTH AUSTRALIA.

Coastline, Roads and grid data courtesy South Australian Department of Lands - Mapping Branch

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1.0 INTRODUCTION

The Upper Eyre Peninsula of South Australia, which constitutes about 20% of the State's wheat (*Triticum aestivum* L.) growing area, is largely characterised by alkaline, calcareous soils of coarse texture and low annual rainfall (<350 mm). The climate is of the Mediterranean type, with predominantly winter rainfall. The mean rainfall does not exceed pan evaporation in any month.

Yields of wheat on these soils are commonly well below the potential which could be obtained from the amount of rain which falls during the growing season (French and Schultz 1984 a,b). The low yields may be due in part to the inability of roots to utilise water in the subsoil since roots are rarely found below 0.5 m, even when the soil below that depth appears to contain available water. In low rainfall environments, the penetration of roots into the subsoil is often directly related to water penetration (Tennant 1976 a). The ability of roots to withdraw water from the subsoil during times of surface drought may enhance drought tolerance and yield (Pearson 1971, Hurd 1974 and Hurd and Spratt 1975).

Soil compaction is a well documented cause of restricted root growth, and some exhaustive reviews on the subject have been published (e.g. Greacen and Sands 1980, Soane *et al.* 1980a,b, 1982, Håkansson *et al.* 1988). However, there are little data available concerning the nature and extent of soil compaction in the agricultural areas of southern Australia. Tillage systems and farming practices differ widely from those in the northern hemisphere, where much of the published research into soil compaction has been carried out. The possible role of mechanical factors in inhibiting root growth on Upper Eyre Peninsula was referred to by Jakobsen and Dexter (1987, 1988) and Dexter *et al.* (1988).

Besides excessive soil strength, soil chemical factors such as extractable boron and salinity may be implicated in the apparently poor root growth. It was considered possible from the limited data available that salinity and extractable boron may be sufficiently high to retard or prevent the penetration of roots into the subsoil.

Boron toxicity in cereal crops in South Australia was first identified in barley (Cartwright *et al.* 1984) at a single location. A subsequent survey of the boron contents in the shoots of barley (*Hordeum vulgare* L.) plants and grain of barley suggested that high concentrations of boron in soils occurred throughout South Australia (Cartwright *et al.* 1986) including all four of the locations sampled on Upper Eyre Peninsula. As a result of the survey, Cartwright *et al.* (1986) referred to the need for more boron data from the alkaline-sodic and saline soils (which occur widely on Upper Eyre Peninsula) to assess the risk to barley in dryland farming. All soils with high boron examined in the survey were sodic, but few could be classified as saline (a salt concentration in clay loams and clays of greater than 0.2-0.3%) after Northcote and Skene (1972)

Experiments were conducted at two sites between 1986 and 1990 to examine the effects of compaction, boron and salinity on the growth of wheat, with particular reference to effects on root growth. The sites were at Minnipa (latitude 32° 51' S, longitude 135° 09' E) about 400 km north-west of Adelaide, and Cungena which lies a further 60 km to the north-west. Mean annual rainfall at Minnipa is 325 mm and at Cungena 281 mm. The soils at both sites are solonised brown soils (Stace *et al.* 1968). Soil Taxonomy (Soil Survey Staff 1975) classifies the soil at Minnipa as a Calcixerollic Xerochrept (loamy, mixed, thermic) and the soil at Cungena as a Calcixerollic Xerochrept (coarse loamy, carbonatic, thermic)

Chemical factors were examined in two experiments, an exploratory field experiment conducted at Minnipa and a glasshouse experiment.

The exploratory field experiment was conducted to test the hypothesis that wheat roots would not grow into the subsoil at Minnipa in the presence of available water and to give preliminary information on the boron, salt and soil strength characteristics of the subsoil. Irrigation was used to bring the water content of the soil close to field capacity at the beginning of the season in some plots, while other plots received rainfall only. The major objective of the glasshouse experiment was to test the hypothesis that the presence of added salt and boron in the subsoil would not affect the growth of roots, or the water use efficiency and production of wheat (cv. Warigal).

A survey was conducted of some of the agronomically important land units of Upper Eyre Peninsula. The objectives of the survey were to assess the potential hazard to wheat presented by boron and salinity and also the variability of the distribution of salt and boron . A further objective was to identify some easily recognised soil features (such as carbonate layers, geological formations or texture) which could help diagnose the presence of high concentrations of boron or salt in the field. Carbonate layers were of interest in the survey because preliminary (unpublished) measurements had indicated high concentrations of extractable boron and salt in IIIA carbonate layers (Wetherby and Oades 1975) at some sites on Upper Eyre Peninsula.

Experiments were conducted at both Minnipa and Cungena in which the hypothesis was tested that several decades of mechanised agriculture would induce soil stengths significantly greater than in virgin soil at depths below the normal depth of cultivation. The hypothesis was tested by comparing soil penetrometer resistances in virgin and cultivated soil. A further objective was to estimate the areas of fields covered by wheels and field traffic intensities in a season of conventional agricultural operations for comparison with data from the northern hemisphere (Håkansson 1985a) .

Tillage below the normal depth of cultivation has led to yield responses on various soil types in other parts of Australia. For instance, mean wheat yield increases of 30% were reported from tillage to 0.3 m in Western Australia from a series of 21 experiments conducted on sandy soils over four years (Western Australian Department of Agriculture 1985). Other responses were recorded from north-eastern Victoria (Ellington 1986, Steed *et al.* 1987).

The objectives of the tillage and recompaction experiments were to assess the effects of tillage deeper (0.15 and 0.30 m) than the normal depth of cultivation (0.05 m) and the effects of tractor induced recompaction on penetrometer resistance, root growth and grain yield. Experiments were conducted at Minnipa in 1987 and at Cungena in 1987 and 1988. The effects of recompaction after tillage were examined at Cungena only in 1987 and 1988.

The studies described in this thesis are concerned with factors which inhibit the penetration of wheat roots into the subsoil on parts of Upper Eyre Peninsula. The field of study is divided into two major areas: high soil strength caused by soil compaction and excessive soil boron and salinity. The final discussion considers the implications of the soil physical and chemical problems studied and the approaches most likely to overcome them.

2.0 LITERATURE REVIEW

2.1 Defining the depth of rooting and root distribution

The question of the definition of rooting depth was addressed by Weaver (1926), an outstanding root ecologist, who distinguished "working depth (the depth to which many roots penetrate and at which considerable absorption must take place)" from maximum penetration depth - the maximum depth at which roots could be found. Forrest *et al.* (1985) used as their criterion for maximum effective rooting depth of wheat, that depth below which the root length density was less than 0.5 m kg^{-1}. (This criterion was based on data indicating that no significant quantities of water were removed from the soil at lower rooting densities.)

Rooting density is one of the major means of describing root distribution and can be expressed as length of roots per unit volume of soil (L_v m m^{-3}), or per unit area of surface (L_a m m^{-2}). Rooting density may also be expressed per unit weight of soil (m kg^{-1}). Root mass data were considered by Barley (1970) to be difficult to interpret because of contamination problems and the large contribution made to the total mass by the main axes when the major absorption is carried out by lateral roots. Ellington (1986) also noted that soil contamination could be a serious problem.

Meyer (1976) reviewed the data of several authors to compile typical L_v values for roots of wheat plants growing in the field at a spacing of 150 m^{-2}.

Depth (m)	L_v (m m^{-3} x 10^4)
0-0.15	5-15
0.15-0.25	2-5
0.25-0.55	1-2
0.55-1.0	0.5-1

Klepper *et al.* (1984) cited several authors to show that root length densities of 1 x 10^4 m m^{-3} were common between 0.5 and 1 m depth in Europe and North America.

Barley (1970) noted that little was known about the variation of L_v with horizontal distance from the base of widely spread plants and this still applies, although Hamblin and Tennant (1987), in calculating L_a values for cereals and grain legumes, assumed a linear decline in rooting density from the centre of the plant outward and checked this by mapping roots on pit walls at regular intervals after sowing. However, van Noordwijk *et al.* (1985) showed that this was unlikely to be the case in the surface soil, at least.

Water and nutrient uptake may be closely related to rooting density. For instance, the water uptake rate of roots of oats was shown to be a function of rooting density and soil water potential by Ehlers *et al.* (1980) and Grimes *et al.* (1975) found a linear relationship between soil water loss and rooting density in cotton (*Gossypium hypogeum* L.) and maize (*Zea mays* L.).

However, the quantity of roots in a volume of soil is not necessarily well correlated with water absorption (Hamblin and Tennant 1987) because permeability varies laterally along the root and because of the finite resistance to water movement within the root (Molz 1971). For instance, Durrant *et al.* (1973) reported that the observed root growth of barley in the field was generally 0.1-0.15 m deeper than maximum depth of water extraction and Kmoch *et al.* (1957) found water depletion to 2.4 m in irrigated winter wheat while roots were present to 4 m. Hurd (1974) cites evidence from the literature of roots being present at levels from which appreciable amounts of water were not being removed. Nevertheless, other authors have established good relationships between water loss and rooting density (Bennet and Doss 1960; Doss *et al.* 1960). The concept of "effective root distribution", those roots actually absorbing water at a given time, was addressed by Molz (1971).

Walter and Barley (1974) and Ponsana (1975) referred to the length of hair-bearing root per unit volume of soil (L_h) as an indicator of effective root distribution in studies of water uptake and considered that L_h was from 0.1 to 0.3 L_v, although Greacen *et al.* (1976) considered that effective rooting densities in cereals are likely to range from 0.05 to 0.2 L_v. They considered that L_h was a more realistic indicator of the water absorbing pattern of the root system, and that L_h was a higher proportion of L_v at the base of the root zone.

Root length can be determined directly by measurement from pitfaces over a surface grid (Böhm 1979) or by counting intersections between roots washed from soil and randomly arrayed lines, a technique developed by Newman (1966). Others have modified this method (Marsh 1971, Tennant 1975) so that intersections are counted on a grid, the size of which depends on the length of roots to be measured. Image analysing methods have since further automated the procedure since the description by Baldwin *et al.* (1971) of the measurement of root length by the 'Quantimet' image analysing computer. Böhm (1979) exhaustively reviewed the wide range of methods and procedures available for describing root growth in field soils.

2.2 Root growth patterns

The observed decrease in rooting density down the soil profile can be fitted by exponential relationships in some circumstances and by linear relationships in others although the rooting densities calculated at each depth by equations which best fit the observations are often widely different from the observed values. Russell (1977) used the data of Ellis *et al.* (1977) for spring barley (*Hordeum vulgare* L.) to derive an exponential relation to describe the decrease in rooting density with depth in a wet year and a linear relation in a dry year. The proportion of cereal roots in the surface layer in semi-arid environments may considerably exceed that of a standard exponential relationship. If "the crop depends on current rainfall, the role of this layer compared to that of the sparsely rooted subsoil becomes critical in the supply of water and nutrients to the crop" (Greacen 1977). Often a high concentration of roots in the surface is a function of cultivation depth with which is associated lower mechanical resistance and higher concentrations of nutrients.

A co-ordinated pattern of extension rates and branching of root axes and first and second order laterals as a relatively constant function of time in cereals has been demonstrated in the laboratory by Hackett (1968, 1969, 1971) and in the glasshouse by Tennant (1976b). In field conditions, Derera *et al.* (1969) identified patterns of seminal root penetration in wheat which occurred in three phases. On a range of soil types over three seasons in field conditions in Western Australia, Tennant (1976a) identified a consistent pattern of root penetration in two stages. Over the first week, penetration was rapid after germination to a depth of 0.05-0.10 m. To week six, penetration slowed to 0.15-0.30 m and corresponded with a critical period of mid-season limited access to available soil water. This was alleviated by rainfall or survival to the second stage of rapid root penetration. Early penetration to depth was considered to be advantageous at this point. Hurd (1964), Taylor *et al.* (1967) and Russell (1977) noted that the ability of roots to extend rapidly enough to maintain contact with available soil water is of major survival value.

The second critical period identified by Tennant (1976a) began when available water reserves defined by maximum root penetration were exhausted. Late rains and climatic conditions are important at this stage. Tennant (1976a) found that greatest root penetration occurred between eight and 13 weeks with maximum depths reached between 10 to 14 weeks post sowing. Maximum penetration depths were a function of soil type.

Derera *et al.* (1969) showed that under simulated field conditions, varieties achieved maximum root penetration by five to seven weeks from sowing with significant varietal differences in rates, and maximum depth, of penetration. Meyer (1976) considered that while rooting density appeared to decline from anthesis to maturity, wheat could produce new roots after anthesis in the presence of adequate soil water.

2.2.1 Seminal and nodal roots - interrelationships

The direction of root growth is the final result of various stimuli. The root tips of seminal axes grow generally downwards in uniform penetrable soil under the influence of gravity (positive geotropism) (Rufelt 1968). Root orientation may be related to the presence of roots of the same or other species either growing concurrently or as a result of previous exploitation.

Historically, there have been conflicting opinions about the relative values of seminal and nodal roots to the growth and yield of wheat. Amputation studies of seminal and nodal roots of graminaceous species suggest that in the absence of nodal roots, seminal roots may penetrate deeper into the subsoil and branch more profusely (Weaver and Zink 1942). Locke and Clarke (1924) and Simmonds and Sallans (1932) showed that where dry surface soil or amputation prevented nodal root development, seminal roots were able to furnish sufficient water to maintain growth of wheat to maturity.

Evidence from the literature suggests that nodal roots are generally restricted to within 0.4 m of the surface (Weaver 1926, Pavlychenko and Harrington 1934), although Ponsana (1975) found that in a red-brown earth, nodal roots penetrated from 0.4 m (dry season) to 0.9 m (wet season). In non-drought situations, water removal from depth may not be necessary and in this case, nodal roots appear to dominate in total water uptake.

Once maximum rooting depth has been achieved, seminal and nodal roots may proliferate at depth (Derera *et al.* 1969) but seminal roots are generally recognised as those responsible for tapping subsoil water reserves (Sallans 1942, Troughton and Whittington 1968, Ponsana 1975).

In maize studied by Taylor and Klepper (1973), deep roots were more effective in water uptake per unit length of root than shallow roots, and this was considered to be because they were younger and in wetter soil (water uptake per unit length of root is also dependent on soil hydraulic conductivity). In terms of the total amount of water absorbed, most water used by cereals is withdrawn by first order laterals since these constitute 60-80 per cent of total root length (Greacen *et al.* 1976).

While deep roots may become more important to the plant as the soil dries from the surface downwards, they may not be able to extract water at a sufficiently high rate to maintain the potential transpiration rate (Proffitt *et al.* 1985). These authors concluded that water needed to be freely available in the upper soil horizons for this to occur.

2.2.2 Genetic factors

Ample evidence can be found in the literature for intervarietal differences in depth of root growth and general root growth patterns in cereals (e.g. Webb and Stephens 1936, Derick and Hamilton 1941, Salim *et al.* 1966, Hurd 1968, Subbiah *et al.* 1968, Derera *et al.* 1969, Katyal and Subbiah 1971, Hurd 1974, Lupton *et al.* 1974). There has been some controversy about the possibility of shorter strawed wheat cultivars having a restricted root system in comparison with taller varieties because of the genetic influence over root:shoot ratios. MacKey (1973) warned that the use of semi-dwarf wheat could produce a shortened or inefficient root system. However, extensive research by Lupton *et al.* (1970) using radioactive tracer techniques showed that semi-dwarf winter wheat tended to have more extensive root systems at depth than the taller varieties in the comparison, and that environmental factors caused much greater variation within cultivars than occurred between cultivars at a single site. Cholick *et al.* (1977) found no significant relationships between cultivar height and rooting depth.

2.3 Soil water

Environmental conditions more often than not modify the expression of genetic control over rooting patterns (Lupton *et al.* 1974, Russell 1977). For crops grown on well drained soil of adequate pore space distribution, the depth of rooting is largely a function of available water supply, provided the shoots can produce sufficient carbohydrate to maintain root growth (Russell 1973), and in low rainfall environments root penetration is often directly related to water penetration (Tennant 1976a).

Tennant (1976a) found that root penetration in soils with sand over clay, and in grey clay soils in Western Australia was a function of water penetration, although in wet years on deep sands, average maximum wheat root penetration rarely exceeded 1.8 m, despite deeper water penetration. In a sandy loam, previous reserves of stored soil water at depth allowed penetration beyond seasonal water penetration.

Most cereal crops will display a deep rooting ability only if grown where the principal source of available water is in the subsoil. In that case, the depth of root penetration and rooting density at depth is largely determined by the hydraulic conductivity of the subsoil (Gardner 1960). In semi-arid environments, rooting depths tend to be shallower because the limits of root exploration are determined by the regular wetting front (Russell 1973, Tennant 1976a).

It has been widely accepted that roots do not generally penetrate soil with water contents drier than that at the permanent wilting point (Hendrickson and Veihmeyer 1931, Salim *et al.* 1966). However, Portas and Taylor (1976) showed that maize roots could elongate slowly into soil having a matric potential of -4 MPa when the plants were sufficiently supplied with water from other soil layers to maintain plant water potential. They noted that in the work of Hendrickson and Veihmeyer (1931), a "compacted clay soil" was used, implying a component of soil strength in the growth equation. The effect of matric potential on root growth is often modified by its effect on soil strength.

When the soil water potential falls to a critical level, root growth slows and finally stops (Gingrich and Russell 1956, Portas and Taylor 1976, Ehlers *et al.* 1980). Greacen and Oh (1972) recorded that the rate of growth of pea radicles began to slow at a soil water potential of -0.5 MPa in "soil of moderate resistance".

Roots absorb less water as the matric potential decreases but the amount of water absorbed is also related to the osmotic potential of the soil water. Wheat root growth also slows as the osmotic potential (Ψ_0) decreases. Lawlor (1973) reported that root growth of wheat ceased at -1 MPa (Ψ_0) but roots were able to compensate for low osmotic potentials in part of the root zone by increasing intake in other parts. Shalhevet and Bernstein (1968) also reported the same effect in lucerne (*Medicago sativa* L.). Sepaskhah and Boersma (1979) studied the interactive effects of osmotic and matric potentials on wheat shoot and root growth. Shoot growth was affected by the interaction between osmotic and matric potentials. Rooting density was not affected by an interaction but in this study, rooting density was decreased by matric potentials less than -0.5 MPa and also decreased as a function of decreasing osmotic potential induced by sodium chloride.

Even short periods of dry weather can restrict root growth and function near the surface of the soil and the ability of roots to penetrate quickly to depth where at least part of the root system has access to available water is therefore of importance in conditions of surface drought. It is unlikely that wheat roots would be able to penetrate dry soil to reach deeper subsoil reserves. Weaver (1926) reported the absence of roots below 0.6 m on short grass plains in the U.S.A. in the absence of subsoil water. These conditions were created by a climate in which dry soil was watered by light showers and the surface remained moist while the subsoil remained dry. However, when the same soil had a wet subsoil and the surface dried, roots penetrated the subsoil.

Tennant (1976a) reported that wheat on a grey clay soil failed to set grain in a dry season because the available water was used early in the season, emphasising the need for available water reserves at depth for later use. Maximum mean depths of penetration ranged from 1.4-1.69 m in deep sand, 1.58-1.73 m in sandy loam, 0.26-0.31 m in grey clay and 0.61-0.73 m in sand over clay. Klepper *et al.* (1984) reported from the literature that wheat roots often penetrate well below 1 m in the field.

The yield of wheat is not necessarily a function of total root length, dry weight of roots, or depth of roots *per se*, nor does the weight of aerial parts of the plant correlate with root depth. If the rooting media is sufficiently well supplied, a restricted or shallow root system may be able to supply all of the water, nutrient and other compounds required for optimum plant growth. Ayling and Gales (1983) suggested that this phenomenon was a form of "insurance" against death or damage to part of the root system. Sharma (1987), in a greenhouse experiment, showed that the plant water status in wheat was not affected by pruning a quarter of the root system, but in the field, root development and the capacity of plants to absorb water are generally closely related (Durrant *et al.* 1973, Hurd 1974, Walter and Barley 1974, Meyer and Alston 1978).

2.3.1 Drought tolerance

Drought tolerance has been related to depth of rooting and high rooting density at depth (Burton *et al.* 1954, Hurd 1974, Katyal and Subbiah 1971). Hurd and Spratt (1975) suggested after reviewing the literature that 0.6 m was a critical depth below which roots must penetrate and extract available water to confer drought tolerance. The majority of roots occur in the top 0.6 m but in semi-arid climates, the available water in this zone is often depleted by grain filling. Hurd (1974) noted that even in very dry years in Saskatchewan, water was available below 0.6 m after harvest and suggested that varieties able to send roots below 1.2 m would have the greatest ability to avoid water stress. Wheat roots in the field do not often attain depths more than 2 m and 1-2 m appears to be the usual depth in temperate climates (Russell 1973, Forrest *et al.* 1985).

Increasing rooting depth or the number of seminal axes in the subsoil may increase water use by reducing the resistance to vertical flow via the metaxylem vessels, provided that sufficient water is available (Meyer and Alston 1978). Changing the number of axes or size of the metaxylem vessel in each axis (Meyer 1976), variation in plant density (Fawcett 1967, Walter and Barley 1974, Fawcett and Carter 1974) and weed competition can modify the amount of water withdrawn in early growth stages and so affect the amount available for grain filling. Passioura (1972) and Meyer (1976) demonstrated that the yield of plants relying on subsoil-stored water could be improved by reducing the number of seminal axes entering the subsoil, thus conserving stored water. The same principle applies where profuse early root growth may dry soil too quickly in semi-arid conditions.

Population densities of plants can be related to rooting depths through their effects on the soil water profile. Single isolated plants or densely crowded plants (Ponsana 1975) both tend to have shallow root systems. An intermediate density encourages maximum depth of rooting. Walter and Barley (1974) showed that on a sandy red-brown earth, plant densities of 20 m^{-2} and 470 m^{-2} depleted soil water to harvest from a shallower depth than an intermediate plant density (90 m^{-2} - 55 kg ha^{-1} of seed) although water was still available in the deeper layers after the growing season in all treatments. Highest grain yields also occurred at the intermediate density. The authors considered that at the lowest plant density, the small number of conducting vessels from the subsoil constituted the major resistance to upward movement of water. At the highest plant densities, the principal resistance to the extraction of deeper water was a soil related factor.

The type of root system likely to optimise yields depends on root geometry and soil water availability as it is determined by soil water storage capacity and recharge frequency (Meyer and Alston 1978). Other environmental and management factors such as time of sowing will also be involved (Fawcett and Carter 1974).

It should be remembered that deep rooting is not the only attribute conferring drought tolerance on wheat. Earliness of maturity and desiccation tolerance have also been reported as shoot related factors (Derera *et al.* 1969, Hurd and Spratt 1975).

The length of time plants are able to withstand water stress is related to depth of rooting. Pearson (1971) estimated that in coastal plain soils in eastern U.S.A. with low water storage capacity, crops could withstand only five days without rain in soil initially at field capacity before suffering water stress at an effective rooting depth of 0.45 m while an effective rooting depth of 0.90 m would more than double this period because of the reduced evaporation of subsoil water.

Similar findings were made by Elkins *et al.* (1977) who observed that the water holding capacity of many soils increases with depth. For soils with relatively low water holding capacity, recharge frequency is an important factor in determining the potential benefits of deep rooting. The depth of soil water extraction can be related to the depth of rooting. Transpiration accounts for much of the available water loss below 0.2 m and soil drying can be used to indicate the presence of roots (Conrad and Veihmeyer 1929, Bennett and Doss 1960).

Water is removed sequentially from shallow to deeper levels when the profile is uniformly wet (Russell *et al.* 1940, Proffitt *et al.* 1985). As transpiration occurs, reduction in water potential in the root xylem vessels creates a potential gradient across the root and water flows from soil at the root surface to the xylem. An osmotic potential gradient may also induce the flow of water into the xylem.

Less energy is required at first to remove water from the shallow depths where root concentrations are highest and the average distance water must move is least. As the water potential becomes more negative in these shallow layers, progressively more energy is required to remove the water until that required to move water the greater distance from lower depths is less (Taylor and Haddock 1956). The combination of root distribution and soil hydraulic properties, then, determines the water uptake pattern (Gardner 1964). The withdrawal of water from all but very dry soils was related primarily to root distribution and root hydraulic properties by Greacen *et al.* (1976).

2.4 Soil structure and texture

Early studies of root growth, often based on inspection of pit faces, suggested a relationship between the physical condition of the soil and depth of root growth. Deep friable soils were found to contain roots at depths not reached by roots of plants growing on poorly structured or compact subsoils (Weaver 1926, Moon 1938, Winters and Simonson 1951, Fehrenbacher and Snider 1954, Fehrenbacher *et al.* 1960). High bulk densities and poor aeration have been associated with finer textured subsoils lacking structural development (Fehrenbacher and Rust 1956).

Root penetration is often a function of water penetration which may be related to soil texture. Tennant (1976a) found in a three year study in Western Australia that cereal roots penetrated to depths in the order: sandy loam > deep sand > sand over clay > grey clay. Root penetration depth varied with water penetration in the sand over clay and grey clay soils and in one season in the deep sand. In the other two seasons of measurement water penetration in the deep sand exceeded root penetration. In the sandy loam soil, root penetration was greater than the depth of water penetration because of stored soil water below this depth. Basically similar associations were established by Fitzpatrick and Rose (1936) in Oklahoma where depth of root penetration was also related to water penetration. High sodium contents, contributing to poor structure, have also been implicated in the prevention of deep rooting (Fehrenbacher *et al.* 1969, Joshi *et al.* 1985).

Compaction can induce the soil to behave as if it were of finer texture, by reducing the proportion of larger pores responsible for air filled porosity at field capacity, and total porosity is simultaneously reduced. At field capacity, the volumetric water content (θ) is at first increased but as compaction continues, so that the reduction in total porosity is of greater importance than the increase in microporosity, θ at field capacity is reduced. This applies particularly to soils having a particle size distribution conducive to packing to a high density such as some loams and sandy loams (Hill and Sumner 1967, Warkentin 1971, Greacen and Sands 1980).

Soil structure may be of much more significance in its effect on root growth in fine textured soils than in sandy soils where soil strength is likely to be of more importance (Taylor 1971).

2.5 Soil compaction

Besides many of the natural processes such as hard setting through drying, age hardening, overburden pressures and compaction by animals, compaction by agricultural machinery is a major cause of increased soil strength. Compaction increases the soil density, and this gives rise to reduction of air-filled porosity, reduction of hydraulic conductivity, and increased soil strength. These effects in turn can result in increased incidence of root diseases in crops; water-logging, run-off and erosion, increased energy requirement for tillage, and reduced rates of root growth and crop yields. The processes of compaction and its consequences have been considered in some detail by Soane 1970, Eriksson *et al.* 1974, Greacen and Sands 1980, Håkansson 1985a, Håkansson *et al.* 1988.

Soil compaction reduces the elongation rate of roots, and rooting density and depth of rooting are restricted (Greacen *et al.* 1969, Taylor and Ratliff 1969, Bennie and Laker 1974, Grimes *et al.* 1975, Russell 1977, Bennie and Botha 1986) especially in drought (Fiskell *et al.* 1968). Root morphology is also altered with roots tending to grow more intensively above compacted layers (Shierlaw and Alston 1984, Bennie and Botha 1986, Wilhelm and Mielke 1988). Dexter (1987) concluded from the literature that the rate of root elongation decreases linearly with increasing mechanical stress on the root.

The effect of soil compaction in limiting root penetration may seriously impede the ability of the plant to absorb water from the subsoil, particularly in a semi-arid dryland environment (Stibbe and Ariel 1970).

Soil changes attributed to compaction have persisted on a tilled clay loam soil for at least nine years (Blake *et al.* 1976), a sandy loam for at least six years (van Ouwerkerk 1968, Pollard and Webster 1978), and on logging tracks on sandy soils for more than 50 years (Greacen and Sands 1980). Håkansson (1985a) considered that compacted plough layers would normally persist four to five years in Sweden where annual freezing and thawing of the soil occurs. Recovery time depends on soil texture, degree of compaction, and climatic factors.

Clay soils have a high compression index which is a function of high porosity, although they take longer to compress than coarse textured soils (Dexter and Tanner 1974). Clay platelets are elastic and recovery after loading tends to increase with clay content. Where clay content is higher than 20%, freezing, swelling and shrinking may help reduce the effects of compaction (Koolen and Kuipers 1983). Sandy soils tend to form "massive pans with few voids" (Koolen and Kuipers 1983). Compaction is most readily achieved in soils having a particle size distribution such that smaller particles can occupy voids between larger grains, as with loams and sandy loams. A comprehensive review of the packing behaviour of sands was published by Panayiotopoulos (1989).

Susceptibility to compaction depends on the organic matter content of the soil, and wet soils high in organic matter are more compaction resistant (Koolen and Kuipers 1983). Surface stones may also help reduce the susceptibility of soil to compaction. Saini and Grant (1980) found that smaller stones were more effective than larger stones in reducing the susceptibility of soil to compaction and the effect was greater at 30% stone content by weight than at 10%.

Regardless of texture, soils having relatively high water content (and sufficient air filled porosity) are more susceptible to compaction than dry soils, and wet soils are particularly prone to compaction by the passage of wheels (Vomocil *et al.* 1958, Soane *et al.* 1980a).

Pneumatic tyres generally exert surface pressures roughly equal to inflation pressure although concentrated at the edges by stiff carcase walls (Gill and van den Berg 1967) and under the lugs (Gill and van den Berg 1967, Koolen and Kuipers 1983) - the uneven distribution is dissipated in the top 0.15-0.20 m where stresses are concentrated.

Soil pressures at greater depths are increasingly independent of the surface pressure distribution and depend more on the total load and pressure concentration factors (Dexter *et al.* 1988).

Wheel slip contributes significantly to soil compaction (Davies *et al.* 1973) since under shear failure the change in voids ratio is defined by the critical state line and greater compression can occur for a given input of energy. Shear forces and vibratory effects are restricted to engine driven machinery.

Most of the work on soil compaction has been done in fairly-high latitudes in North America and northern Europe. In the mechanized farming systems used in these areas, high proportions of the areas of arable fields are covered every year by the wheels of machines. Soane (1970, 1975) reported that, in Britain, the traditional method of seedbed preparation for cereals (after an earlier ploughing) involved: fertilizer distribution, harrowing twice, sowing and rolling. These five operations resulted in 0.91 of the area being covered by wheels. On fields used for cereal production in Sweden, Eriksson *et al.* (1974) reported that the total area of wheel tracks produced each year (including ploughing) may be up to five times the area of the field and Håkansson (1985a) measured factors in the range three to 5.5.

In some experiments in The Netherlands on the effects of tillage and different levels of traffic on soil conditions and crop growth, Lumkes (1984) measured wheel track areas in the approximate range 1.25 to three times the area of the experimental plots. The lower end of this range was considered to be the minimum which could be achieved.

The pattern of the wheel tracks produced is not random, but neither does it occur in any organized way. It depends on the pattern of field working in combination with the wheel spacings on the various machines. Wheel spacings are not standardized in agriculture and tend to be different on every machine used by a given farmer. The resulting pattern of wheel tracks has been described by Greacen and Sands (1980) as a systemised function of mechanical operations.

To sum-up or integrate the total amount of field traffic, Håkansson (1985a) has used the term "traffic intensity" which is in units of t km ha^{-1}. For typical Swedish cereal farms, he obtained values of traffic intensity in the range 110-230 t km ha^{-1}.

The effect of heavy machinery and high axle loads in compacting subsoil below the normal depth of tillage has become an increasing cause for concern (Håkansson

1985a, Voorhees *et al.* 1986). Several authors refer to the earlier work of Danfors (1974) who showed that at high axle loadings, the major compacting effect may occur in the subsoil below 0.4 m. The effect of compaction above 0.3 m is not considered to be a problem in European and North American soils because the normal tillage depth is 0-0.3 m (Voorhees *et al.* 1986). These authors reported that heavy axle loads (of 9,000 and 18,000 kg) were able to alter significantly the bulk density, penetrometer resistance and hydraulic conductivity to these depths when the subsoil was relatively dry. Bulk density increases to a depth of 0.5-0.6 m occurred in wet subsoil.

Braunack (1986) reported similar changes in soil surface properties in tracks left by a single passage of tracked armoured fighting vehicles. On a range of soil textures, bulk densities were greater in tracks than between tracks to the depth of measurement, 0.1 m. Penetrometer resistances were considerably greater in the tracks and at two sites the maximum possible depth of penetration was 0.04 m with a between-track penetration of 0.45 m. It was concluded from all sites that soil strength in the 0.05-1 m interval was increased by passage of a vehicle. It was concluded from the literature that, depending on impact conditions, the initial passage of a vehicle on undisturbed soil causes greater compaction than subsequent passes in the same conditions. Saturated hydraulic conductivity (K_0) was less in the 0-0.05 and 0.05-1 m depth intervals in the tracked areas, although the K_0 values increased after wetting and drying. There was some suggestion that recovery could occur after sufficient wetting and drying.

Voorhees *et al.* (1978) reported that wheel traffic compaction is generally limited to the upper 0.3 m when axle loads are less than 4,500 kg. They may extend below 0.4 m when axle loads exceed 6,000 kg (Håkansson *et al.* 1988). Håkansson (1985b) showed that compaction caused by agricultural machines having high axle loads (10,000 kg) could be measured at a depth of 0.5 m and persisted for seven to eight years. The use of wider or larger diameter tyres does not reduce the subsoil compaction problem in the case of high axle loads since soil stress extends deeper for a higher load (Blackwell and Soane 1981, Voorhees *et al.* 1986). Where freezing and thawing, shrinking and swelling do not occur and clay content is low, the persistence of subsoil compaction is likely to be considerable.

Generally, compaction under wheels can be related to a complex of parameters including soil texture, compacted state, water content, axle load, contact pressure, wheelslip, tyre dimensions and carcase construction, inflation pressure, forward speed and number of passes. The literature on wheel parameters associated with compaction has been reviewed by Soane *et al.* (1980a,b, 1982), and by Håkansson *et al.* (1988).

The term 'hardpan' is often used loosely to describe any zone of high impedance to root growth, and includes natural claypans and other artificially induced high strength zones such as tillage pans. Tillage pans are characterised by higher soil strength, bulk density, and lower pore space than proximate soil layers (Kashirad *et al.* 1967).

When roots encounter a soil pan, often at the base of the seedbed, they may be diverted horizontally so that the entire root zone is restricted to the soil depth above the pan. Productivity may not necessarily be reduced if the plants' requirements for water and nutrients can be met in this zone. However, Peterson *et al.* (1984) reported that in an environment adequately supplied with water and nutrients, confining the roots of winter wheat (*Triticum aestivum* (L.) em Thell. cv. Stephens) to a sufficiently small volume was itself sufficient to limit the co-ordination of plant growth and plants were significantly smaller. If, as often occurs in drought, access to subsoil water reserves is required, yield may be considerably reduced.

If roots are able to penetrate a soil pan, lateral proliferation may occur in lower layers if soil strength is sufficiently low. Soil pans may also allow penetration and proliferation of roots when the pan strength is reduced by high water content. Taylor *et al.* (1966) concluded that the root restricting nature of 17 soil pans studied was caused by high soil strength which was induced by soil drying.

Soils may crack as a result of being dried out by root activity and these vertical cracks provide another important method by which roots can penetrate through soil pans. Root morphology is often determined by the geometry of soil crack patterns (Whiteley and Dexter 1984). Examples have been reported from several countries of roots following preferred paths to considerable depth via cracks and other planes of weakness in the subsoil (Cannell 1977).

Artificial cracks can be created by machines either before sowing using deep tillage machines or by the use of slit tillage (Whiteley and Dexter 1982). Root penetration into compact subsoils is also facilitated by the presence of biopores. Biopores can be created by earthworms and other fauna and by the roots of preceding plants. The gradual disappearance of channels left by tree roots in newly cleared land may also lead to reduced penetration of crop roots into the subsoil. Barley (1954) showed that decaying roots left channels which improved soil permeability. Elkins *et al.* (1977) found that the use of Pensacola bahiagrass (*Paspalum notatum* Flugge) preceding cotton allowed cotton roots to penetrate the subsoil via biopores left by the bahiagrass roots to depths of up to 1.8 m and so increase water uptake. Lucerne has also been used on calcareous soils in Egypt to improve the physical condition of the soil for root penetration (Talha *et al.* 1974).

Root distribution has been closely correlated with zones of faunal activity (Edwards and Lofty 1978). Dexter (1978) showed that earthworms could penetrate soil having a penetration resistance of 3 MPa by soil ingestion.

The improvement in the numbers of earthworms and the frequency of continuous biopores and planes of weakness in direct drilled or otherwise uncultivated soil used for cropping has been considered to be responsible for root growth and water extraction equivalent in depth to that of conventional cropping systems (Ellis *et al.* 1977). Water penetration has also been improved by continuous biopores reaching the surface (Ehlers 1975). Compaction and tillage operations destroy the continuity of biopores and severely decrease faunal populations (Gooderham 1976).

2.6 Bulk density

Bulk density is often used to indicate the compacted state of soil, and small changes in bulk density lead to large changes in soil strength (Henderson *et al.* 1988) particularly at low water potentials (Prihar *et al.* 1975). Jakobsen and Dexter (1987) noted that increases in bulk density of 100 kg m^{-3} corresponded to increases in penetrometer resistances of 52-57% on a red brown earth and a solonised brown soil. Penetrometer resistances are also more directly influenced by bulk densities at lower water contents than high water contents (Ayers and Perumpral 1982). In dry environments, small increases in bulk density are likely to have significant effects on root growth.

Some authors have listed values of critical bulk densities for various texture groups beyond which root penetration is likely to be limited. The critical density is a function of the size, distribution and shape of particles (Greacen and Sands 1980). Bowen (1981) suggested that approximate densities of 1,550, 1,650, 1,800 and 1,850 kg m^{-3} would severely limit root growth on clay loams, silt loams, fine sandy loams and loamy fine sands respectively. Roots growing in coarse sand, having other conditions favourable, typically have well branched and extensive root systems but Russell (1973) suggested that roots are unable to enter a coarse textured soil having a bulk density greater than 1,700-1,800 kg m^{-3} or a fine textured soil if the bulk density exceeds 1,500-1,600 kg m^{-3} (unless the soil strength is low because the soil is wet). Critical bulk densities increase as the sand content increases.

Root branching in soils of low bulk density tends to be restricted and this may lead to inadequate soil exploration (Soane *et al.* 1982). Some compaction then may be beneficial and improve water availability (Raghavan *et al.* 1979). This leads to the concept of an optimum bulk density which was considered by Archer and Smith (1972) to be that at which available water content was at a maximum in the presence of adequate aeration - at least 10% at a matric potential of -5 kPa. They listed optimum bulk densities at 1,200 kg m^{-3} for clay loam, 1,400 kg m^{-3} for a silt loam, 1,500 kg m^{-3} for a sandy loam and 1,750 kg m^{-3} for a loamy sand.

When bulk density is increased by compaction, the proportion of larger pores responsible for air filled porosity of the soil at field capacity (pores larger than 30-60 µm in diameter) is reduced, and this change in void size distribution alters the water retention and transmission properties of the soil, so that water infiltration rate and saturated hydraulic conductivity are decreased.

An increase in bulk density may indicate a restriction in root penetration, due to a decrease in pore continuity or in the number of pores of sufficient diameter for roots to enter. Reduction in pore size also adversely affects soil aeration. However change in bulk density as a fundamental indicator of soil compaction is limited, and may not always indicate changes in pore structure. Information on soil water contents and texture is needed to allow interpretation of bulk density data, and as Greacen and Sands (1980) have pointed out, it is soil strength which determines resistance to compaction, and the state of compaction is described in soil mechanics theory by the voids ratio (e). Soane *et al.* (1981a) suggested that the use of a ratio of bulk density or voids ratio to the same soil in a defined reference state, such as specific volume (1 + e) would be a more useful parameter for field and laboratory studies.

More recently, Håkansson *et al.* (1988) suggested that bulk densities of different soil types could be compared by expressing bulk density as the "degree of compactness" a percentage of the reference bulk density achieved in the laboratory by applying a static pressure of 200 kPa in long term uniaxial compression. They reported that maximum crop yields of spring barley were achieved at the same degree of compactness independent of soil type in a large number of experiments.

The relationship between bulk density and plant growth is usually a function of a set of circumstances applying to the soil type where the relationship was measured. At any bulk density, there may be a wide range of pore sizes. Problems of interpreting the relationships between soil texture and bulk density were addressed by Jones (1983) who used the data of several authors to calculate texture - critical bulk density relationships at which root growth would be severely restricted (20% of maximum value) at close to optimum water contents. Highly significant negative relationships were found between percentage clay, or silt plus clay, and the bulk density at which root growth was either a maximum or 20% of maximum.

Bulk density data was recently used by Vepraskas (1988) in a diagnostic model for estimating where root growth of tobacco (*Nicotiana tabacum* L.) would cease because of mechanical impedance or where deep tillage could be predicted to increase root growth and yield.

2.7 Soil strength

The concept that soil strength has a major and pervasive influence on root growth was expressed by Barley *et al.* (1965). They found that soil strength was the major property controlling root penetration and growth over a range of bulk densities and matric potentials.

Taylor (1971) concluded from the literature that soil strength was a function of water content, bulk density, organic matter and clay mineral characteristics, particle contact parameters, and saturating cations, which contribute to internal cohesive forces so that soil strength can not be directly related to parameters such as soil texture.

Taylor and Ratliff (1969) reported that root elongation rates of peanuts (*Arachis hypogaea* L.) and cotton decreased with increasing soil strength but that this relationship was independent of matric potentials between 0.017 and 0.7 MPa for cotton and 0.019 and 1.25 MPa for peanuts in a low water holding capacity soil.

Soil strength is often correlated positively with soil bulk density and negatively with the water content of coherent soils (Gerard *et al.* 1982). Ayers and Perumpral (1982) derived equations expressing penetrometer resistance as a function of bulk density and water content for five soil types artificially composed of varying clay and sand contents. Maximum penetrometer resistances were achieved for a given bulk density at a specific water content which depended on the soil type. The water content at which maximum penetrometer resistance was achieved increased as the percentage of clay. In each soil type, soil water content at which maximum penetrometer resistance was achieved was less than the water content at which maximum dry bulk density was achieved. Similarly Ehlers *et al.* (1983) used multiple regression equations to relate penetrometer resistance to bulk density and water contents for field soils.

The effects of soil strength and matric potential on root growth have been considered by several authors, with the conclusion that soil strength had the predominant effect in reducing root growth in compacted soil (e.g. Barley 1962, Taylor and Gardner 1963, Taylor and Burnett 1964, Taylor *et al.* 1966). Mirreh and Ketcheson (1973) showed that the relationship between soil penetration resistance and elongation of maize roots was affected by matric potential. At a specific resistance, elongation was reduced further with decreasing potential. Yapa *et al.* (1988) also determined that soil strength had the greater effect on the root growth of grain legumes but that the effects of matric potential and soil strength were independently significant. Relative root penetration was 20% of the maximum or less at penetrometer resistances greater than 3.3 MPa. This agrees with a model developed by Dexter (1987) who analysed the data of several authors to express relative root growth mathematically in terms of matric potential and penetrometer resistance. From this model, it can be shown that root growth is likely to be severely restricted in soils having penetrometer resistances of more than 2 MPa in semi-arid environments where the soil rarely reaches field capacity. At this value of penetrometer resistance, root growth is predicted to cease at a matric potential of -0.5 MPa.

Much research in recent times has been devoted to assessing the relationships between soil strength and root growth. Efforts were made to determine the minimum soil pressures which could reduce root elongation but as Dexter (1975) pointed out, much of this research was undertaken in artificial media such as sand or ballotini beads or remoulded soils which are likely to give results unrepresentative of field conditions. Because of the incompressible, frictional (non cohesive) nature of ballotini beads and sands, very low pressures (e.g. 0.1 MPa) applied externally to the growth medium are able to arrest root elongation. Because the cohesion of remoulded samples is reduced, compressibility at a given density and water content is increased so that pressures applied to remoulded samples will not have the same effect on root elongation as those applied to undisturbed samples.

2.7.1 Mechanics of root growth

Greacen and Oh (1972) contributed to a fundamental understanding of the processes involved in root penetration by showing that hydrostatic pressure P within the cell was opposed by wall pressure W, and the external reactionary soil pressure σ_n resisting deformation by the root. The relationship was expressed as:

$$P + W + \sigma_n = 0$$

The elongation rate of the root R was related to m, extensibility of the cell wall material, W, the tensile stress in the cell wall, and W_c, the critical threshold stress for growth, by

$$R = m\,(W - W_c)$$

With the internal water potential, external water potential, and mechanical stresses of the root cell balanced, the cell is in mechanical equilibrium. Dexter (1987) later described the elongation rate (R) in terms of m, the cell wall extensibility factor with $|\Psi_i|$, the total internal water potential, $|\Psi_0|$ the total external water potential, W_c, the critical wall pressure component which must be exceeded for elongation to occur, and σ, external pressure of the surrounding medium (or pressure exerted by the root), so that

$$R = m[\,|\Psi_i| - |\Psi_0| - W_c - \sigma].$$

R is the elongation rate of a single cell but is applicable to the concerted efforts of all cells in the elongation zone. For elongating cells, σ denotes the pressure required for soil deformation.

Differentiation of this equation enables the relationship between root elongation rate and soil mechanical resistance to be examined. Roots are able to osmoregulate by modifying the internal water potential of the cell in response to changes in external matric or osmotic potentials or soil strength. This is done by controlling the concentrations of osmotically active compounds in the vacuole. Root growth ceases when osmoregulation is limited by the combined influences of Ψ_o and σ.

When root elongation is arrested, roots may expand radially, leading to shorter but thicker roots (Abdalla *et al.* 1969). Penetrating root tips use less energy in straining soil cylindrically than spherically and for real soils, Dexter (1975) used data by Farrell and Greacen (1966) and Greacen *et al.* (1968) to suggest that the ratios of pressures required to expand cylindrical cavities P_c and those required to expand spherical cavities P_s were in the ratio $2.5 < P_s/P_c < 4$, with decreasing values of the coefficient of soil friction giving lower ratios.

Some spherical soil deformation may occur with an impeded root and this expansion may lead to failure of the soil by tension ahead of the tip, allowing further penetration (Barley 1968, Abdalla *et al.* 1969, Gerard *et al.* 1972). Whiteley (1989) produced micromorphological evidence to suggest that root exudates help reduce the mechanical strength of the soil in the region of the root tip.

Scholefield and Hall (1985) showed that the roots of grasses could penetrate rigid pores smaller than their nominal thickness but no smaller than the root cap and stele. Constricted root tips could grow at a reduced rate down restricted tubes in adequately aerated conditions. This has important implications for the ability of roots to penetrate to depths in soils of high strength containing continuous vertical pores.

2.7.2 Soil penetration resistance

In studies of root penetration, the use of hand held penetrometers has proved to be a convenient and widely accepted means of assessing soil strength and the effects of soil strength on root elongation (Taylor and Gardner 1963, Taylor *et al.* 1966, Greacen *et al.* 1968, Bowen 1981, Gerard *et al.* 1982, Yapa *et al.* 1988), because of their ease of use and the number of measurements which can be made rapidly with recording penetrometers (Anderson *et al.* 1980). They appear to have particular value in uniform non-stony sandy soils where undisturbed sampling is difficult or precluded (Perumpral 1987, Henderson 1989). Penetrometer resistances at which root elongation ceases are considerably greater than those causing a large reduction in root elongation rates (Dexter 1987). Taylor *et al.* (1967) found a curvilinear decrease in the percentage of cotton taproots penetrating through cores of five soils as soil strength increased. Ehlers *et al.* (1983) found that root growth of oats was linearly related to penetrometer resistance and Dexter (1987) concluded from the literature that root elongation rates decrease linearly with increasing external mechanical stress on the root tip.

Penetrometer resistances are an integrated function of bulk density, water content and potential, soil texture (particularly size and shape), particle bonding, soil organic matter, cone shape, size, material, and the speed of penetration (Taylor *et al.* 1967, Gill 1968, Whiteley *et al.* 1981, Ayers and Perumpral 1982, Gerard *et al.* 1982, Shierlaw and Alston 1984, Henderson 1989). Also, penetrometer resistances can be the same in various combinations of shear cohesion and modulus, angle of internal friction,and compressibility (Dexter and Woodhead 1985). Greacen *et al.* (1968) listed limiting values of penetrometer resistance found in the literature. The range was 0.8 to 5 MPa. They referred to work by Eavis (1967) who showed that the axial force exerted by a root penetrating soil was "less than a quarter of the force opposed to a fine metal probe in weak soil and less than an eighth of that opposed to a probe in strong soil". Farrell and Greacen (1966) proposed that penetrometer probes strained surrounding soil in a spherical manner. This was expanded by Greacen *et al.* (1968, 1969) to explain the cylindrical straining of surrounding soil by elongating root tips. These differences, together with the fact that root-soil friction is smaller than penetrometer-soil friction, account for some of the differences between penetrometer resistances and root penetration pressures. Dexter (1987) noted that the ratio between penetrometer resistance and root mechanical pressure increased progressively with increasing soil strength and ranged from three to 10 or more in very strong soil.

Gooderham (1976) referred to the need to standardise penetrometer techniques and Bradford (1980) suggested procedures for standardisation of penetrometer design and tests, particularly on coarse structured soils. He considered that besides providing matric potential-soil water content data, details of soil macrostructure should be provided with penetrometer data. Differences in technique partly explain the wide range of critical penetration resistances reported in the literature.

Several authors have suggested critical penetrometer resistances at which root growth is likely to cease in the presence of available water. However, many of these critical values are based on measurements carried out with remoulded soils which give values different from field soils (Chesness *et al.* 1972). Taylor and Burnett (1964) reported that a field penetrometer resistance of 2.5 MPa prevented root growth, while there was abundant root growth through a hard pan with a penetrometer resistance of 1.9 MPa. Ellington (1987) suggested that a penetrometer resistance of 2 MPa or more measured at field capacity would seriously restrict root growth. Other authors (e.g. Pearson 1966, Ide *et al.* 1984) refer to a value of 3 MPa below which root growth is likely to be suppressed. Gerard *et al.* (1982) conducted laboratory tests in which root growth ceased at critical strengths which increased with decreasing clay content in a simple exponential relationship. Root growth decreased linearly in a fine sandy loam soil in the 0-0.3 m and 0.3-0.6 m depth intervals with increasing penetrometer resistance. In both laboratory and field studies, limiting values of penetrometer resistance appear to decrease with increasing depth (Grimes *et al.* 1975, Gerard *et al.* 1982,), although Ehlers *et al.* (1983) reported higher limiting values of penetrometer resistances in subsoil than topsoil. Conflicting evidence about the effect of clay content on limiting penetrometer resistances led Vepraskas and Wagger (1989) to conclude that critical penetrometer resistances determined on sieved soils were not applicable to field soils with less than 20% clay and structural cracks.

Penetrometer resistances have been principally related to root growth rather than other growth parameters. Although the relationship between root growth and yield is not always clear, Henderson (1989) was able to develop equations predicting the effects of soil compaction on wheat yield on the uniform sandy soils of Western Australia, in which the effects of soil compaction on the growth and yield of wheat were highly correlated with the mean penetrometer resistance in the 0-0.4 m depth interval over a wide range of sites and seasons. A soil water term was not employed in the model because in these coarse textured soils, soil water content had only a slight influence on penetrometer resistance when the gravimetric water content exceeded 0.05 kg kg^{-1}.

2.8 Tillage

Tillage may have direct effects on root growth by reducing soil strength or by smearing soil in the seedbed in which case root penetration into the subsoil may be severely restricted (Prebble 1970). Because most conventional tillage machinery shears soil under large pressures normal to the plane of shearing, packing densities may actually be increased (Dexter 1975). In this way, densities of seedbeds may be higher at sowing than before tillage. Tillage may indirectly affect depth of rooting by interactions with soil water. If infiltration is improved or soil water loss is reduced through weed control by tillage, then depth of root growth into the subsoil may be modified as a consequence.

2.8.1 Deep tillage

Soil compaction is often treated by deep tillage, the aim of which is to loosen or break up a compacted soil layer without inversion or mixing to permit the free movement of air and water and enhance root growth. The literature on deep tillage was reviewed by Ellington (1987).

Russell (1957) reviewed the results of more than 100 experiments in which deep tillage was involved and found that yield responses were generally small. Overall, cereals responded to deep tillage on clays, loams and light loams, but not on sands where yields were actually reduced in many of the experiments surveyed. It was not possible to identify specific soil properties which related to the increases or decreases in yield. This contrasts with data collected by the Western Australian Department of Agriculture (1985) where responses to deep tillage occurred mainly on sandy soils, with little response on soils of finer texture.

Pearson (1966) noted that it may be impossible to interpret crop responses to deep ripping from the data often provided. If prolonged drought has prevented recharge of subsoil water, root penetration may be restricted by water availability alone. Little improvement in root growth can be expected if conditions other than mechanical impedance, which may be alleviated by deep tillage, are limiting.

Even in the case of mechanical impedance, the effects of deep ripping may be transitory and normal seedbed preparation may reform soil pans in a short time (Soane *et al.* 1986). If deep tillage is carried out in soil wetter than the plastic limit, the tillage equipment itself may induce serious compaction (Swain 1975). Maximum shattering occurs if deep tillage is carried out with dry soil.

Spoor and Godwin (1978) demonstrated that for a given tyne design, there is a critical working depth below which soil is compacted rather than loosened and the draught per unit area of disturbance (specific resistance) increases. Increased soil disturbance and lower specific resistance can be achieved by attaching correctly designed wings to the tynes and using preceding shallow tynes. Deep tillage requires a large expenditure of energy and costs increase with depth. Because of the energy and labour inputs required and because yield responses have been variable, more research is needed to enable the effects of deep tillage to be more predictable.

Fragipans close to the surface and some soil pans may remain shattered and permeable after a single operation and in this case deep tillage may be cost effective. Cannell (1985) considered that annual deep tillage would be impracticable and unnecessary on most soils, and his observation that the ability of a variety of machines to loosen the subsoil has outstripped judgement as to when it is appropriate to use them is certainly apt. Responses to deep tillage in Australia have been recorded in the acid to neutral soils of north-eastern Victoria (Ellington 1986, Coventry *et al.* 1987a, Steed *et al.* 1987,) and the earthy and loamy sands of Western Australia (Western Australian Department of Agriculture 1985) where a mean yield increase of wheat of 30% from tillage to 0.3 m was reported from 21 experiments conducted over four years. Deep tillage has led to increased root growth and water and nutrient (especially nitrogen) uptake at depth (Ide *et al.* 1984, Jarvis *et al.* 1986, Coventry *et al.* 1987b, Steed *et al.* 1987).

Penetrometer resistances have also been reduced by deep tillage. Vepraskas and Wagger (1989) measured mean penetrometer resistances at both the 0.2-0.3 m and 0.3-0.4 m depth intervals of 1.3 MPa below that of standard cultivation. Oussible and Crookston (1987) reported a reduction in penetrometer resistance of 19-33% at 0.20-0.35 m in a clay loam soil deep tilled to 0.7 m.

In the marginal cereal growing areas of Australia, root penetration may depend to a great degree on the availability of water. While deep tillage is unable to improve the supply of water, water use efficiency may be improved (Bennie and Botha 1986, Ellington 1987). Oussible and Crookston (1987) attributed yield increases of wheat on a deep tilled soil to a change in root morphology (despite no significant change in root length density) with finer, more profuse roots in the tilled layer between 0.25 and 0.35 m and, as a consequence, a more efficient uptake of water.

Responses to deep tillage in drought have been variable. Ellington (1986) reported that deep tillage to 0.2 and 0.4 m had no effect on wheat yield in a drought in north eastern Victoria in 1982. Wheat dry matter production was reduced by deep tillage at one site (1982 rainfall 214 mm) however and this was attributed to the plants having dried the deep tilled plots more rapidly because of a more extensive root system, or looseness of the subsoil preventing capillary rise of water from below the tilled layer. Conversely, Coventry *et al.* (1987a) reported the largest response to deep tillage over a three year period in the same drought (1982 rainfall 295 mm) where increased soil water use from the 0.4-1 m depth interval resulted in increased grain yields and dry matter production.

Even after deep tillage, recompaction may occur rapidly due to normal field operations (Soane *et al.* 1986) which may actually induce subsoil densities equal to or greater than before treatment (Kosters 1978 in Soane *et al.* 1986, Ellington 1986). Willatt (1986) showed that penetrometer resistance was increased and root growth of barley decreased by one and six passes of a small (57 kW) tractor with rooting density greatest in the uncompacted treatment and least in the most compacted. Henderson (1985) reported that from two to four passes of a tractor weighing 5,000 kg over uncompacted soil could create a compacted layer just below normal cultivation depth.

Whiteley and Dexter (1982) showed that artificially produced cracks extending from the seedbed into the subsoil provided a zone for unrestricted root growth to the base of the crack. In the presence of a soil pan, machinery capable of forming artificial cracks through the pan - a system known as slit tillage - has been able to reduce soil strength and aeration problems (Elkins *et al.* 1983) in compacted loamy sand soils. The authors used a subsoil planter with chisel points which ran on top of a tillage pan impervious to roots. Attached below the tyne was a sharpened fin of 4 mm width which penetrated a further 0.15 m into the subsoil to cut to a depth of 0.33 m. Slits eventually filled with decaying organic material and became a continuing part of the soil profile. This system was much more energy efficient than the use of high draught subsoil machines.

2.9 Soil Fertility

Early in the history of the science of root ecology, research workers noted that a relationship appeared to exist between the depth and profusion of root growth and the chemical variability of the soil. For instance, Fox *et al.* (1953) noted the proliferation of roots around fertiliser bands and deduced that the fertility of the soil would be reflected in the rooting density.

Fehrenbacher *et al.* (1969) examined the root growth of wheat and other crops on fertilised and non-fertilised soil ranging from silty loess to a "claypan" soil high in sodium. They found that wheat roots penetrated to 1.4 m in the silty loess soil which was well structured and permeable. The claypan soil high in sodium permitted only shallow penetration to 0.75 m, and this was attributed to the poor structure. However, the addition of fertiliser to the surface layer enhanced root penetration in each soil. Maize roots increased their penetration of a claypan from 1.1 to 1.5 m with fertilisation. The use of fertilisers has been shown to improve root penetration into claypan soils (Fehrenbacher *et al.* 1960) although, as Schuurman (1971) later demonstrated, oats were unable to penetrate compacted sand having a bulk density of 1,720 kg m^{-3} even when adequate nutrients were provided. Bertrand and Kohnke (1957) showed too that while fertilisers promoted root growth of maize in loose soils, fertilisation was unable to promote penetration of a silty clay loam subsoil compacted to a bulk density of 1,500 kg m^{-3} and having 5.4% pores of greater diameter than 60 μm.

Because root systems occupy only up to about 2% of the soil volume, the phenomenon of compensatory growth enables limited zones of soil to support the plant's requirements in favourable conditions. Whether it applies to the uptake of water or nutrients, the ability of root systems to compensate for unfavourable conditions in part of the root zone by increasing growth or uptake in other parts has a large bearing on root morphology. Weaver (1926) noted that where roots grew into layers rich in nitrates, they were more dense and branched more profusely and tended to penetrate less into deeper soil.

Subsoil infertility has been referred to as a probable factor in restricted root growth for many years (e.g. Weaver 1926) but evidence for the requirements of specific ions at specified concentrations is not abundant and is at times contradictory (Troughton 1962).

2.10 Soil reaction and salinity

Because ion uptake is generally pH-dependent, and this has effects on toxicities and deficiencies, the main effects of pH on plant growth are generally a secondary effect rather than effects of pH *per se*. Nevertheless, from a review of nutrient solution studies, Pearson (1966) concluded that the root growth of many species is depressed by excessive hydrogen ion concentrations at pH <5. Growth of wheat roots decreased as pH fell below pH 6 with a sharp reduction below pH 5.

Most of the research into the effects of pH on root growth has been associated with the effects of low pH and associated toxicities and deficiencies. Much less effort has been directed at the effects of high pH. Russell (1973) divided the effects of high pH on crop yield into those associated with calcareous soils with low exchangeable sodium percentage (ESP) which are generally restricted to pH<8.5 and soils with high ESP in which sodium carbonate may occur in the soil solution and in which pH values of up to 10 may occur. These soils may be poorly structured and root growth is often inhibited as a consequence. Sodium carbonate and bicarbonate were reported by Mozafar and Goodin (1986) to be particularly severe in reducing the growth of wheat roots, although no direct explanation was given for this effect.

Griffiths and Walsgott (1985) speculated that one cause for the lack of root growth in the subsoils of north western Victoria may be "soils too alkaline at depth" with pH values as high as 10, but they did not elaborate further. Joshi *et al.* (1985) reported that wheat roots were unable to penetrate a soil layer of pH 9.8 although root growth at depth was better when the pH in the top 0.12 m was within the range 9.1 to 9.2 than when within the range 9.4 to 9.6.

Saline sodic soils may remain nutritionally adequate but in non saline sodic soils which contain high concentrations of sodium and low concentrations of calcium and magnesium, nutritional disorders in plants may occur (Bernstein 1975). The poor structure of sodic soils often leads to limitations in water and air penetration and these soils are often impenetrable to roots (Fehrenbacher *et al.* 1969, Gupta and Abrol 1990). Saline soils are defined as having electrical conductivities of the saturation extract (EC_e) at 25°C > 4 dS m^{-1}, an ESP< 15, and generally a pH < 8.5. Saline alkali soils have the same conductivity criterion but have an ESP> 15. The pH may vary. Sodic soils have an ESP>15. (United States Salinity Laboratory Staff 1954).

Plant growth in saline soils may be affected by toxic concentrations of specific ions which induce metabolic disorders (Kingsbury *et al.* 1984, Mozafar and Goodin 1986). Root growth is susceptible to osmotic potential and specific ion effects. Excessive quantities of any ion may reduce the uptake of others. For instance, Carlos and Bingham (1973) suggested that a sufficient absorption of chloride by wheat plants could lead to chloride-induced nitrogen deficiency.

Wheat is generally considered to be moderately tolerant of salinity (United States Salinity Laboratory Staff 1954, Hoffman 1981, Francois *et al.* 1986) although there is a wide range of variability in the tolerance of different cultivars (Ayers *et al.* 1952, Kingsbury and Epstein 1984, Kingsbury *et al.* 1984). Bernstein (1964) showed that the yield of wheat was reduced by 50% at an EC_e of 14 dS m^{-1} and Francois *et al.* (1986) showed that the tolerance threshold for salinity below which grain yield declined for the cultivar Probred was 8.6 dS m^{-1} averaged over 1.2 m. Each unit increase in salinity above this reduced yield by 3%. Paliwal and Yadav (1978) found that wheat "grew well" where the EC_e in the 0-0.3 m zone was 6-10 dS m^{-1}. Abdul-Halim *et al.* (1988) determined that soil water became a limiting factor in controlling wheat growth when EC_e >8.0 dS m^{-1}. They recorded independent effects of salt and available water on dry matter, tillers, grain yield and dry root weight per plant but recorded no interactions between salinity and available water. Root growth was more sensitive than other growth parameters to available soil water and salinity. Reducing the available soil water from 75% to 25% resulted in a 35% reduction in root dry weight. Increasing soil salinity from 1.7 to 11 dS m^{-1} resulted in a decrease in root dry weight of 46%. Maas and Hoffman (1977) indicate a threshhold salinity (at which yield begins to decline) for wheat of 6.0 dS m^{-1} with a 7.1% decrease in yield per unit increase in salinity beyond the threshold.

As the amount of available water increases, the ability of wheat plants to tolerate a wider range of salinity also appears to increase (Mashhady *et al.* 1982). On a calcareous soil adjusted to four salinities ranging from 3.5 to 11 dS m^{-1} (EC_e at 20°C) and at three plant-available water contents (100%, 40% and 20%), retardation of growth due to stress induced by salinity or lack of available water was reported, but the rate of reduction was far greater in the case of salinity. The effect of salt toxicity may also be aggravated by nutrient deficiency, particularly in the case of phosphorus, where a deficiency of phosphorus may reduce the tolerance of cells to accumulated ions (Gibson 1988).

It has generally been observed that shoot growth is more sensitive to salinity than root growth (Hoffman 1981, Munns and Termaat 1986). At low salinities, Delane *et al.* (1982) found that root growth of barley did not alter while shoot growth was affected.

However, Abdul-Halim *et al.* (1988) found that wheat root growth was more sensitive to salinity than above-ground parts of the plant. Devitt *et al.* (1984) found that the elongation of wheat roots in saline-sodic root media increased with the concentration of sodium at each osmotic potential measured, but that root mass decreased as the osmotic potential decreased. Ayers *et al.* (1943) reported that the depth of penetration of bean roots was limited by concentrations of sodium chloride of 0.2% (about 3 dS m^{-1} EC_e) even in wet soil.

Wadleigh *et al.* (1947) demonstrated the inability of maize roots to penetrate regions of excessive salinity. Only a few maize roots were found in soil containing 0.2% sodium chloride (about 3 dS m^{-1} EC_e) and none were found at 0.25%. The ability of roots to remove water from the soil also decreased as the soil salt concentrations increased.

It is not always easy to interpret experiments in which the effects of salinity on the various parameters of plant growth are investigated and comparisons may also be difficult because of different ways of expressing results. Mozafar and Goodin (1986) observed significant two and three way interactions between wheat cultivar, form of salt and salt concentration for germination, growth of the coleoptile and roots and root-coleoptile ratios. The responses of roots and coleoptiles to salts differed with the form of salt used.

Many experiments have been carried out with artificial media or with soil in which the salinity in the root zone was controlled in such a way that the roots were presented with a uniform environment. Noting that uniformity of salinity with depth was the exception rather than rule, Shalhevet and Bernstein (1968) designed an elegant experiment in which two chambers containing solutions of different salinity were separated by wax barriers permitting the growth of roots of lucerne into both chambers without the transfer of the root medium from one chamber to another. Water uptake from a given chamber fell as the salinity increased but there was some compensatory uptake from less saline chambers. Water uptake was not directly related to root length and uptake per unit root length increased nearly 1.5 times when another part of the root system was under stress.

Because osmotic potential is a component of the total potential, the presence of salts in the soil solution has a direct bearing on water availability. At sufficiently high salinities, water may be unavailable to plants within the range of matric potentials normally considered to be "available".

Measurements of direct effects of matric and osmotic potentials on root growth were carried out by Sepaskhah and Boersma (1979), who found that rates of root elongation and rooting density decreased when the osmotic potential of the soil water decreased from 0 to -1.2 MPa. They attributed the decrease in the rate of root elongation where sodium chloride was present in the soil solution to toxic effects, ionic imbalances, or accumulation of ions in root cells, rather than to water shortage because the effects of matric potential in decreasing the root elongation rate were severe only at the osmotic potential of -1.2 MPa. As the concentration of sodium chloride increased in the soil water, roots appeared to be less able to osmoregulate effectively against more negative matric potentials. There was no significant interaction effect between matric and osmotic potential on rooting density. The authors noted that at low matric potentials increased soil strength may have been the critical determinant of root elongation rates.

2.11 Soil boron

Boron is one of the elements commonly associated with salinity in producing toxic effects in plants (e.g. Bernstein 1975, Hoffman 1981, Bingham *et al.* 1987). A comprehensive review of the factors which influence boron toxicity in plants was published by Gupta *et al.* (1985).

The range of soil boron concentrations outside which deficiencies or toxicities occur in wheat is relatively narrow. Wheat was long considered to be tolerant of boron (United States Salinity Laboratory Staff 1954) although Bingham *et al.* (1985) more recently reported that they considered wheat to be a sensitive species. However, wheat cultivars differ widely in their tolerance to boron (Nable 1988, Paull *et al.* 1990). In discussing the varietal tolerance of wheat, Cartwright *et al.* (1987) noted that the only plant symptoms of boron toxicity observed were gradual browning and necrosis of older leaf tips, proceeding in the most sensitive varieties to all leaves. The authors considered that despite a genetic exclusion mechanism, other mechanisms related to root morphology may also help confer resistance on some varieties, the roots of which may not grow into deeper layers where boron concentrations tend to be higher. Nable (1988) reported that the sensitivity of wheat cultivars to boron was governed solely by their ability to exclude it. No cultivars were able to tolerate high concentrations of boron in the tissue.

Bingham *et al.* (1987) conducted two experiments to test the effects of salinity on the uptake of excessive boron concentrations by wheat. In the first experiment, shoot weight was affected independently by boron and osmotic potentials but not by their interaction, so that changes in salinity did not affect responses to boron. Boron treatments alone affected concentrations of boron in the leaves. There were no significant interactions between boron and osmotic potential with respect to leaf boron concentrations, so that changes in salinity did not affect the concentration of boron in the leaves.

In the second experiment, the responses of wheat to variable boron concentrations up to anthesis were tested to determine whether wheat responds to the time integrated mean of boron concentration. Boron concentrations were kept constant or increased or decreased with time. Shoot weights did not differ significantly where the time integrated mean of boron concentrations in the nutrient solution remained constant over the course of the experiment. The concentrations of boron in the shoots and leaves, however, increased with increasing boron concentration over the experimental period, indicating that boron uptake rates were higher in mature plants than in seedlings.

The toxic effects of boron on wheat yields have been documented by Cartwright *et al.* (1984), Rathjen *et al.* (1987), and Paull *et al.* (1990) but little information is available concerning the effects of boron on wheat root growth, particularly over an entire growing season. Bennett (1971) summarised information concerning boron toxicity to that time by stating that boron did not appear to be sufficiently toxic to roots to prevent the uptake of sufficient quantities of boron to damage above ground tissues.

Cartwright *et al.* (1983) reported a paucity of data on boron in soils, due in part, to procedural difficulties in routine analysis. The use of inductively coupled plasma atomic emission spectrometry has enabled rapid routine assessment of the concentrations of boron in soil. A range of procedures has been investigated in attempts to find a more efficient procedure than the standard hot water extraction method of Berger and Truog (1939) for measuring the availability of boron. The mannitol extraction procedure (Cartwright *et al.* 1983) was widely adopted for use in alkaline soils, but Aitken *et al.* (1987) found that the hot 0.01 M calcium chloride method of Bingham (1982) was a more versatile extractant which could be used for both acid and alkaline soils.

The relationship between calcium chloride extractable boron and boron concentrations in plants appears to be dependent on soil type. Aitken and McCallum (1988) considered that hot 0.01 M calcium chloride estimated a "quantity factor" and recommended analysis of soil solution extracts obtained by centrifugation for studies of boron toxicity. However, because the amount of boron taken up by plants is a function of soil solution boron (plus boron in the solid phase), the distribution of roots, soil water movement, and exclusion mechanisms within the plants, it is difficult to predict how extractable soil boron or boron concentrations in the soil solution could indicate accurately critical values at which plants will suffer from boron toxicity in field soils where the vertical distribution of boron is not uniform.

Keren *et al.* (1985) demonstrated that for a given amount of boron added to the soil, boron activity in the soil solution decreased with increasing clay content of the soil, and suggested that adsorption sites in the soil were a "pool" from which boron could be removed or added in response to changes in the boron concentration of the soil solution. The amount of boron taken up by wheat plants and consequent effects on yield were closely related to the concentration of boron in the soil solution rather than to the amount of boron added to soil-sand mixtures.

Boron toxicity in cereal crops in southern Australia was first identified by Cartwright *et al.* (1984) who associated leaf blotching and yield depression in barley on a red-brown earth in the mid-north of South Australia with high concentrations of soil boron. The authors reported spatial variation of mannitol extractable boron concentrations in the soil which corresponded with variation in leaf symptoms. Extractable boron concentrations increased with depth and were highest in the subsoil in areas where the crop was most affected. Above-ground symptoms and concentrations of boron in plants were more strongly influenced by boron in the subsoil than in the topsoil. Measurements of rooting density were not taken and so no information was available on the extent to which roots grew into the 0.7-0.8 m zone containing high concentrations of boron. The contribution of the whole soil volume explored by roots is vital in predicting potentially toxic concentrations from soil samples, assuming no other limiting factors. Extractable soil boron from the 0.3-0.4 m zone showed an exponential relationship with plant boron but for 0.7-0.8 m a linear relationship was obtained, and this was explained in terms of varying distributions of rooting density and soluble boron.

In a later study, Cartwright *et al.* (1986) observed that soils in which toxic concentrations of boron occurred were invariably sodic, although sodium concentrations in plants were not sufficiently high to be considered toxic. The salt concentrations in subsoils consisting of clay loams and clays tended to remain below the concentrations of 0.2-0.3%, defined as saline by Northcote and Skene (1972), although the sodicity of soils was reflected in high pH values, at times above pH 9.5 (a salt concentration of 0.2 - 0.3% roughly corresponds with an EC_e of 4 dS m^{-1}, the standard adopted to define saline soils by the United States Salinity Laboratory Staff 1954). Statistically significant relationships were established between extractable boron and ESP, cation exchange capacity and clay content within individual soil profiles with high concentrations of extractable boron. But these relationships were not significant between soil profiles having high and low concentrations of extractable boron respectively. While unable to establish significant statistical relationships between extractable boron concentrations and other soil properties, Cartwright *et al.* (1986) did observe that soils containing toxic concentrations of boron were also generally calcareous.

The use of concentrations of boron in leaves, shoots, and other plant parts to predict boron toxicity is difficult. Gupta *et al.* (1985) pointed out that boron may not only be distributed unevenly between plant parts but also within them. For example boron in leaves tends to be concentrated at the margins and tips, and boron concentrations in plants may vary with time. Nable *et al.* (1990) uncovered further difficulties in this area with a solution culture experiment in which the distribution of boron in barley leaves and critical values for boron toxicity in shoots were investigated. Glasshouse plants were able to produce maximum grain yields at much higher concentrations of boron in shoots than field plants were able to tolerate without loss of yield. Boron accumulation in plants and leaves increased with increasing water use. Boron accumulation in shoots was significantly affected by evaporation, and boron was concentrated in leaf tips. Spraying with water at regular intervals removed a significant amount of boron from the leaves without altering dry matter production. Nable *et al.* (1990) considered that these problems made the establishment of critical values and the use of foliar analysis for diagnosing boron toxicity unreliable. Similarly in field conditions, variation in rainfall, evaporation and water use are likely to affect the concentration of boron in plants, with similar implications for the establishment of critical values.

Nable *et al.* (1990) considered that grain analysis could be adopted as an alternative to foliar analysis for diagnosing boron toxicity. Cartwright *et al.* (1984) suggested that boron concentrations of more than 3 mg boron kg^{-1} of grain in barley would indicate boron toxicity. There appear to be no similar data for wheat for southern Australia.

2.12 Assessment of the potential hazards of salinity and boron

To assess the potential of boron toxicity in lucerne grown under irrigation in Saskatchewan Province, Canada, Nicholaichuk *et al.* (1988) studied the properties of soil and irrigation water at 29 locations. At each location, two sites were selected, one close to the source of irrigation water, the other near where surplus water drained from the area. Data were analysed by a split plot technique using time of sampling as the replicate, and depth and sampling position as the first and second split respectively. Extractable soil boron (mannitol extraction) rarely exceeded 20 mg kg^{-1}. Where soils exhibited an

EC (determined on the vacuum filtration of a soil paste) of more than 8 dS m^{-1}, it was suggested that only very salt tolerant crops would grow. It was considered that salinity was likely to affect crop production under irrigation more seriously than boron at the levels measured.

Khan and Nortcliff (1982) considered the spatial variability of the concentrations of four readily extractable soil micronutrients (iron, manganese, copper and zinc) in three grids of one hectare each in the same soil series at a single location. The grids were located within a few hundred metres of each other. Each 100 m x 100 m grid was subdivided into 49 subgrid squares with a sampling point selected within each of these. Five samples of 500 g were collected at random from within a 1 m square around each point. (Differences in the concentrations of the micronutrients were significant between grids). The patterns of variability for the different nutrients varied so that the number of samples required to achieve a given degree of precision was much larger for manganese and iron than for copper or zinc. The authors concluded that the morphological and chemical criteria which normally define soil series may not correspond with homogeneity of micronutrients and finer units of subdivision may need to be considered.

Beckett and Webster (1971) produced an extensive review of the then current data on the lateral variability of the properties of soil, with a discussion on soil variability. They defined a soil mapping unit as "an area coherent enough to be represented to scale on a map, of which the soil can be adequately described in a simple statement, commonly but not necessarily in terms of its main profile classes". Mapped soil units may be referred to in terms of their "purity" - the minimum area covered by the dominant profile class, but there is usually no indication of the maximum variation of measured properties. Were such an indication given, it would assist with sampling strategies and indicate the precision of a particular survey.

More recently, geostatistics theory has been used to examine the variation of a range of soil properties (McBratney and Webster 1983, Webster 1985) including soil salinity (Chang *et al.* 1988). The theory comprises variography, a method of estimating and constructing models of the spatial nature of variance, and kriging, a predictive method of estimating soil properties at unsampled sites based on a consideration of the spatial dependence of the properties, so that is is possible to produce contour maps for the property under consideration.

Geostatistical techniques have the advantage over classical methods when considering properties which are spatially dependent since they are able to account for the relationships between the sample and its location relative to other samples. On the other hand, classical statistical methods assume that the variation between samples is not spatially correlated and that the population is represented by the mean of the measured samples for any property.

Chang *et al.* (1988) compared measurements of soil salinity to a depth of 1.2 m from 64 locations in an area 20 x 25 m using classical statistical and geostatistical methods. Salinity was highly variable and not uniformly distributed through the sampling area. Contour maps for the properties generated by block kriging estimated smaller variances than those calculated using standard statistical techniques. The use of geostatistics however, normally requires the collection of a large number of samples, which is often prevented by the constraints of time and cost. The use of statistical methods such as those adopted by Nortcliff (1978) appear to be better adapted to studying soil properties over large areas.

Studying soil variability within a relatively large area, Nortcliff (1978) utilised a hierarchical sampling design in which parent material strata formed the highest level for analysis. This design allowed the patterns of soil variability to be analysed over a range varying from 5 m to more than 2 km. The large number of variables recorded in the study were compared by principal component analysis because of the difficulty in analysing each variable separately and intepreting the results. It was considered that an acceptable alternative was to analyse the major principal components and use eigenvectors to interpret the analyses. Interpretation of the data was based on the vector and degree of positive and negative loadings on each of the components.

The results indicated that the parent material strata in the survey could be ranked in terms of the "survey effort" which would be necessary to map each of the strata to the same degree of uniformity. It was proposed that this assessment of soil variability could lead to a situation where the required number of mapping units to produce a similar degree of variance with respect to soil properties could be predicted. This approach offers great improvements in the efficiency of soil survey compared to methods which do not assess the variability of the parameters under study.

An important advance in the diagnosis of field salinity was described by Rhoades *et al.* (1977, 1988a,b,c, 1990) who conducted an extensive series of detailed experiments, the data from which were used to develop a model to allow soil salinity (EC_e) to be related to field measurements of the electrical conductivity of bulk soil (EC_a). The models developed to predict EC_e from EC_a determinations were tested by four procedures aimed at determining whether soil salinity could be determined adequately from field estimates of parameters which would normally only be determined in the laboratory. Each of the procedures was based on actual measurements of EC_a using a four-electrode probe, an electromagnetic induction measuring device, and a four-electrode surface array compared with laboratory determinations of EC_e. The model required the following parameters:- θ_s, the volumetric content of the soil; θ_w, the volumetric water content of the soil; θ_{ws}, the volumetric water content in the fine pores (immobile or unavailable water); EC_s, the average electrical conductivity of the soil particles; ρ_b, the bulk density of the soil and ρ_s, the bulk density of the soil particles. However, because of the establishment of empirical relationships, simple field estimates of soil water content, saturation percentage and percentage clay could be used to derive acceptable EC_e values from field determinations of Ec_a to some depth. The field procedures used to determine EC_a were considered to be of a similar order of accuracy. Such developments should lead to much more rapid and efficient methods of accurately estimating soil salinity compared with detailed laboratory procedures.

2.13 Summary

In semi-arid environments, the major determinant of maximum penetration of roots is usually the depth of water penetration, although soil structure and texture, (which also affect water penetration), are also important in determining maximum rooting depth. Nodal roots, which are generally restricted to the top 0.4 m of soil, play the major role in the absorption of water, but the ability of seminal roots to withdraw water from reserves deeper in the subsoil during times of surface drought is likely to be vital in determining final yields. In general the ability of wheat plants to extend their rooting depth to below 0.6 m does appear to confer some degree of drought tolerance, depending on the capacity of the subsoil to store water and the recharge frequency. However, in semi-arid regions there exists the problem of roots penetrating to depth rapidly and drying the soil, thus inducing a water deficit later in the season.

As the soil dries, root growth slows and may eventually cease. Soil drying is associated with a rapid increase in soil strength and while both matric potential and soil strength have combined and independent effects on the elongation rate of roots, soil strength has the greater effect. Soil strength is conveniently indicated by penetrometer resistance and root growth is likely to be severely restricted where penetrometer resistance exceeds 2 MPa. Penetrometer pressures may be several times root growth pressures because soil is deformed by roots and penetrometers in ways that are fundamentally different.

Cracks and biopores constitute an important source of access for roots into the subsoil in strong soils and there is some potential for the use of machinery to create artificial cracks.

Soil compaction, with which is associated an increase in soil strength, reduces root elongation rate, root length density and rooting depth, especially in drought. The effects of compaction tend to last longer in coarse textured soils because of the absence of ameliorative processes. Wheel traffic is a major contributor to soil compaction and the depth of compaction increases with the total load. The area of the field covered by wheels in northern Europe and North America may be from 0.9 - 5.5 times the field area.

Deep tillage, applied to alleviate soil compaction, has had variable results and the effects may be transitory, although positive yield responses to deep tillage have been recorded in Australia. Deep tillage is more likely to be beneficial where the access of roots to subsoil water reserves is enhanced. However, rapid recompaction may occur as a result of normal field operations.

Wheat is considered to be moderately tolerant of salinity and relatively sensitive to high concentrations of boron in the soil, although tolerance varies widely between cultivars. While the effects of salinity and boron on wheat have generally been well documented and several authors have referred to the more damaging effects of salt on shoots than on roots, there are not a large amount of data on the effects of salt or boron on the growth of wheat roots in soil over an entire growing season.

The prediction of critical values for toxic effects of salinity and boron is difficult, and it is likely that field measurements on the effects of salinity and boron on shoot and root growth will be interpretable only for conditions closely related to those in which the measurements were taken. A means of approaching this difficulty has been the development of increasingly comprehensive models, of which those described by Rhoades *et al.* (1977, 1988a,b,c, 1990) are good examples. The development of useful models is of course dependent on a sufficient source of accurate data, and where the effects of salinity and boron on root growth are concerned at present, very little data exist.

3.0 THE EFFECTS OF PRESEASON IRRIGATION ON ROOT GROWTH AND WHEAT PRODUCTION - AN INITIAL INVESTIGATION

3.1 Introduction

In the arable areas of Upper Eyre Peninsula, a characteristic of many of the subsoils which contain Class I or Class IIIA carbonate layers (Wetherby and Oades 1975) is that wheat roots are rarely abundant below 0.5 m.

Frequently, high concentrations of boron and salt occur in the IIIA carbonate subsoil (Wetherby and Oades 1975) and the soil to 0.45 m is also characterised by high strengths (Dexter *et al.* 1988).

It is not clear whether roots do not proliferate below 0.5 m because of the effects of boron or soil strength, or whether, in the dry environment of the region, the availability of water in the subsoil, and hence root growth, is reduced by the presence of salt.

A field experiment was conducted in 1986 to test the hypothesis that wheat roots would not grow into a IIIA carbonate layer in the presence of available water at the beginning of the season. Irrigation was used to bring the water content of the soil close to field capacity at the beginning of the season in some plots which were compared with others watered by rainfall only.

3.2 Materials and methods

The experiment was conducted in field N8, Minnipa Research Centre (site details are given in Appendix 1.2) and was laid out in a block design with two treatments which consisted of supplementary pre-season irrigation and a non-irrigated control. The treatments were replicated four times. Plots were 3.9 m wide and 15 m long.

The irrigated plots were watered through perforated hoses from 9 April to 13 May and the amount of water applied was measured by rain gauges set in the soil with receiving funnels at ground level. Gravimetric soil water contents of the soil were monitored to 1.5 m weekly until 13 May. Soil water retention characteristics were measured for potentials of -100 kPa and -1.5 MPa on samples dried from saturation on pressure plate apparatus. For potentials of -10 kPa, samples were drained from saturation on "porosity 4" sintered glass funnels. Irrigation ceased when the soil water potential was between -100 kPa and -10 kPa to a depth of 1.5 m. During the period of irrigation, the irrigated plots received 406 mm of irrigation plus rainfall, while the rainfed plots received 28 mm of rain.

The plots were sown to wheat (cv. Aroona) on 6 June at 50 kg ha^{-1} with 9.5 kg ha^{-1} of nitrogen and 6.5 kg ha^{-1} of phosphorus applied as ammonium sulphate and diammonium phosphate.

Two days before sowing, gravimetric water contents of the soil were determined on samples collected using a thin walled core sampler (50 mm diameter) with a hardened cutting tip, with five cores per plot. Soil samples were taken from the 0-0.05, 0.05-0.1, 0.1-0.15, 0.15-0.3, 0.3-0.6, 0.6-0.9 and 0.9-1.2 m depth intervals. Soil water contents were measured again from the same depth intervals on 26 August (Feekes growth stage 5; Large 1954). At anthesis, on 16 October, five core samples per plot were taken at 0.1 m depth intervals to 1.2 m.

Root length densities were also determined from the samples (Hignett 1976). Although root density data are normally presented in units of root length per unit volume of soil, root length density data in this thesis are presented in units of length per unit weight of soil (m kg^{-1}) because of difficulties encountered in measuring bulk density in some experiments and because these units were adopted by Forrest *et al.*. (1985) in an extensive survey of wheat growing soils of eastern Australia. A line intersect method was used to determine root lengths (Tennant 1975).

Boron concentrations (mannitol extraction - Zarcinas and Cartwright 1983) and electrical conductivities in 1:5 (by weight) soil: water extracts (Rhoades 1982) ($EC_{1:5}$) were also measured in these samples. The $EC_{1:5}$ data were converted to ECe_{25} values (Rhoades 1982) after Wetherby (1990).

Soil strength was measured to a depth of 0.45 m immediately after each collection of samples for the determination of soil water content, using a Bush electronic recording penetrometer (Anderson *et al.* 1980). The penetrometer cone had a diameter of 12.6 mm and a total enclosed angle of 30°. Penetrometer resistances were measured at 0.03 m depth intervals. Ten measurements were made at random in each plot.

At harvest, on 20 November, grain yields were determined after reaping each plot with a small-plot harvester (Wintersteiger). Boron concentrations in the grain were determined by inductively coupled plasma spectrometry (Zarcinas and Cartwright 1983).

After harvest, a pit was dug at the site and 20 clods sampled from each stratigraphic layer in the profile for the determination of dry bulk density with the Saran resin coating method (Brasher *et al.* 1966).

On 15 September 1988 (anthesis) the dry weight of tops of oats (*Avena sativa* L.) grown on the experimental area was measured from 10 paired quadrats (0.25 m^2) cut from areas which were control and irrigated plots in 1986. Gravimetric soil water contents were determined on 11 paired core samples taken to a depth of 1 m. At harvest, each of the eight plots was reaped with a small-plot harvester and grain yield determined. Five core samples were taken at random to a depth of 1 m from each plot immediately after harvest and gravimetric water content and total soil water storage determined for each 0.1 m depth interval.

Data were analysed by analysis of variance. Soil water content, soil water loss between sowing and anthesis, penetrometer data, root length densities and salt and boron data were analysed statistically for the whole profile and also separately for each 0.1 m depth interval. Rooting density, boron concentration and salinity data were $\log_{10}$ transformed before analysis. Simple correlations were also calculated on this data.

3.3 Results and discussion

3.3.1 Soil water

Water loss was calculated as the change in water storage to the depth of maximum rooting between sowing and anthesis (water extraction) plus the amount of water added as rainfall in that period.

Water retention profiles for the site are shown in Fig. 3.1. Some water was lost from the soil between the cessation of irrigation on 13 May and sowing on 6 June when the soil water potential in the irrigated plots was closer to - 100 kPa than -10 kPa (Table 3.1). In the control plots, the soil water potential was close to -1.5 MPa to a depth of 1.2 m and the soil was significantly drier between 0.15 and 1.2 m than that of the irrigated plots. Total soil water storage to 1.2 m in the control plots was 229 mm compared with 342 mm in the irrigated plots ($P \leq 0.001$).

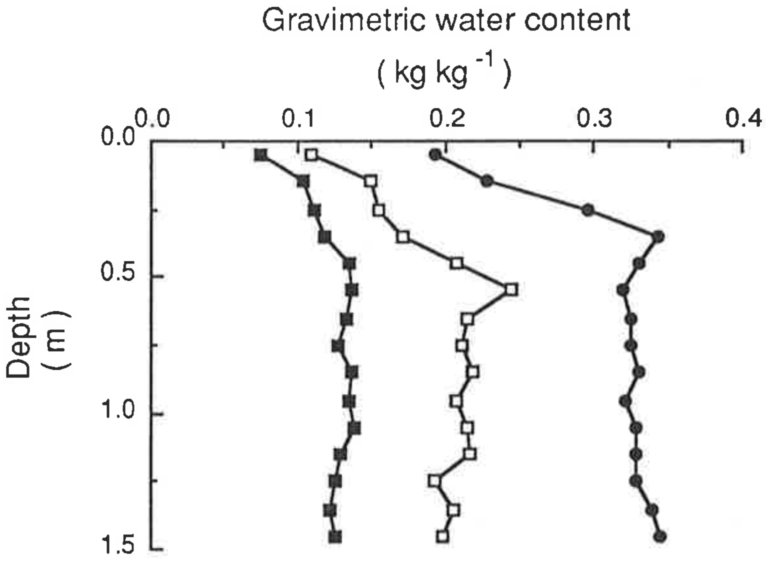


Fig. 3.1. Depth distribution of soil water holding capacities at equilibrium with matric water potentials of -1.5 MPa (■), -100kPa (□), and -10 kPa (●).

Total water reserves in the subsoil to 1.2 m depth increased in the control plots between sowing and 26 August, through the input of 132 mm of rain , but the control plots remained significantly drier over part of the profile. During the same period there was some loss of water between 0.1 and 0.3 m from the irrigated plots, but below that depth there had been little change (Table 3.1).

At anthesis, on 16 October, there were no significant differences in soil water contents between treatments apart from the 0.0-0.1 m depth interval (Table 3.2). Mean total water storage in the irrigated plots to 1.2 m depth was 246mm and in the control plots, 223 mm.

No soil water measurements were taken at crop maturity. However, the plant available water capacity in the soil profile to 1.2 m was calculated by the method of Russell (1980) as approximately 113 mm, based on the soil water contents of the irrigated and control plots at sowing. The condition of the soil at sowing was taken as an approximation of the soil water after depletion by a wheat crop.

Table 3.1. Mean gravimetric water contents (kg kg^{-1}) of soil in irrigated and control plots on 6 June (sowing) and 26 August.

Depth (m)	Irrigated	Control	LSD (0.05)
		6 June	
0.00-0.05	0.050	0.036	0.018
0.05-0.10	0.105	0.083	0.024
0.10-0.15	0.142	0.103	0.042
0.15-0.30	0.188	0.109	0.011
0.30-0.60	0.228	0.139	0.055
0.60-0.90	0.212	0.145	0.015
0.90-1.20	0.202	0.145	0.017
		26 August	
0.00-0.05	0.134	0.116	0.017
0.05-0.10	0.126	0.116	0.021
0.10-0.15	0.123	0.105	0.021
0.15-0.30	0.169	0.132	0.025
0.30-0.60	0.225	0.200	0.065
0.60-0.90	0.207	0.178	0.020
0.90-1.20	0.192	0.169	0.024

Table 3.2. Mean gravimetric water contents (kg kg^{-1}) of soil in irrigated and control plots on 16 October (anthesis).

Depth (m)	Irrigated	Control	LSD (0.05)
0.0-0.1	0.048	0.067	0.013
0.1-0.2	0.065	0.092	0.037
0.2-0.3	0.075	0.100	0.033
0.3-0.4	0.100	0.119	0.035
0.4-0.5	0.126	0.137	0.053
0.5-0.6	0.147	0.150	0.045
0.6-0.7	0.156	0.159	0.043
0.7-0.8	0.161	0.163	0.029
0.8-0.9	0.160	0.170	0.020
0.9-1.0	0.162	0.171	0.014
1.0-1.1	0.163	0.174	0.013
1.1-1.2	0.161	0.175	0.023

To the depth of maximum rooting, mean soil water extraction between sowing and anthesis for the irrigated and control treatments was 92 mm and 17 mm respectively ($P \leq 0.05$). Water loss during the same period for the irrigated and control treatments respectively was 346 mm and 271 mm.

3.3.2 Soil strength

Soil strength at depth often exceeded the capacity of the penetrometer (7 MPa) and large numbers of missing values occurred, particularly at anthesis, with consequent skewing of the distribution of the data. Medians were therefore used in preference to means to represent soil strength at each depth, but where more than four missing values in 10 attempted penetrations occurred at any depth, no median was calculated. Where there were missing values at some depths but not at others, medians were used at all depths to allow comparison between penetrometer resistances over the depth of measurement.

Where there were no missing values, coefficients of variation (CV) were calculated on the means for each depth to obtain a measure of the variability of the data. An example is given in Fig. 3.2. Penetrometer resistances measured at sowing are shown in Fig. 3.3.

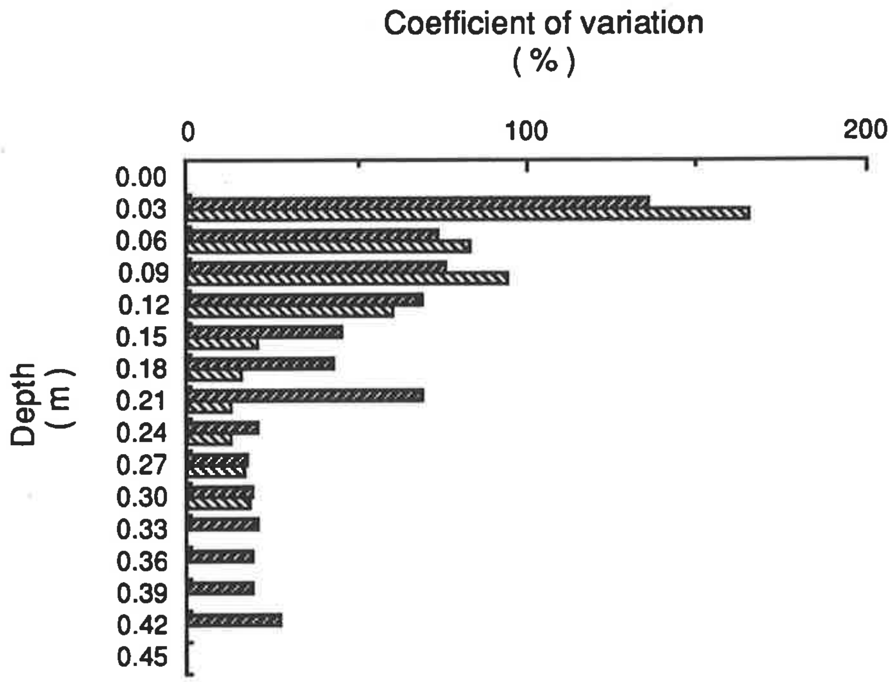


Fig. 3.2. Coefficients of variation of penetrometer resistances measured in irrigated (▨) and control (▩) plots on 6 June, 1986 at Minnipa. CV values were not calculated where missing values occurred.

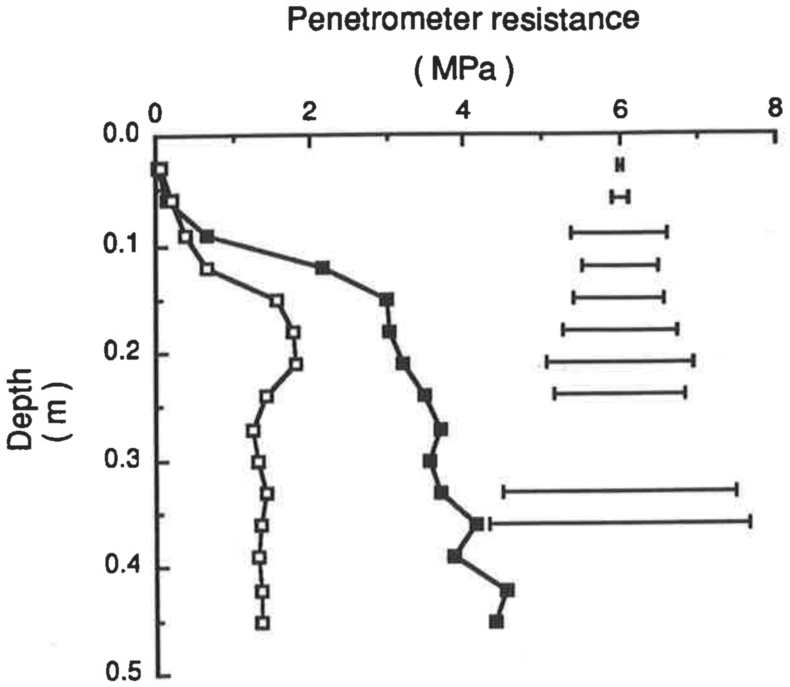


Fig. 3.3. Penetrometer resistance as a function of depth in irrigated (□) and control (■) plots on 6 June, 1986 at Minnipa. LSD bars at each depth interval are for P=0.05. (Where bars are not shown, differences between treatments were not significant).

The irrigated soil was significantly weaker ($P \leq 0.01$) than the control soil to 0.45 m and there was a significant depth by treatment interaction ($P \leq 0.001$). There were no missing values to 0.21 m and to that depth the mean penetrometer resistance of the soil in the irrigated plots was 0.93 MPa and in the control plots 1.76 MPa. Calculations by Dexter (1987) show that in the absence of low resistance pathways, root growth is likely to be seriously impeded where penetrometer resistances are of the order of those measured in the control plots.

Jakobsen and Dexter (1987) developed a model to estimate the effect of soil structure on wheat root growth and water uptake. They used data from this site in the model to show that soil strength had a large effect on root growth and water uptake when the penetrometer resistance of the soil at field capacity exceeded 1 MPa, so that even in the irrigated soil, root growth could have been retarded to some degree by soil strength.

Penetrometer resistances measured in August (Fig. 3.4) further illustrate the importance of the effect of water on soil strength. Comparison of the data on soil strength shown in Fig. 3.4 with those in Fig. 3.3, indicates that penetrometer resistances had increased in the irrigated plots and decreased in the control plots over the same period. These changes corresponded to a decrease in soil water content in the irrigated plots (between 0.1 and 0.3 m) and an increase in the control plots between June and August.

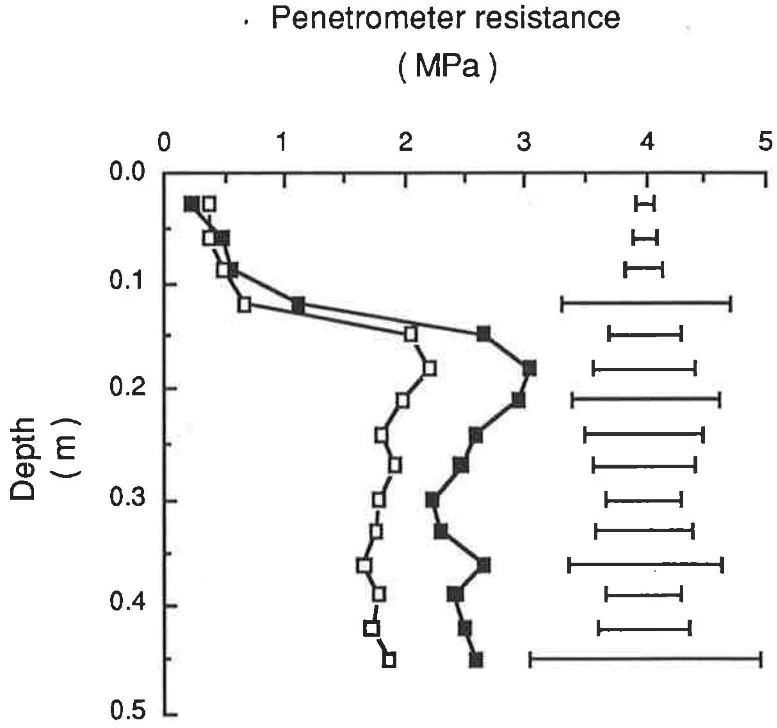


Fig. 3.4. Penetrometer resistance as a function of depth in irrigated (□) and control (■) plots on 26 August, 1986 at Minnipa. LSD bars at each depth interval are for P=0.05.

At anthesis, there were no significant differences between treatments for penetrometer resistances to 0.18 m (Appendix 3.1). Below this depth no measurements were possible because the soil was too strong - an indication of the lack of water in the soil profile.

3.3.3 Rooting density

Root length densities measured at anthesis are shown in Fig. 3. 5. For the 0-1.2 m profile as a whole there were significantly more roots in the irrigated plots than in the control plots (P≤0.05) and there was a significant (P≤0.05) depth by treatment interaction. Root length densities were also significantly higher in each 0.1m interval between 0.8 m and 1.1 m depth in the irrigated soil than in the control.

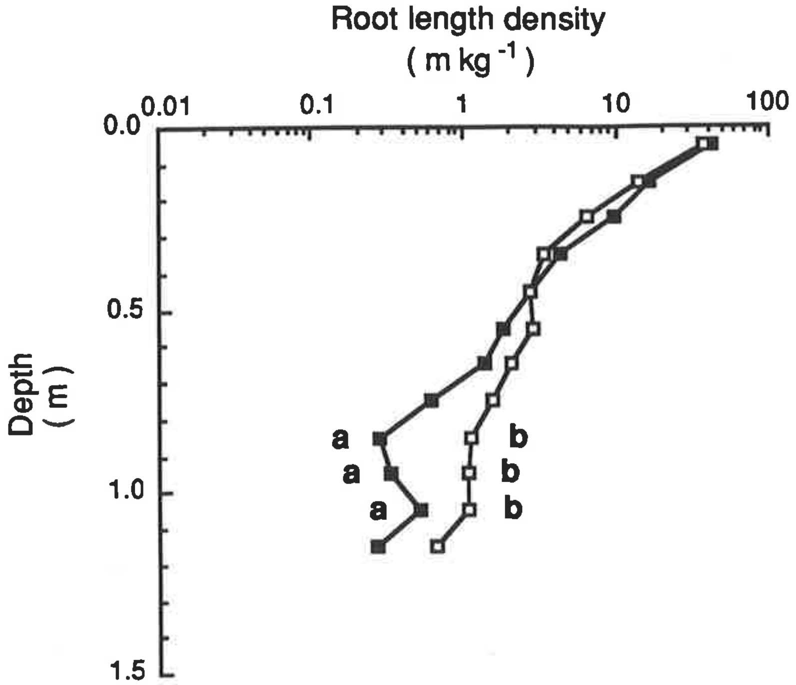


Fig. 3.5. Root length density of wheat as a function of depth for irrigated (□) and control (■) plots at anthesis, 1986 at Minnipa. Values are significantly different at $P \leq 0.05$ only where indicated by different letters.

Adopting the criterion of Forrest *et al.* (1985), in which the maximum rooting depth is that depth below which root length density is less than 0.5 m kg^{-1}, maximum rooting depths were calculated for each plot. Maximum rooting depth in the irrigated soil was 1.15 m, compared with 0.7 m for the control ($P \leq 0.05$). The model of Jakobsen and Dexter (1987) predicted root depth in 1986 for wheat in the control plots (a prediction made only in terms of soil physical and water parameters) as 1.35 m, with a wetting front of 1.05 m. It was assumed in this experiment that roots would reach their maximum depth at anthesis (Troughton 1962, Hurd and Spratt 1975). There was some evidence of compensatory growth in the control plots for roots above 0.5 m, with slightly higher root length densities in that zone than in the irrigated plots.

Root length densities in the subsoil are generally lower than those reported in the literature. Klepper *et al* (1984) referred to European data which showed root length densities of up to 6.8 m kg^{-1} were common at 0.5-1 m. Meyer (1976) compiled data from southern Australian authors which showed that the average depth of maximum penetration of wheat roots in the experiments considered varied from 1 to 2 m and mean rooting densities in the 0.55-1 m depth interval varied from 3.4-6.8 m kg^{-1}.

3.3.4 Salt and Boron

Measurements of EC_{e25} and exchangeable sodium indicate that the subsoil in the control plots at this site was alkaline-saline (United States Salinity Laboratory Staff 1954). For the 0.7-1.1 m depth interval, the difference between the irrigated soil (mean 1.9 dS m^{-1}) and the control (mean 5.9 dS m^{-1}) was significant ($P \leq 0.05$) although there were no significant differences between individual 0.1 m depth intervals (Appendix 3.2). A large amount of salt was leached from the irrigated subsoil. Salinity increased with depth from the surface to 0.8 m in the control soil but below that depth there was no significant increase in EC_{e25}. Soil boron concentrations increased with depth and were not significantly different between the two treatments. Maximum values occurred below 0.8 m. (Appendix 3.2).

Simple correlations performed on ($\log_{10}$) transformed data for the whole profile to 1.1 m indicated significant negative relationships between root length density and EC_{e25} ($r= -0.64$, $P \leq 0.01$) and root length density and extractable boron ($r= -0.83$, $P \leq 0.01$). Water loss from the profile to maximum rooting depth was significantly negatively correlated with boron concentration ($r= -0.26$, ≤ 0.05) and EC_{e25} ($r= -0.44$, $P \leq 0.01$), but was not related to root length density.

Hamblin and Tennant (1987) conducted a comprehensive study of the relationship between root length density and water uptake by cereals (including wheat) and grain legumes on several soil types. They obtained a significant regression coefficient between total water loss from sowing to maturity and maximum rooting depth. The relationship between root length density (expressed as total root length per unit ground area, m m^{-2}) and water loss was not significant.

In the current experiment, the total amount of water stored in the soil to the depth of maximum rooting at anthesis, was also significantly correlated with EC_{e25} ($r=0.34$, $P \leq 0.01$) and mannitol-extractable soil boron ($r=0.84$, $P \leq 0.01$) to that depth. It is possible that the presence of boron and salt in the subsoil may have inhibited the uptake of water.

3.3.5 Grain yield

Mean grain yields for the irrigated (1350 kg ha^{-1}) and control plots (1320 kg ha^{-1}) were not significantly different. The lack of difference in yield between treatments may be explained by the fact that the considerable extra amount of water stored in the profile at sowing in the irrigated soil was no longer present at anthesis. Significantly more water was lost from the irrigated soil in the period between sowing and anthesis . Soil under both treatments had similar water contents at anthesis. Although dry matter production at anthesis was not measured, the irrigated plots had considerably larger plants. It is hypothesised that the rapid early growth and withdrawal of water from the irrigated soil led to a critical water deficit between anthesis and maturity. This phenomenon has been reported by several authors (e.g. Passioura 1972, Meyer and Alston 1978).

The presence of salt is likely to have decreased the osmotic potential of the subsoil water in the control plots particularly where the mean EC_{e25} at 0.7-1.1 m was 5.9 dS m^{-1}. (Values of up to 12.3 dS m^{-1} were recorded at some depths in some control plots). Besides affecting osmotic potential, salt may be directly toxic to both roots and shoots (Bernstein 1975, Mozafar and Goodin 1986). This also appears to be the case with boron.

Cartwright *et al.* (1984) reported marked spatial variation of soil boron at distances of a few metres which corresponded with variation in leaf symptoms in barley. The authors did not measure root length densities, but suggested that the symptoms and concentrations of boron in the plant were most strongly influenced by subsoil boron, which increased in concentration with depth.

The mean boron concentration in the grain from the irrigated plots (10.3 mg kg^{-1}) was significantly higher ($P \leq 0.05$) than in grain from the control plots (5.8 mg kg^{-1}). These data indicate a greater uptake of boron coincident with a higher water use and deeper rooting. The effect of added boron uptake on yield of grain in both treatments in this experiment is unknown, but a grain boron concentration of more than about 3 mg kg^{-1} grain was considered by Cartwright *et al.* (1984) to be indicative of a potential boron toxicity hazard in barley. While plants under both treatments were probably subject to boron toxicity, it is likely that plants in the irrigated treatment were affected to a greater degree.

Cartwright *et al.* (1984) indicated that where boron concentrations tend to be greater at some depth in the subsoil, shallow rooted cultivars may take up less boron if their roots do not reach the zones of highest boron concentration in the soil. In this experiment, the deeper rooted plants in the irrigated treatments appear to have taken up a significantly greater amount of boron as a result of the increase in available water at the start of the season.

3.3.6 Measurements made in 1988 - results and discussion

Soil water

Gravimetric water contents measured at anthesis from soil core samples from two plots which were control and irrigated plots respectively in 1986 were compared by the paired t-test. The soil which was irrigated in 1986 had an EC_{e25} less than 3 dS m^{-1} in the subsoil to a depth of 1 m and was significantly drier than the control at all depths below 0.3 m at anthesis.

At harvest there was a significant difference ($P \leq 0.05$, Table 3.3) in mean total soil water storage to 1 m between the previously irrigated plots (151 mm) and control plots (184 mm).

Table 3.3. Total soil water storage (mm) measured in 1988 at harvest at Minnipa for plots which were irrigated and controls in 1986.

Depth (m)	Irrigated (1986)	Control (1986)	LSD (0.05)
0.0-0.1	7.2	8.5	3.5
0.1-0.2	11.2	13.8	3.1
0.2-0.3	11.3	16.7	3.8
0.3-0.4	13.7	19.0	2.2
0.4-0.5	15.2	20.9	3.3
0.5-0.6	15.9	21.3	2.9
0.6-0.7	18.2	21.7	2.2
0.7-0.8	18.8	20.8	1.4
0.8-0.9	19.2	20.5	0.6
0.9-1.0	20.3	21.1	3.3

Dry matter production at anthesis and grain yield

Production of dry matter of tops from paired quadrats in two adjacent oat plots at the experimental site in 1988 was compared for the two treatments by the paired t-test. Mean dry matter production for the plot which was a control in 1986 was 890 kg ha^{-1} and for the irrigated plot 1582 kg ha^{-1}. The difference was significant ($P \leq 0.05$). Grain yields, however, were very low because of a severe drought in 1988 and were not significantly different between treatments.

It is hypothesised that the significantly wetter profile at harvest in the control plots was a function of lower osmotic potential in these plots and the reduced availability of water. In a severe drought, roots were able to withdraw more water from plots having a non-saline subsoil, resulting in significantly increased dry matter production at anthesis.

As in 1986, plants in the (previously) irrigated plots had more abundant top growth and were less able to cope with a water deficit after anthesis. Where salt was leached from the subsoil in 1986 in the irrigated soil, plants were able to extract more water and produce more shoot growth in 1988, but in the absence of finishing rains, the plants suffered a severe water shortage and yields were not different from those on plots with a saline subsoil.

3.4 Conclusions

The presowing irrigation of plots in 1986 reduced soil strength, reduced soil salinity between 0.7 and 1.1 m and increased the availability of water to 1.2 m at sowing. This is believed to be responsible for increased root growth, increased uptake of water to anthesis, and a greater uptake of boron, which was reflected in high boron concentrations in the grain. It is concluded that the lack of difference in grain yield between treatments was due to higher boron uptake and to water stress in the plants growing in the irrigated plots after anthesis.

In 1988, oats growing in plots having a non-saline subsoil extracted significantly more water to anthesis and to harvest to a depth of 1 m, and they produced significantly more dry matter at anthesis, but this was not reflected in increased grain yield. Again, the lack of difference in grain yield is attributed to more severe water stress in plants in the previously irrigated plots after anthesis.

The data from this preliminary study indicate that the effects of water, soil strength, boron and salt on root growth and wheat production in the environment require more investigation. Some of these parameters are considered in following chapters.

4.0. THE EFFECTS OF SALT AND BORON ON GROWTH OF WHEAT

4.1 Introduction

Boron toxicity in cereal crops in southern Australia was first identified by Cartwright *et al.* (1984) and the effects of high boron concentrations on yields of barley and wheat have been documented by Cartwright *et al.* (1986) and Paull *et al.* (1990). However, little information is available concerning the effects of boron on root growth.

In the glasshouse experiment described here, the effect of boron on the growth of wheat roots in solonised brown soil (Calcixerollic Xerochrept) containing a IIIA carbonate layer was examined in relation to dry matter and grain production and water use. As Cartwright *et al.* (1986) observed that the soils with toxic concentrations of boron in their study were generally sodic, and contained elevated concentrations of soluble salts, the effects of added salt were also considered.

4.2 Materials and Methods

4.2.1 Experimental design and treatments

The experiment was conducted in an evaporatively cooled glasshouse with deep pots (0.125 m x 0.125 m x 1.2 m) containing 0.2 m of topsoil above 0.6 m of treated subsoil and a base layer 0.26 m deep.

A randomised block design was adopted, with 16 factorial combinations of boric acid (0, 20, 38 and 73 mg boron kg^{-1} of soil) and mixed salts (0, 13, 39 and 75 mmol$_c$ salt kg^{-1}) added to the soil. The treatments, which were designed to cover the ranges of boron and electrical conductivities found in the soils of Upper Eyre Peninsula, produced mean concentrations of 3.1, 13.4, 22.0, and 37.6 mg $CaCl_2$-extractable boron and electrical conductivities ($EC_{1:5}$) of 0.16, 0.42, 0.69 and 0.92 dS m^{-1} in the carbonate layer at the end of the experiment. Each treatment was replicated four times: the replicates were blocked and the treatments randomised within each block.

4.2.2 Procedure

The topsoil and base layer for the experiment were collected from the 0-0.1 m and 1-1.5 m depth intervals respectively from Minnipa, and the subsoil (IIIA carbonate layer) from Piednippie where the salt and boron concentrations were known to be low. The soils were sieved (<10 mm) and air dried. Some of their properties are shown in Table 4.1

The salt and boron treatments were applied to the IIIA carbonate layer. The mixed salt consisted of $CaSO_4.2H_2O$ (8.3%), NaCl (61.5%), Na_2SO_4 (20.4%), KCl (0.5%) and $MgSO_4.H_2O$ (9.3%).

Table 4.1. Some properties of the soils used in the experiment.

Soil property	Depth in pot (m)		
	0 - 0.2	0.2 - 0.8	0.8 - 1.06
Material	Topsoil	IIIA carbonate	Wiabuna Formation*
Field texture	Sandy loam	Sandy loam	Light clay
pH (1:5 soil:water)	8.5	8.8	9.0
Electrical conductivity EC_{e25} (dS m^{-1})	1.0	2.15	10.6
Electrical conductivity $EC_{1:5}$ (dS m^{-1})	0.15	0.16	1.20
Gravimetric water content at -10 kPa (kg kg^{-1})	0.192	0.202	0.281
Gravimetric water content at -1.5 MPa (kg kg^{-1})	0.060	0.089	0.180
Hot 0.01M $CaCl_2$ extractable B (mg kg^{-1})	4.8	0.77	26.0
$NaHCO_3$ extractable P (mg kg^{-1})	61.0	-	-

* The Wiabuna Formation occurs widely on Upper Eyre Peninsula at depths below 0.5 m and it is considered by Wetherby (1980) to be a parent material of the carbonate layers.

The composition of the mixture was based on analysis of saturated paste extracts from a IIIA carbonate layer at Minnipa but excluded carbonates and bicarbonates. The salt was mixed with the soil in 0.3 dm^3 of water kg^{-1} soil. This was more than sufficient water to saturate the soil. The soil was allowed to dry and it was then subjected to two more wetting and drying cycles. The boric acid was then added in solution and thoroughly mixed with the soil.

Basal fertiliser was added to all layers of soil. Solutions containing 33.3 mg phosphorus (as potassium dihydrogen orthophosphate), 3.3 mg manganese (as manganous sulphate), 2.7 mg copper (as copper sulphate) and 1.3 mg zinc (as zinc sulphate) kg^{-1} of soil were sprayed onto the soil with repeated mixing. The topsoil was also treated with 16.7 mg nitrogen (as calcium nitrate) kg^{-1} soil.

The pots were constructed of galvanised steel and were lined with thin polythene tubes open at the top and bottom. The soil was retained in the pots by a fine mesh plate supported by lugs 2 cm from the ground. The water contents of the topsoil, subsoil and basal layer were adjusted to 85% of the available water holding capacity as the best consistency for packing into each pot. The soils were packed in 0.1 m thick increments to give bulk densities of 1440 kg m^{-3} for the topsoil and carbonate subsoil layer, and 1260 kg m^{-3} for the basal clay layer. (Pots were sealed until sowing to prevent loss of water).

On 27 May 1988, six seeds of wheat (cv. Warigal) were sown in each pot at a depth of 2.5 cm. By 6 June, all seedlings had emerged and the number of seedlings per pot was reduced to three. To prevent water running between the soil and the polythene pot lining, 0.1 m lengths of PVC pipe (0.1 m diameter) were inserted 2.5 cm into the soil which was then covered with 0.48 kg of gravel (~1 cm 'diameter') to act as mulch. Later, when the plants reached the three leaf stage, a 15 cm high cylinder of black polythene mesh providing 40% shade was placed around the plants to restrict tillering.

On 9 June when the plants were at the 1-2 leaf stage, each pot was weighed and sufficient water added to replace water lost by evaporation since the time of sowing. At this and subsequent waterings, the amount of water added to each pot was recorded. The water content of the soil was gradually increased to field capacity between 9 and 14 June. The soil was then allowed to dry gradually until 14 September to encourage the roots to grow into the subsoil. During this period, water was added on three occasions to bring all pots to the same weight, *viz.* that of the pot having the greatest amount of water. From mid-September until 28 October, the soil was allowed to dry further, but the pot weights were not allowed to fall below that corresponding to 17% of the available water holding capacity of the soil. Watering ceased on 28 October and the plants were harvested on 11 November.

4.2.3 Measurements

Counts were made on 16 August of the number of tillers, and on 6 September, at anthesis, one 'average' tiller was collected from each pot, dried and ground for the determination of boron and sodium contents. Plant material was digested with nitric acid (Zarcinas 1984) and boron and sodium contents determined by inductively coupled plasma spectrometry (Zarcinas and Cartwright 1983).

At harvest, all pots were weighed and the plants were harvested by cutting at ground level. Total shoot weight and grain weight were determined. The concentrations of boron and sodium in the grain were also measured.

The pots were opened and the soil sectioned at 0.1 m depth intervals. Roots were removed from samples of soil from each 0.1 m section by the method of Hignett (1976), and their lengths determined by the line intersect method described by Tennant (1975).

Samples of soil were also taken for the determination of gravimetric water content, hot 0.01 M $CaCl_2$-extractable boron (Bingham 1982) and electrical conductivity in 1:5 (by weight) soil:water extracts (Rhoades 1982). Water contents and electrical conductivities ($EC_{1:5}$) were measured on soil from each 0.1 m interval, but boron analyses were made only on bulked samples from the carbonate layer. Electrical conductivities (EC_{e25}) in saturated paste extracts of soil were determined at the beginning of the experiment on bulk samples of soil at each salt concentration (Rhoades 1982).

4.3 Results and discussion

4.3.1 Growth and dry weight of shoots and grain

Tillering was unaffected by boron, but significantly decreased by the presence of salt in the subsoil (Table 4.2.). Data on dry weight are presented in Table 4.3. Both added salt and boron significantly decreased the dry weight of shoots and grain, with boron having the greater effect. Significant negative interactions occurred in each case. This contrasts with the results of Bingham *et al.* (1987), who reported that shoot weight of wheat grown in sand culture was reduced independently by lowering the osmotic potential or by increasing the concentration of boron in solution: there were no significant interactions.

Table 4.2. The effects of salt and boron on tillering of Warigal wheat.

Salt ($mmol_c\ kg^{-1}$)	Tillers (pot^{-1})	Boron ($mg\ kg^{-1}$)	Tillers (pot^{-1})
0	5.38	0	4.75
13	4.75	20	4.50
39	4.50	38	4.44
75	3.81	73	4.75
LSD (P=0.05)	0.88	LSD (P=0.05)	0.88

The least amount of added boron (20 mg kg^{-1} soil) produced a grain yield equal to 75% of the control. Soil with this treatment had 13 mg extractable boron kg^{-1}, and symptoms of boron toxicity were visible in all plants. The effect of boron was greater on grain yield than on total dry weight of the shoots: the highest addition (73 mg boron kg^{-1} soil) yielded only 48% of the control while the mean dry weight of shoots was 56% of the control. Conversely, added salt had a greater effect on the dry weight of shoots than on grain yield: the mean dry weight of shoots at the highest salt treatment (75 $mmol_c$ kg^{-1}).

Table 4.3. The effects of salt and boron on dry weight of shoots and grain at maturity.

Salt	Boron ($mg\ kg^{-1}$)			
($mmol_c\ kg^{-1}$)	0	20	38	73
	Dry weight of shoots ($g\ pot^{-1}$)			
0	24.1	20.0	14.5	9.4
13	16.2	12.7	13.9	10.4
39	15.1	11.4	10.0	10.0
75	12.9	11.1	8.2	7.9
LSD (P=0.05)		3.78		
	Grain weight ($g\ pot^{-1}$)			
0	9.1	6.1	4.7	3.0
13	6.2	5.1	5.5	3.4
39	6.5	4.5	3.8	3.8
75	5.3	4.5	3.5	2.7
LSD (P=0.05)		1.15		

Analysis of variance produced significant F values ($P \leq 0.05$) for the interaction of salt and boron.

The effects of boron added to the subsoil on the growth of wheat (cv. Warigal). Amounts of boron added are from left, 73 and 0 mg boron kg^{-1} soil.

The effects of increasing amounts of mixed salt added to the subsoil on the growth of wheat (cv. Warigal). Amounts of salt added are from left, 75, 39, 13 and 0 $mmol_c$ kg^{-1} soil.

soil) was 59% of the control, while the mean grain yield was 69% of the control. Francois *et al.* (1986) also found that the vegetative growth of wheat was decreased by soil salinity more than was grain yield with a threshold soil salinity of 4.5 dS m^{-1} (EC_{e25}), which corresponds to about 10 $mmol_c$ salt kg^{-1} soil in this experiment. The dry weight of tops here was significantly reduced by the lowest addition of salt (13 $mmol_c$ kg $soil^{-1}$). The effect of salinity was to reduce the number of tillers (Table 4.2). Maas and Grieve (1988) found that the major effect of salt on the grain yield of wheat was in the reduction of the number of tillers, and Cerda and Bingham (1978) also reported a significant depression in the grain and straw yield of wheat grown in saline conditions due principally to a decrease in the number of tillers and heads per plant.

4.3.2 Root growth

Root growth was significantly affected by both the salt and boron treatments. Root length densities for each 0.1 m depth interval are shown in relation to added salt and boron in Figs. 4.1 and 4.2 respectively, while Table 4.4 contains data for each soil layer and for the profile as a whole.

Analysis of variance showed that the treatments had no significant ($P \leq 0.05$) effect on root length in the topsoil and the upper part of the carbonate layer, but that root length below 0.3 m was restricted by both boron and salt. Boron had a much greater effect than salt on root growth in the carbonate layer . As the concentration of added boron increased, rooting densities declined more rapidly with depth than in the control, and at the highest addition of boron few roots penetrated below 0.4 m. Roots were able to penetrate to the basal layer of soil with lower additions of boron, but in general, rooting was restricted by all boron treatments below 0.6 m.

Root length density with the highest salt treatment was significantly greater in the 0.3-0.4 m depth interval and significantly smaller below 0.6 m than with the other salt treatments. There were no differences between between 0.4 and 0.6 m The total length of root in the carbonate layer was less than the control only with the highest additions of salt (39 and 75 $mmol_c$ kg^{-1} soil). The ability of roots to grow through the carbonate layer

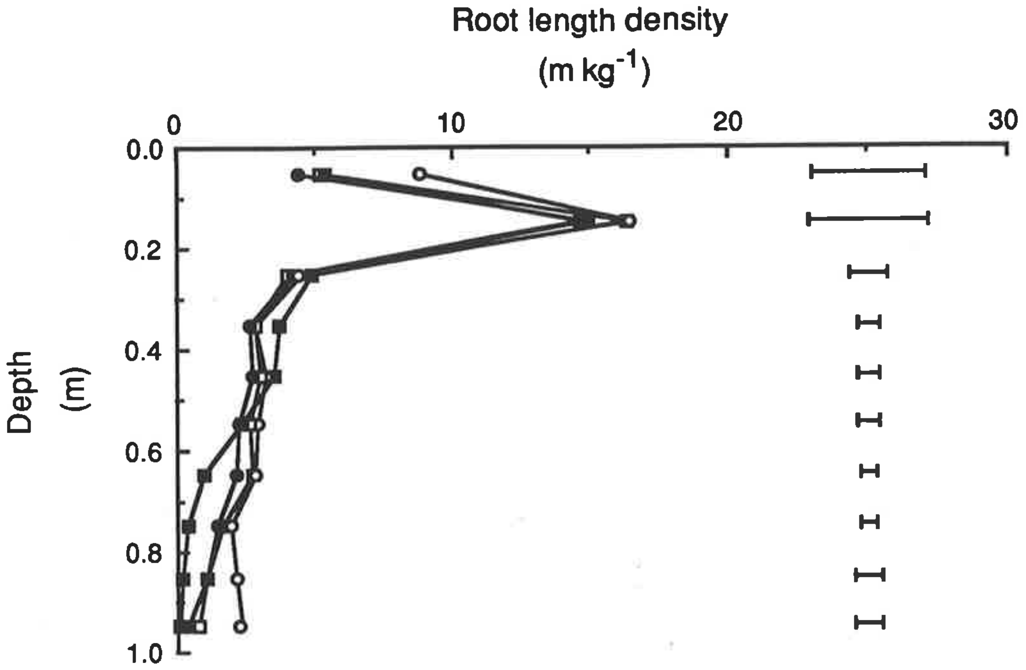


Fig. 4.1. Root length density of wheat as a function of depth and salt added to the subsoil: 0 (○), 13 (□), 39 (●) and 75 (■) mmol$_c$ salt kg^{-1} soil. LSD bars at each depth interval are for P=0.05.

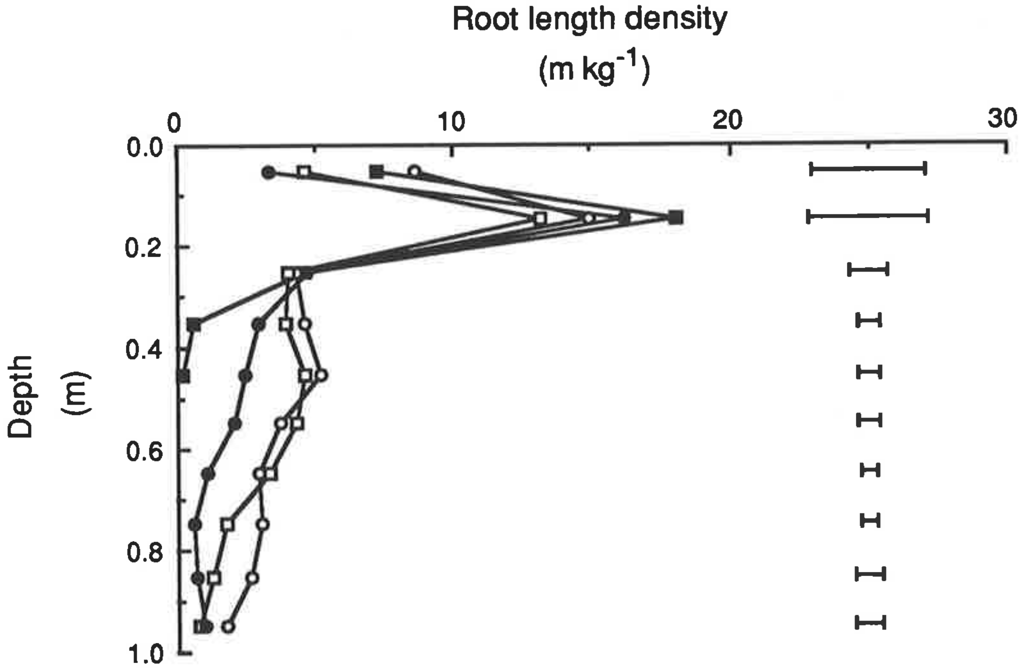


Fig. 4.2. Root length density of wheat as a function of depth and boron added to the subsoil: 0 (○), 20 (□), 38 (●) and 73 (■) mg boron kg^{-1} soil. LSD bars at each depth interval are for P=0.05.

is indicated by total root length in the basal layer. All added salt and boron treatments significantly reduced root growth in the basal layer. This has important implications for the ability of plants to use reserves of subsoil water in the field since water use may be closely related to rooting depth (Hamblin and Tennant 1987), although water uptake is not a specific function of root length (Shalhevet and Bernstein 1968). In wet seasons, plants may be able to withdraw sufficient water from the topsoil and upper subsoil to maintain optimum growth but in drought the effects of salt and boron may discourage or prevent root growth deeper into the subsoil and as a consequence impose greater stress on the plants. Even where roots are able to penetrate the subsoil to any depth, plants may then be exposed to increased uptake of potentially toxic ions.

Table 4.4. The effects of salt and boron on root length at maturity.

Soil layer	Salt (mmol$_c$ kg^{-1})				
	0	13	39	75	LSD (P=0.05)
	Root length (m)				
Topsoil (0 - 0.2 m)	57.8	45.3	44.0	49.7	15.3
Carbonate layer (0.2 - 0.8 m)	42.0	38.4	35.3	36.3	5.8
Base layer (0.8 - 1.06 m)	10.4	4.2	3.4	0.6	2.8
Total profile (0 - 1.06 m)	110.2	87.9	82.7	86.6	17.8
	Boron (mg kg^{-1})				
	0	20	38	73	LSD (P=0.05)
	Root length (m)				
Topsoil (0 - 0.2 m)	53.5	40.6	44.7	57.9	15.3
Carbonate layer (0.2 - 0.8 m)	57.5	50.4	31.6	12.5	5.8
Basal layer (0.8 - 1.06 m)	10.0	4.5	3.8	0.2	2.8
Total profile (0 - 1.06 m)	121.0	95.5	80.1	70.6	17.8

Analysis of variance produced significant F values ($P \leq 0.05$) for the effects of salt on roots in the base layer and the total profile, and for the effects of boron in all layers except the topsoil.

4.3.3 Water use efficiency

The amount of water used from sowing to harvest was used to calculate water use efficiency with respect to total dry weight of shoots and to grain production (Table 4.5.).

Table 4.5. The effects of salt and boron on water use efficiency of dry matter production in shoots and grain.

Salt (mmol_c kg^{-1})	Boron (mg kg^{-1}) 0	20	38	73
	Water use efficiency (kg shoots m^{-3} water)			
0	2.67	2.40	2.35	1.89
13	2.44	2.21	2.07	1.74
39	2.39	2.17	1.86	1.81
75	2.42	2.08	1.54	1.73
LSD (P=0.05)		0.41		

Analysis of variance showed no significant interaction between salt and boron.

Salt (mmol_c kg^{-1})	Boron (mg kg^{-1}) 0	20	38	73
	Water use efficiency (kg grain m^{-3} water)			
0	1.02	0.79	0.74	0.60
13	0.94	0.89	0.82	0.56
39	1.02	0.86	0.72	0.68
75	0.99	0.83	0.64	0.59
LSD (P=0.05)		0.15		

Analysis of variance showed significant F values ($P \leq 0.05$) for the interaction of salt and boron.

Water use efficiency was significantly reduced by increasing boron both in terms of total shoot weight and grain yield, with the more pronounced effect being on grain yield. By contrast, water use efficiency was not affected by salinity with respect to grain production, although it was progressively decreased by increasing salinity in terms of total dry matter in the shoots. Effects of both matric and osmotic potential are likely to have influenced the growth of plants in this experiment. At the beginning of the experiment, osmotic potentials of the saturated soil solution in the carbonate layer were estimated (United States Salinity Laboratory Staff 1954) to have been -0.08, -0.26, -0.54 and -0.88 MPa respectively for the four salt treatments (0, 13, 39 and 75 mmol_c kg^{-1}).

As salinity increases, water uptake decreases (Shalhevet and Bernstein 1968) and transpiration is also reduced (Aceves-Navarro *et al.* 1975). Sepaskhah and Boersma (1979) and Mashhady *et al.* (1982) reported interactive effects of osmotic and matric potential on the growth of wheat, but Abdul-Halim *et al.* (1988) recorded only additive effects on several growth parameters, including the number of tillers per plant, total dry matter and grain yield.

4.3.4. Sodium and boron concentrations in wheat

Concentrations of sodium in the shoots decreased with increasing addition of boron to the soil (Fig. 4.3), possibly due to the reduction in rooting density caused by the boron treatments. However, there was no effect of boron on sodium concentrations in the grain.

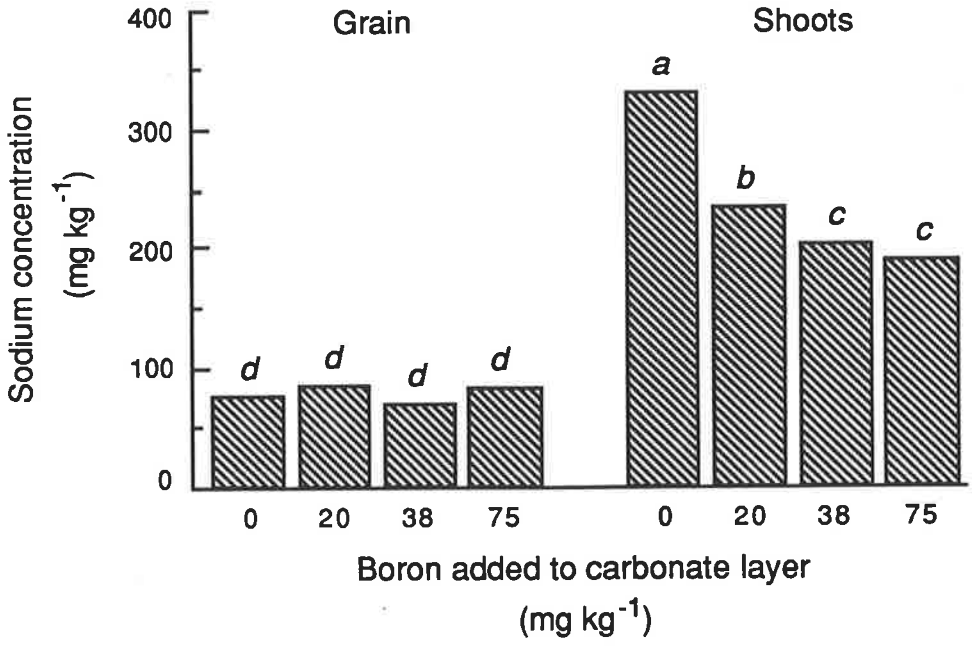


Fig. 4.3. Sodium concentrations in shoots at anthesis and in grain as functions of boron added to the subsoil. Statistical analyses were performed on log-transformed data: columns with the same letter are not significantly different at $P \leq 0.05$.

Concentrations of sodium in the grain and shoots were increased significantly by the addition of salt to the subsoil (Fig. 4.4). This result was expected, as the mixture of salts used contained 61% sodium chloride. These results agree with the findings of Devitt *et al.* (1984) who measured increasing sodium concentrations on a whole plant basis (after six weeks' growth) as the sodium concentration in the root medium increased. Cerda and Bingham (1978) recorded increasing leaf sodium concentrations with decreasing osmotic potentials, and Storey *et al.* (1985) measured a proportionate increase in sodium concentration in wheat shoots with an increase in salinity in the root medium. These results suggest that sodium concentrations in the grain or shoots may provide a guide to the occurrence of salinity of the root zone in field conditions. However, sodium concentration does not appear to be a useful indicator of varietal tolerance to salinity. Kingsbury *et al.* (1984) found that two cultivars of wheat which differed in tolerance to salinity contained similar concentrations of the major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and chloride in roots and shoots, suggesting similar absorption and translocation of ions. The authors suggested that the differences in tolerance may have been due to the ability of the tolerant cultivar to compartmentalise toxic ions within the vacuole more efficiently than the sensitive cultivar.

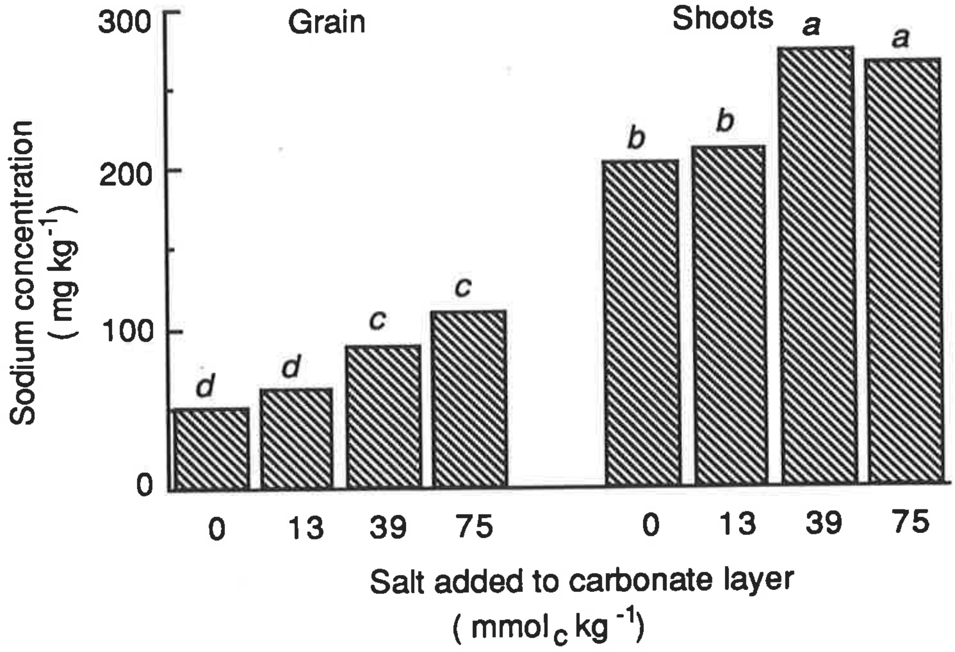


Fig. 4.4. Sodium concentrations in shoots at anthesis and in grain as functions of salt added to the subsoil. Statistical analyses were performed on log-transformed data: columns with the same letter are not significantly different at $P \leq 0.05$.

Concentrations of boron in the shoots at anthesis and in the grain were increased by the application of boron and decreased by the application of salt to the carbonate layer in the subsoil (Table 4.6.). The effect of salt on boron concentration is here attributed to a decrease in the uptake of water and ions as a result of reduced osmotic potentials, although Bingham *et al.* (1987) reported that boron concentrations in the leaves of wheat in their study were affected only by the boron content in the substrate, not by osmotic potential.

Table 4.6. The effects of salt and boron on the concentration of boron in the shoots at anthesis, and in the grain.

Salt ($mmol_c$ kg^{-1})	Boron ($mg\ kg^{-1}$) 0	20	38	73
	Boron in shoots at anthesis ($mg\ kg^{-1}$)			
0	43(b)	490(d)	540(de)	720(f)
13	57(b)	371(d)	542(de)	691(e)
39	61(b)	226(c)	419(de)	567(de)
75	12(a)	205(c)	405(de)	467(de)
	Boron in grain ($mg\ kg^{-1}$)			
0	2.1(a)	9.7(b)	19.3(d)	37.3(f)
13	1.9(a)	10.1(b)	15.1(cd)	30.6(f)
39	2.2(a)	9.9(b)	16.3(cd)	22.7(e)
75	1.9(a)	8.8(b)	13.3(c)	23.3(e)

Analyses were performed on log-transformed data. Within each section of the table, values followed by the same letter are not significantly different at $P \leq 0.05$. Analysis of variance produced significant F values ($P \leq 0.05$) for the interactions between salt and boron.

Although significant negative correlations have been obtained, both in this experiment ($r= -0.53$, $P\leq0.001$) and elsewhere (*e.g.* Rathjen *et al.* 1987 $r= -0.89$, $P\leq 0.001$), between final grain yield and the boron concentration in wheat shoots at and prior to anthesis, boron concentration in shoots is not regarded as a satisfactory predictor of boron toxicity (Nable *et al.* 1990). Accumulation of boron varies considerably with water use, and its distribution in the shoots is very uneven. Nable *et al.* (1990) considered that grain analysis was preferable to foliar analysis for diagnosing boron toxicity.

It appears from the data of Cartwright *et al.* (1984) that a concentration of more than 3 mg boron kg^{-1} grain is likely to indicate a boron toxicity hazard to barley. However, there are few published data available on which to base a critical boron concentration for toxicity in wheat. Our data show that grain yield was significantly decreased by the lowest application of boron (20 mg kg^{-1} soil), which produced grain with a mean concentration of 9.6 mg boron kg $^{-1}$, compared with 2.0 mg kg^{-1} for the control. It should be noted here that glasshouse-grown plants may be able to produce their maximum grain yields at greater concentrations of boron than field grown plants are able to tolerate without yield loss (Nable 1988). In part, this is due to loss of boron from the leaves of field-grown plants by the leaching action of rainfall (Oertli 1962).

4.3.5. Electrical conductivity

At the beginning of the experiment, the EC_{e25} of the treated carbonate layers, determined on bulked subsamples for each salt concentration were: 2, 7, 13.5 and 22 dS m^{-1}, while the $EC_{1:5}$ were 0.16, 0.51, 0.98 and 1.60 dS m^{-1} respectively. The relationship between EC_{e25} and $EC_{1:5}$ for the different soil materials is as follows.

Topsoil $EC_{e25} = 28.0\ EC_{1:5} - 3.11$ $(r = 0.99, P \leq 0.01)$
Carbonate layer $EC_{e25} = 13.8\ EC_{1:5} - 0.06$ $(r = 0.96, P \leq 0.01)$
Basal layer $EC_{e25} = 10.1\ EC_{1:5} - 1.59$ $(r = 0.99, P \leq 0.01)$

The values of $EC_{1:5}$ in 0.1 m depth increments of soil at the end of the experiment are shown in Table 4.7. These data provide evidence of considerable movement of salt during the course of the experiment, and of loss of soluble salts from the soil

The $EC_{1:5}$ of the topsoil, initially 0.15 dS m^{-1}, remained unchanged at harvest in the control treatment. However, the electrical conductivity of the topsoil at harvest increased with increasing addition of salt to the carbonate layer. At the highest addition (75 mmol$_c$ salt kg^{-1} soil), the mean electrical conductivity of the 0.1-0.2 m depth interval had increased to 0.34 dS m^{-1} by harvest. The electrical conductivity of the topsoil also increased with the addition of boron to the subsoil. This upward movement of salt may be a function of the lower amounts of water added to the soil containing the higher amounts of salt and boron. With less added water, there was less opportunity for downward leaching; and with drier topsoil, further opportunity for the upward movement of salt.

The highest boron treatment (73 mg kg^{-1} soil) produced significantly lower $EC_{1:5}$ at harvest in soil between 0.4 and 0.6 m, than did the other treatments. This zone of soil may have been depleted by upward movement of salt, since below 0.6 m, values of $EC_{1:5}$ were not significantly affected by the boron treatments.

Table 4.7. Electrical conductivities measured in 1:5 soil:water suspensions at the conclusion of the experiment.

Depth (m)	Salt ($\mathrm{mmol_c\ kg^{-1}}$) 0	13	39	75	LSD (0.05)
	Electrical conductivity ($\mathrm{dS\ m^{-1}}$)				
0.0-0.1	0.16	0.15	0.26	0.22	0.086
0.1-0.2	0.14	0.14	0.23	0.34	0.044
0.2-0.3	0.19	0.25	0.46	0.68	0.079
0.3-0.4	0.23	0.38	0.71	1.07	0.079
0.4-0.5	0.29	0.51	0.88	1.16	0.081
0.5-0.6	0.29	0.49	0.79	0.99	0.071
0.6-0.7	0.28	0.47	0.64	0.80	0.075
0.7-0.8	0.28	0.42	0.63	0.81	0.051
0.8-0.9	0.49	0.59	0.84	1.04	0.046
0.9-1.0	0.68	0.73	0.92	1.08	0.065
1.0-1.06	0.92	1.01	1.14	1.40	0.201

Depth (m)	Boron ($\mathrm{mg\ kg^{-1}}$) 0	13	39	75	LSD (0.05)
	Electrical conductivity ($\mathrm{dS\ m^{-1}}$)				
0.0-0.1	0.17	0.17	0.21	0.26	0.086
0.1-0.2	0.17	0.18	0.22	0.29	0.044
0.2-0.3	0.32	0.33	0.42	0.51	0.079
0.3-0.4	0.58	0.59	0.65	0.58	0.081
0.4-0.5	0.74	0.76	0.76	0.59	0.081
0.5-0.6	0.67	0.66	0.67	0.55	0.071
0.6-0.7	0.53	0.56	0.58	0.51	0.075
0.7-0.8	0.53	0.53	0.56	0.50	0.051
0.8-0.9	0.74	0.75	0.76	0.72	0.046
0.9-1.0	0.84	0.87	0.87	0.81	0.065
1.0-1.06	1.05	1.18	1.15	1.10	0.201

When the salt treatments are considered independently of boron, values of $EC_{1:5}$ in the carbonate layer were highest at harvest in the 0.4-0.5 m depth interval, and this became more pronounced with increased addition of salt. The concentration of salt in the centre of the pot is likely to be the end result of both upward and downward movement. Both the carbonate layer and the basal clay layer lost soluble salts during the course of the experiment, the losses increasing with the amount of salt added. Precipitation of insoluble salts may have contributed to the losses, but there was evidence that some salt was removed from the soil by through drainage although attempts had been made to minimise losses by this means.

4.4 General discussion and conclusions

Many of the experiments reported in the literature concerning the effects of salinity on wheat growth refer to root environments where the salt distribution is uniform. However, subsoil in the field is rarely uniform with respect to the vertical (and horizontal) distribution of salt. The changes in salt distribution during the course of this experiment demonstrate the mobility of salt and the likelihood of roots encountering non-uniform salt distribution in the subsoil. Where only part of the root zone is affected by high salt concentrations, the effects of salt on wheat growth are likely to be a function of the cultivar, the kind of salt, seasonal conditions, soil water movement, and other soil factors, physical and chemical (Shalhevet *et al.* 1968, Mashhady *et al.* 1982, Kingsbury and Epstein 1984, Abdul Halim *et al.* 1988). Interactions between cultivar, kind of salt and salt concentration are common (Mozafar and Goodin 1986). Similarly, the effect of boron in field soils is modified by cultivars and seasonal factors which affect the concentration of boron in the soil solution, the absorption rates of boron and water, and patterns of root growth (Cartwright *et al.* 1984).

In the cereal-growing areas of Upper Eyre Peninsula, high electrical conductivities and high boron concentrations tend to occur in the subsoils, with low values in the top 0.2 m of soil. An attempt was made to reproduce this situation here. The treatments produced mean concentrations in the carbonate layer of 3.1, 13.4, 22.0 and 37.6 mg extractable boron kg^{-1} at the end of the experiment. These values are typical of the range of concentrations in carbonate layers on Upper Eyre Peninsula, although extractable boron concentrations in excess of 100 mg kg^{-1} have sometimes been recorded. Likewise, the values for EC in the salt-treated subsoil represent the range of salinities likely to be found in carbonate layers in the region, although the highest values shown in Table 4.7 are not often encountered. The wheat cultivar used in the experiment (Warigal), is considered to be in the mid-range of the tolerance-susceptibility spectrum to both boron (Paull *et al.* 1990) and salt (A. J. Rathjen, pers. comm.) for cultivars in southern Australia.

Although the results obtained are specific to the conditions of the experiment and the cultivar chosen, it is concluded that the concentrations of salt and boron typical of the subsoil in large areas of Upper Eyre Peninsula are likely to restrict the growth and production of wheat. The degree of restriction will depend on seasonal factors, the depth at which maximum salt and boron concentrations occur, and the rooting habits and tolerance of the cultivar concerned. The ability of wheat to tolerate drought is likely to be severely restricted by the deleterious effects of salt and boron on root growth and water use efficiency. The selection of cultivars for their ability to tolerate high salt and boron concentrations in the subsoil and produce an efficient root system should lead to an improvement in the efficiency of wheat production on Upper Eyre Peninsula and in other regions where similar soils and environmental conditions exist.

5.0 A SURVEY OF SALT AND BORON CHARACTERISTICS OF SOME AGRICULTURALLY IMPORTANT LAND UNITS OF UPPER EYRE PENINSULA.

5.1 Introduction

Boron toxicity in cereals has only recently been recognised throughout southern Australia as a major problem (Khan *et al.* 1985, Cartwright *et al.* 1986, Riley 1987) since the first identification of boron toxicity in a field of barley at Gladstone, South Australia by Cartwright *et al.* (1984). In fact, neither the boron nor the salt status of the soils of southern Australia have been thoroughly investigated. There is evidence of widespread boron toxicity in crops in the region (including Upper Eyre Peninsula) (Cartwright *et al.* 1986, Hirsch and Manton 1989), but little information exists for the effects of salt.

A preliminary investigation was conducted at five of the South Australian Department of Agriculture's wheat cultivar testing sites on Upper Eyre Peninsula. Samples were taken after harvest from pits 2 m deep dug across the plots of two commonly grown cultivars, Halberd and Aroona. The sites were at Minnipa, Cungena, Piednippie, Nunjikompita and Penong.

Analysis of samples taken from each horizon showed that extractable boron exceeded 15 mg kg^{-1} at depths of less than 1 m at Minnipa, Nunjikompita and Penong. Cartwright *et al.* (1984) have referred to the difficulty in determining critical values of boron for field soils. However, concentrations of greater than 15 mg kg^{-1} were considered to be indicative of a potential boron toxicity hazard (B. Cartwright, pers. comm.). Saline soil ($EC_{e25} > 4$ dS m$^{-1,}$ United States Salinity Laboratory 1954) also occurred at depths of less than 1 m at Minnipa, Nunjikompita and Penong. (The definitive work of Northcote and Skene (1972) described soil salinity in terms of the percentages of soluble salts although the 4 dS m^{-1} EC_{e25} standard was considered to apply to Australian soils). Examinations of pit faces showed that roots did not extend below 1 m at any site other than Piednippie.

In view of these observations, a more extensive survey was undertaken in 1989-90. The aims of the survey were to: (1) - determine the potential hazard to cereals presented by boron and salt and hence the need to develop and use resistant cultivars, (2) - determine the variability of boron and salt distribution between and within land units, and (3) - to assess the feasibility of predicting high salt and boron concentrations by association with other soil factors.

5.2. Materials and methods

Four of the agronomically important land units of Upper Eyre Peninsula were selected for study from the preliminary soil map produced by Wetherby (see map). This map was based on mapping units segregated by landform and geological associations. The units chosen were (sampling localities are in brackets) Unit 10 (Minnipa-Wudinna), Unit 8b (Cungena and Nunjikompita), Unit 8a (Penong) and Unit 11 (Buckleboo).

Because of the large size of mapping unit 8b, two separate localities were individually sampled within the unit, so that distinct sampling sequences were conducted at Cungena and Nunjikompita. For the purpose of the present survey, each locality has been referred to as a land unit.

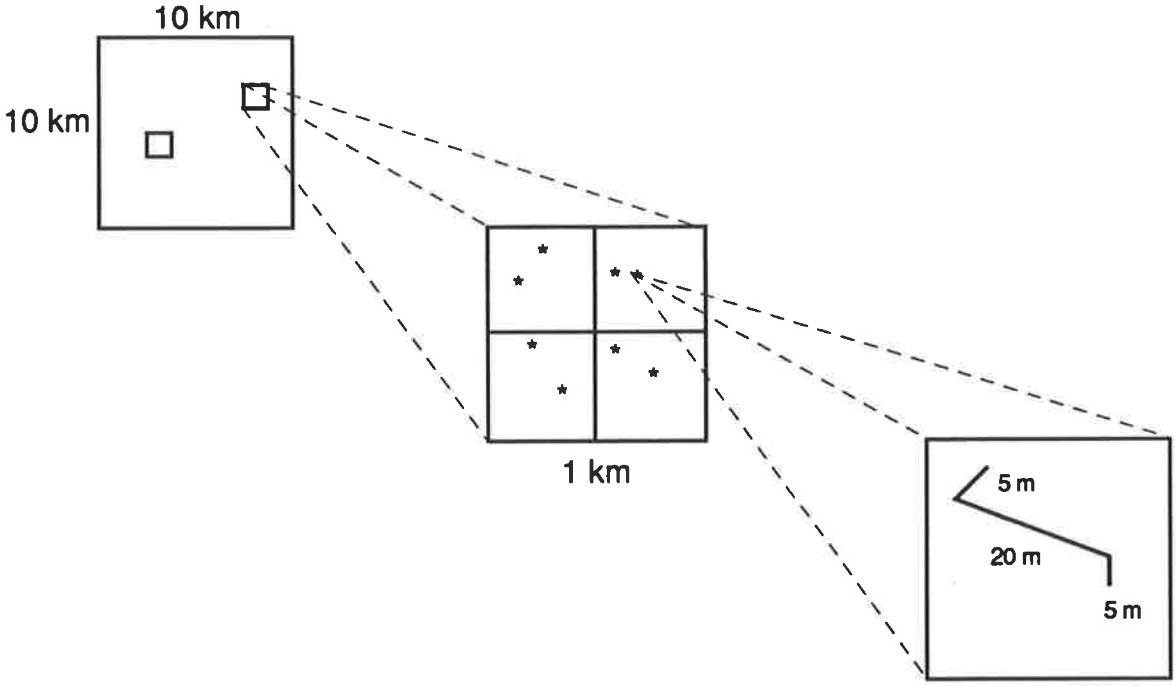


Fig. 5.1 Diagrammatic representation of the sampling design for the survey, with sectors (10km x 10km), subsectors (1km x 1km), sites (*), and the arrangement of the four pits at each site.

The hierarchical sampling design used for the survey was similar to that of Nortcliff (1978). Within each of the land units surveyed, two areas (referred to as sectors) each 10 km x 10 km were selected for sampling. The selection of sites was at random subject to the willingness of landowners to co-operate in the survey. Within each 10 km x 10 km sector, two 1 km x 1 km areas (subsectors) were selected at random. Each subsector was further divided into quarters. In each quarter, two sites were chosen at random. At each site, four sampling points were located as follows. With the original point as the first sampling location, another point was selected in a random direction at a distance of 20 m. Two more points were selected in a random direction 5 m away from the first two (Fig 5.1). A pit for sampling was dug at each point. Each land unit was then to be represented by samples taken from 128 locations.

Pits were dug 1.2 m deep, 1 m wide and 2 m long at each location except at Wudinna (part of Unit 10) where a 50 mm diameter thin walled core tube sampler was used to collect samples.

At each pit, soil profiles were described with respect to soil horizons, texture, colour, field pH, carbonate layers (Wetherby and Oades 1975) and geological formations (Crocker 1946b, Firman 1971, Wetherby 1973, Firman 1978, Wetherby 1980). The position of each site was located on 1:50,000 topographical maps so that the altitude of each could be determined.

Soil samples were taken from 0.1 m increments down the profile, provided that any single 0.1 m interval did not overlap a distinct horizon boundary. Where such boundaries occurred, the depth interval for sampling above the boundary was increased or decreased accordingly so that soil from separate horizons was not mixed. Two samples of about 0.5 kg each were taken from sides of each pit at corresponding depth intervals at a horizontal distance apart of 0.5 - 1.0 m. The sampling procedure was designed to represent the volume of soil which could be explored by the roots of a single wheat plant.The samples from each depth interval were bulked, mixed, and the composite sub-sample used for measurements. At Wudinna, four cores were collected to represent a single pit. The cores were cut into appropriate lengths (as described above), bulked for each depth interval and sub-sampled as for the pit samples.

Composite sub-samples for each depth interval were air dried and sieved (<2 mm). Electrical conductivity measurements were taken on 1:5 (by weight) soil:water extracts (Rhoades 1982). EC_e s were calculated from the $EC_{1:5}$ values using data from these land units (Wetherby 1990). Soil boron was determined by hot 0.01 M $CaCl_2$ extraction (Bingham 1982) and inductively coupled plasma spectrometry (Zarcinas and Cartwright 1983). Because of the costs involved, boron was measured only from selected depth intervals, except that a complete series of samples from a single location in each subsector were measured for $EC_{1:5}$ and boron concentrations.

5.3 Results and discussion

Measurements were taken on soil from all depth intervals from a single location chosen at random from each subsector in the survey. The results from these tests confirmed observations from the preliminary study which indicated that the highest concentrations of salt and boron in any profile were restricted to the subsoil below 0.4 m.

Because the normal depth of wetting in these localities does not normally exceed 1.1 m (B. Jakobsen, pers. comm.), it was considered that the 0.4-1.1 m depth interval represented the potential subsoil root zone. Therefore, to represent the boron and salt characteristics of each soil profile within the constraints of time and cost, soil from four depth intervals was subject to measurement viz, 0.4-0.5 m, 0.6-0.7 m, 0.8-0.9 m, 1.0-1.1 m.

Differences in salt and boron distribution with depth, differences in root growth and nutrient uptake patterns in different seasons, and differences in varietal tolerance to salinity and boron make the determination of critical values in field soils difficult. However, it is useful to suggest concentrations of salt or boron in the root zone which are likely to pose a hazard to wheat. For the purposes of this survey, a mean extractable boron concentration of >15 mg kg^{-1} was considered to be at the lower level of the toxic range, as was an ECe of >4 dS m^{-1}, the criterion for a saline subsoil set by the United States Salinity Laboratory Staff (1954)

5.3.1 The variability of salt and boron distribution.

Table 5.1. Summary of the survey design levels

Level	Name	Comments
6	Sector	Two sectors were sampled within each land unit
5	Subsector	Two subsectors were sampled within each sector
4	Quarter	Each subsector was divided into four equal areas (0.5 km x 0.5 km)
3	Site	Two sites were sampled within each quarter
2	Pit20	At each site, two pits were located 20 m apart
1	Pit5	For each pit 20 m apart, another was located 5 m away

To examine the patterns of variability of boron and salt distribution between and within levels, the overall variance was broken down into components for individual levels. Rather than perform separate statistical analyses for each of the four depths chosen for the investigation, a principal component analysis was used initially to replace the four depth variables with a smaller number of variables while retaining as much of the original information as possible.

The first principal component, which constitutes a linear equation combining those variables to which the greatest proportion of the total variance is due, accounted for more than 80% of the variation in both boron and salt. For each of the four depths analysed, component loadings were of a similar magnitude and all had the same numerical sign. Because the first principal component was largely determined by the mean over the four depths, the mean rather than the first principal component could be used in this study and the analysis and interpretation of the data were greatly simplified.

In the survey design used, each individual observation (the mean extractable boron or EC_e over the four depth intervals) could be represented by the model:

$$Y_{ijklmn} = \mu + a_i + b_{ij} + c_{ijk} + d_{ijkl} + e_{ijklm} + f_{ijklmn}$$

where Y_{ijklmn} is the observation for sector i, subsector j, quarter k, site l, pit20 m and pit5 n :- (i = 1,2; j = 1,2; k = 1...4; l = 1,2; m = 1,2 and n = 1,2). a_i, b_{ij}, c_{ijk}, d_{ijkl}, e_{ijklm} and f_{ijklmn} are independently distributed variables with zero mean and variances σ_{sector}^2, $\sigma_{subsector}^2$, $\sigma_{quarter}^2$, σ_{site}^2, σ_{pit20}^2 and σ_{pit5}^2. These variances are the sector, subsector within sector, quarter within subsector, site within quarter, pit20 within site and pit5 within pit20 variance components of the total variance respectively.

According to the model then, the variance of an observation is given by the sum of the variance components, so that

$$\mathrm{Var}\,(Y_{ijklmn}) = \sigma_{sector}^2 + \sigma_{sub}^2 + \sigma_{quarter}^2 + \sigma_{site}^2 + \sigma_{pit20}^2 + \sigma_{pit5}^2$$

To indicate the relative contribution of each level of the design to the variance of an observation, the variance component of each level may be expressed as a percentage of the sum of the variance components.

With no missing values, variance components may be estimated by the technique used by Nortcliff (1978) of equating mean squares (MS) from the analysis of variance (Anova) table with their expected values (Table 5.2).

Table 5.2. Estimating variance components from the Anova table.

Source of variation	df	MS	Expected MS
Between sectors	1	MS_{sector}	$\sigma_{pit5}^2 + 2\sigma_{pit20}^2 + 4\sigma_{site}^2 + 8\sigma_{quarter}^2 + 32\sigma_{subsector}^2 + 64\sigma_{sector}^2$
Between subsectors	2	$MS_{subsector}$	$\sigma_{pit5}^2 + 2\sigma_{pit20}^2 + 4\sigma_{site}^2 + 8\sigma_{quarter}^2 + 32\sigma_{subsector}^2$
Between quarters within subsectors	12	$MS_{quarter}$	$\sigma_{pit5}^2 + 2\sigma_{pit20}^2 + 4\sigma_{site}^2 + 8\sigma_{quarter}^2$
Between sites within quarters	16	MS_{site}	$\sigma_{pit5}^2 + 2\sigma_{pit20}^2 + 4\sigma_{site}^2$
Between pit20 s within sites	32	MS_{pit20}	$\sigma_{pit5}^2 + 2\sigma_{pit20}^2$
Between pit5 s within pit20 s	64	MS_{pit5}	σ_{pit5}^2
TOTAL	127		

The mean for a land unit is then:

$$\bar{Y} = \Sigma_i \Sigma_j \Sigma_k \Sigma_l \Sigma_m \Sigma_n \Sigma_{ijklmn} / 128$$

and the variance:

$$\begin{aligned} var(\bar{Y}) &= \sigma_{pit5}^2 + 2\sigma_{pit20}^2 + 4\sigma_{site}^2 + 8\sigma_{quarter}^2 + 32\sigma_{subsector}^2 + 64\sigma_{sector}^2 /128 \\ &= MS_{sector}/128 \end{aligned}$$

The 100.(1 - α)% confidence interval for the mean is:

$$\bar{Y} \pm t_{\alpha}(1).\sqrt{var(\bar{Y})} \quad \text{(df for t is as for } MS_{sector}\text{)}$$

and the coefficient of variation (CV):

$$CV(\%) = 100.MS_{sector}/(\bar{Y})$$

When MS_{sector} is large, then the coefficient of variation will be large and as a consequence the confidence interval for the mean also becomes large. As Table 5.2 shows, MS_{sector} is a weighted sum of all of the variance components, with the greatest weighting coefficient, (64), applied at the sector level, and correspondingly lower coefficients at lower levels of the table. Therefore, the higher the level at which variation occurs, the greater the effect on the CV and the confidence interval for the mean, so that when variance components at the higher levels are large relative to the lower levels, coefficients of variation will be large and confidence intervals wide. Confidence intervals are also determined by t for the respective number of degrees of freedom, and in this study, where only two sectors have been sampled from each land unit, the resulting one degree of freedom leads to very wide confidence intervals for the standard levels of confidence (95%). For this reason, confidence intervals were calculated for the 80% level.

There were missing values in the data, principally because of the presence of sheet limestone and boulder calcrete throughout the surveyed area (There were 89, 110, 127, 114 and 124 observations at Cungena, Nunjikompita, Minnipa-Wudinna, Penong and Buckleboo respectively, rather than the 128 planned). Therefore, the normal method of estimating variance components from mean squares and expected values could not be used legitimately in this study. Instead, variance components were estimated using the residual maximum likelihood technique (Patterson and Thompson 1971) for "unbalanced" data. The programme REML (Scottish Agricultural Statistics Service) was used for this purpose.

Coefficients of variation of mean extractable boron concentrations ranged from 83% and 90% respectively at Nunjikompita and Cungena, (which both represent a single mapping unit as defined by Wetherby (see map) to 297% at Penong (Table 5.3.). Both Cungena and Nunjikompita had similar patterns of variation of boron distribution, with most of the variation occurring at the site level (81.0% and 70.0% respectively), (the mean distance between sites was about 300m). Contributions from higher levels of the design were negligible. For this reason, coefficients of variation for these land units were relatively low.

At Minnipa-Wudinna, approximately equal variation in extractable boron occurred in the subsector (27.6% - mean sampling distance 6.5 km.) and quarter (30.4%) - levels, with smaller components at the lower levels.

At Buckleboo, the major part of the variance (48%) occurred within the subsector level. The remaining variance was evenly divided between quarter, site and pit5 levels.At Penong, a large amount of the total variation occurred at the sector (45.9% - mean sampling distance 20 km) level. The only other major contributor was the subsector level, so that 73.3% of the total variation occurred within the sector and subsector levels.

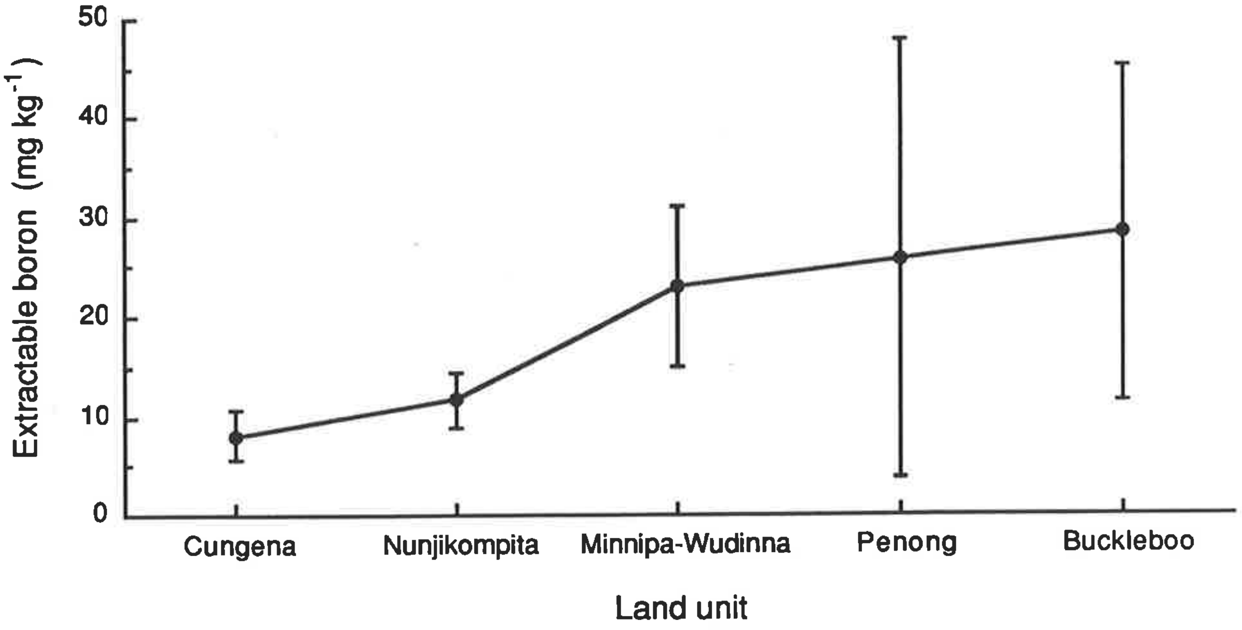
Large coefficients of variation for Penong (297%) and Buckleboo (214%) indicate that mean boron concentrations were estimated by the survey with low precision. As Fig. 5.2 shows, the 80% confidence interval for the mean boron concentration at Penong lies between 3.7 and 47.8 mg kg^{-1} and at Buckleboo between 11.6 and 45.3 mg kg^{-1}.

Assuming that 15 mg kg^{-1} extractable boron indicates a potential toxicity hazard to wheat, it may be inferred from Fig. 5.2 that the soils in the mapping unit represented by Cungena and Nunjikompita are not likely to present a major hazard to wheat production in terms of toxic concentrations of boron, although some areas of toxicity may occur in the Nunjikompita locality. Conversely, the Minnipa-Wudinna unit may be expected to present a widespread hazard to wheat production. A similar conclusion may be drawn from the data for Buckleboo despite the wide confidence interval, with the low limit at 11.6 mg boron kg^{-1}.

At Penong, the range of extractable boron concentrations was wider than in other land units, with some extremely high values and a considerable portion of the range below the concentration likely to be toxic. It is apparent that the Penong unit would require a different survey strategy to assess the boron characteristics of the unit more reliably and precisely.

Table 5.3. Mean extractable boron (mg kg^{-1}) and EC_e (dS m^{-1}) for each of the land units with variance components of the mean and coefficients of variation, CV.

Land unit	Level comp.	Boron Variance comp.	Boron Variance %	Boron Cumulative comp.	EC_e Variance comp.	EC_e Variance %	EC_e Cumulative %
Cungena	6	0.00	0.0	0.0	0.00	0.0	0.0
	5	0.51	2.6	2.6	1.36	13.1	13.1
	4	0.00	0.0	2.6	0.00	0.0	13.1
	3	16.09	81.0	83.6	7.38	71.4	84.5
	2	0.47	2.4	86.0	0.95	9.2	93.7
	1	2.78	14.0	100.0	0.65	6.3	100.0
	Mean	8.15			4.65		
	Variance of mean	0.61			0.49		
	CV (%)	90			143		
Nunjikompita	6	0.00	0.0	0.0	4.11	23.0	23.0
	5	1.33	5.5	5.5	0.85	4.8	27.7
	4	0.00	0.0	5.5	2.33	13.0	40.8
	3	16.80	70.0	75.5	6.69	37.4	78.1
	2	3.63	15.1	90.6	2.53	14.1	92.3
	1	2.25	9.4	100.0	1.38	7.7	100.0
	Mean	11.67			7.29		
	Variance of mean	0.86			2.43		
	CV (%)	83			224		
Minnipa-Wudinna	6	0.00	0.0	0.0	30.66	68.4	68.4
	5	19.92	27.6	27.6	5.46	12.2	80.6
	4	21.92	30.4	58.0	2.07	4.6	85.2
	3	12.00	16.6	74.6	0.64	1.4	86.7
	2	7.72	10.7	85.3	3.99	8.9	95.6
	1	10.59	14.7	100.0	1.98	4.4	100.0
	Mean	23.05			7.43		
	Variance of mean	6.92			16.89		
	CV (%)	129			623		
Penong	6	81.82	45.9	45.9	15.42	21.0	21.0
	5	48.91	27.4	73.3	40.61	55.2	76.2
	4	6.80	3.8	77.1	0.00	0.0	76.2
	3	27.86	15.6	92.7	8.34	11.3	87.5
	2	2.50	1.4	94.1	4.55	6.2	93.7
	1	10.56	5.9	100.0	4.64	6.3	100.0
	Mean	25.73			9.71		
	Variance of mean	51.41			17.39		
	CV (%)	297			459		
Buckleboo	6	0.00	0.0	0.0	0.00	0.0	0.0
	5	107.23	48.0	48.0	0.00	0.0	0.0
	4	39.22	17.6	65.5	0.70	5.5	5.5
	3	35.57	15.9	81.5	6.88	54.6	60.1
	2	10.96	4.9	86.4	2.65	21.1	81.2
	1	30.46	13.6	100.0	2.37	18.8	100.0
	Mean	28.45			8.12		
	Variance of mean	29.92			0.31		
	CV (%)	214			76		



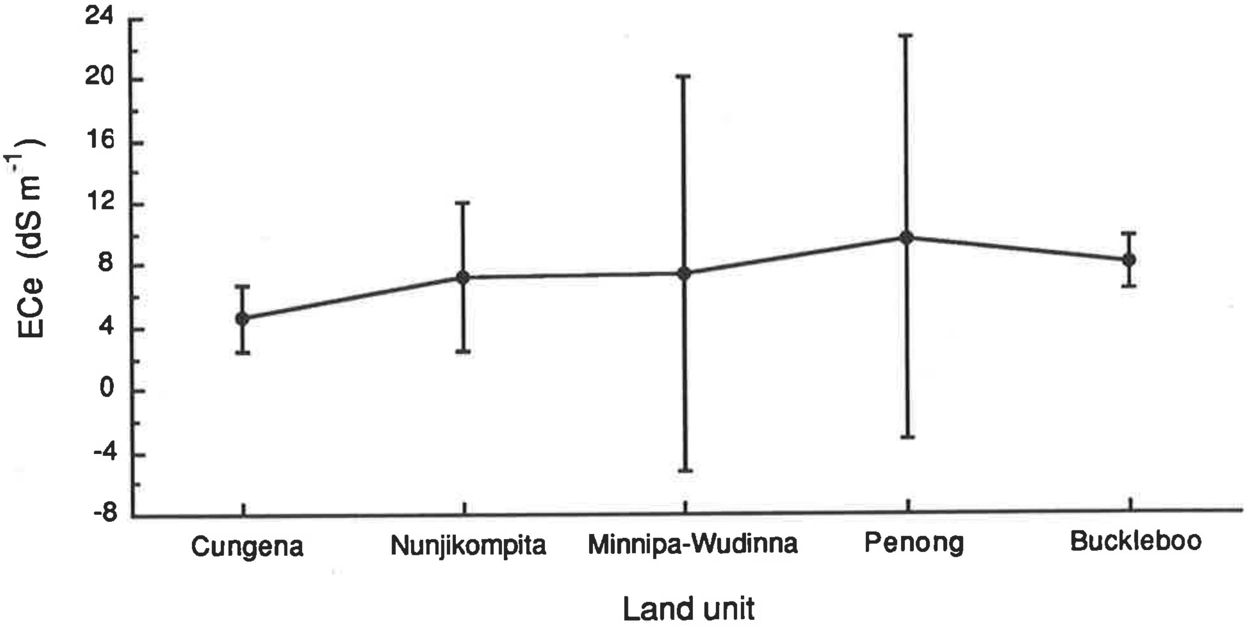


Fig. 5.2 Mean extractable boron and EC_e for each of the land units surveyed. Bars represent the 80% confidence interval about the mean.

Salinity was much more variable than boron in this study. Coefficients of variation ranged from 76% at Buckleboo to 623% at Minnipa-Wudinna. As was the case with boron, salt distribution varied to the greatest extent at the site level at Cungena and Nunjikompita (71.4% and 37.4% respectively) although a considerable proportion of the variance at Nunjikompita was also due to that between sectors (23.0%). Variance at the sector level (68.4%) was also large in the Minnipa-Wudinna unit and in the Penong unit, although in the latter, most of the variation occurred at the subsector level (55.2%). Conversely, at Buckleboo most of the variation occurred a the local scale at sampling distances of 300 m or less, with 94.5% of the total variation occurring at the site, pit20 and pit5 levels.

5.3.2 Relationships between land units with respect to soil boron and EC_e

To compare land units with respect to mean boron and EC_e, each pair of means was compared using a t-test for unequal variances. If $\bar{Y}_M$ is the mean boron concentration or EC_e for Minnipa-Wudinna, and $\bar{Y}_B$ for Buckleboo, and var $(\bar{Y}_M)$ and var $(\bar{Y}_B)$ the variances of the means respectively, then:

$$t = \frac{\bar{Y}_M - \bar{Y}_B}{\sqrt{\text{var}\,(\bar{Y}_M) + \text{var}\,(\bar{Y}_B)}}$$

Var $(\bar{Y}_M)$ and var $(\bar{Y}_B)$ are based on MS_{sector} for Minnipa-Wudinna and Buckleboo respectively. The degrees of freedom for t is a weighted mean integer of the degrees of freedom for the two variances (Snedecor and Cochran 1980).

For the purposes of this survey, a comparison resulting in $P \leq 0.2$ was considered to indicate significant difference between means because of the low number of degrees of freedom used in calculating variances at the MS_{sector} level (Table 5.4).

In general, the Minnipa-Wudinna and Buckleboo units were higher in boron than the Nunjikompita and Cungena units. Although the last two localities represented the same mapping unit, they contained different amounts of boron. However, the difference is of academic interest only since at neither locality were high concentrations of boron a common occurrence. The Penong unit was too variable to be considered different from any other land unit. With respect to differences in EC_e between land units, only Cungena and Buckleboo differed significantly.

Table 5.4. Comparison of mean extractable boron and EC_e for individual land units by the t test for unequal variances.

Land Units	Boron			Salt		
	df	t	P	df	t	P
Cungena x Nunjikompita	2	-2.91	0.10	1	-1.55	NS
Cungena x Minnipa-Wudinna	1	-5.43	0.12	1	-0.67	NS
Cungena x Penong	1	-2.44	NS	1	-1.20	NS
Cungena x Buckleboo	1	-3.67	0.17	2	-3.86	0.06
Nunjikompita x Minnipa-Wudinna	1	-4.08	0.15	1	-0.03	NS
Nunjikompita x Penong	1	-1.95	NS	1	-0.54	NS
Nunjikompita x Buckleboo	1	-3.02	0.20	1	-0.50	NS
Minnipa-Wudinna x Penong	1	-0.35	NS	2	-0.39	NS
Minnipa-Wudinna x Buckleboo	1	-0.89	NS	1	-0.17	NS
Penong x Buckleboo	2	-0.30	NS	1	0.38	NS

NS - Not significant (P>0.2)

5.3.3 Relationships between boron, EC_e and other parameters

In an attempt to assess the diagnostic value of some easily identifiable field characteristics with respect to high concentrations of salt and boron, carbonate layers, field textures, and geological formations were noted at each pit unless observations were not possible because of the presence of sheet calcrete.

The carbonate layers identified in each pit were based on those described by Wetherby and Oades (1975). For the purpose of statistical analysis, carbonate layers were divided into five broad groups based on the proportions of visible calcrete fragments. (Table 5.7).

The geological formations considered in this analysis were limited to the most frequently occurring formations. These were, the Wiabuna Formation (Firman 1978), the Bakara-Ripon calcretes (Firman 1978) and the Blanchetown Clay (Firman 1971).

The geological formations of importance to the arable lands of Eyre Peninsula have been described by Firman (1978) and Wetherby (1973, 1980, 1990, Appendix 5.1). The base stratigraphic layer in the soil profile at Buckleboo and Minnipa-Wudinna is the Blanchetown Clay (equivalent to the Hindmarsh Clay in eastern South Australia) which lies beneath Ripon calcrete. The less indurated Bakara calcrete lies above the Ripon calcrete.

It is considered that the Ripon calcrete formed in the Lower Bridgewater Formation, and the Bakara calcrete in the Upper Bridgewater Formation. The Bridgewater Formation is thought to be of marine-aeolian origin. Overlying the Ripon and Bakara calcretes is the Wiabuna Formation, the principal surface formation on Upper Eyre Peninsula. (The Wiabuna formation is equivalent to the Woorinen Formation in the Murray Basin of South Australia). The Wiabuna Formation is considered to exist in two phases (K.G. Wetherby, pers. comm.) - the reddish phase, found at Penong, Minnipa-Wudinna and Buckleboo, and the calcareous phase, found at Cungena and Nunjikompita. It is considered that the reddish phase of the Wiabuna Formation was derived from inland materials associated with the Ripon and Bakara calcretes and possibly soils related to granitic inselbergs which are a prominent topographical feature of these land units. The calcareous phase may be related to reworking of the Ripon and Bakara calcretes.

Within the Wiabuna Formation was formed a paleosol (or pedoderm) known as the Loveday Soil. Carbonate layers (III A, B, C) appear within the paleosol and are classified according to the degress of calcrete induration. The Wiabuna Formation also occurs independent of the Loveday Soil.

Within the depth of sampling (1.1 m), the Blanchetown Clay was sampled only at Buckleboo where the Ripon-Bakara calcretes were not reported from any of the sampling sites. Other formations, such as Crocker's Loess (Crocker 1946b, Wetherby 1973) or tertiary formations occurred only in occasional pits and in insufficient quantities to allow valid statistical comparisons to be made.

The relation of depth intervals, carbonate layers, geological formations and soil textures to boron and EC_e were examined statistically by one way analyses of variance since these parameters were considered at the "within pit" level and so constituted a lower stratum of the hierarchical design.

Soil sampling at Nunjikompita.

Digging pits for soil sampling at Buckleboo.

Where significant F values were obtained by analysis of variance and Bartlett's test of equal variances showed unequal variances, the two sample t test for unequal variances was used to compare data. In the case of equal variances, least significant differences were calculated for each contrasting pair.

Relationships between soil boron, EC_e and depth.

In each of the land units, soil boron concentrations tended to increase with depth to about 0.8-0.9 m (Table 5.5). The lowest layer (0.4-0.5 m) generally contained less boron than the deeper layers.

Table 5.5. Relationships between mean extractable boron (mg kg^{-1}), EC_e (dS m^{-1}), and depth below soil surface in each land unit.

Depth (m)	Cungena	Nunjikompita	Land unit Minnipa-Wudinna	Penong	Buckleboo
			Boron		
0.4-0.5	5.9a	10.6a	12.8a	20.3a	18.1a
0.6-0.7	8.4b	12.0ab	23.6b	26.7b	27.8b
0.8-0.9	8.7b	12.2b	28.0c	28.8b	33.4c
1.0-1.1	9.5b	12.0b	27.9c	27.1b	34.5c
			EC_e		
0.4-0.5	3.0a	6.6a	6.0a	5.7a	7.3a
0.6-0.7	4.6b	7.1ab	8.1b	9.4b	8.5b
0.8-0.9	5.2b	7.4ab	9.6c	10.6b	8.4b
1.0-1.1	5.9b	8.0b	10.0c	13.3c	8.4b

Within each land unit, values followed by the same letter are not significantly different at $P \leq 0.05$ (one way analysis of variance - two sample t test).

The distribution of EC_e with depth was similar to that of boron. In every land unit some pits had saline subsoils as defined by the United States Salinity Laboratory Staff (1954) ($EC_{e25} < 4$ dS m^{-1}). The 0.4-0.5 m depth intervals were generally less saline ($P \leq 0.05$) than the deeper layers.

Relationships between soil boron, EC_e and geological formations

Significant relationships between geological formations and soil boron concentrations occurred only in the Minnipa-Wudinna and Buckleboo units (Table 5.6.). In the Minnipa-Wudinna unit, the reddish phase of the Wiabuna Formation (Firman 1978) contained significantly more boron ($P \leq 0.05$) than the Ripon-Bakara calcretes (Firman 1978). The Ripon-Bakara calcretes were not observed in the Buckleboo unit where the Blanchetown Clay (Firman 1971) contained more boron than the reddish phase of the Wiabuna Formation ($P \leq 0.05$). Only in the Minnipa-Wudinna and Buckleboo units are geological formations likely to indicate soil horizons which differ significantly in their potential for boron toxicity.

It has been proposed by Wetherby (unpublished) that consistently high (>15mg kg^{-1}) concentrations of boron may be associated with the reddish phase of the Wiabuna Formation and the Blanchetown Clay. The Blanchetown Clay was observed only in the Buckleboo and Minnipa-Wudinna units. In the latter, the Blanchetown Clay was found only below 1.5-2m, but at Buckleboo it was found much closer to the surface, occasionally appearing at the surface. The Blanchetown Clay appears to occur closer to the surface in more elevated portions of the landscape. The mean extractable boron concentration of the Blanchetown Clay was 35.0 mg kg^{-1} and the reddish phase of the Wiabuna Formation 23.3 mg kg^{-1}, supporting Wetherby's hypothesis.

The calcareous phase of the Wiabuna Formation, which was the principal geological formation at Cungena and Nunjikompita, was generally low in extractable boron. However, individual pits were sampled with high extractable boron (e.g. 45 mg kg^{-1}) and EC_e (e.g. 13 dS m^{-1}) for which no explanation can be offered at present.

Differences in EC_e between geological formations occurred only at Nunjikompita where the Wiabuna Formation was significantly less saline ($P \leq 0.05$) than the Ripon-Bakara calcretes and at Buckleboo , where the Wiabuna Formation was more saline than the Blanchetown Clay. While the differences in salinity were statistically significant, the magnitude of the differences was not large.

Table 5.6. Relationships between mean extractable boron (mg kg^{-1}), EC_e (dS m^{-1}), and geological formations in each land unit.

Geological formation	Land unit Cungena	Nunjikompita	Minnipa-Wudinna	Penong	Buckleboo
			Boron		
Wiabuna	8.0a	11.6a	23.6b	25.8a	20.6a
Bakara Ripon	8.7a	12.7a	15.6a	23.1a	-
Blanchetown Clay	-	-	-	-	35.0b
			EC_e		
Wiabuna	4.6a	7.1a	8.3a	9.8a	8.9b
Bakara Ripon	5.0a	9.3b	8.5a	7.9a	-
Blanchetown Clay	-	-	-	-	7.5a

Within each land unit, values followed by the same letter are not significantly different at $P \leq 0.05$ (one way analysis of variance - two sample t test).

Relationships between soil boron, EC_e and carbonate layers

Boron concentrations were not widely different with respect to carbonate layers in the Cungena and Nunjikompita units although some significant ($P \leq 0.05$) differences were recorded (Table 5.7).

In the Penong land unit, although significant differences in boron concentrations occurred between carbonate layers, all layers were relatively high in boron. Higher concentrations occurred in IIIA and IIIB carbonate layers.

Table 5.7. Relationships between mean extractable boron (mg kg^{-1}), EC$_e$ (dS m^{-1}), and carbonate layers in each land unit.

Carbonate[†] layer	Calcrete fragments	Cungena	Nunji-kompita	Land unit Minnipa-Wudinna	Penong	Buckleboo
				Boron		
III A	<30%	8.5ab	12.0ab	25.1a	29.5b	23.2b
III B	30-45%	7.5a	10.8a	19.7b	21.2a	17.5a
III B	45-60%	9.1bc	12.0ab	12.3c	31.0b	17.4a
III C & II	>60%	8.6b	13.0b	15.6c	22.7ab	-
I	-	-	-	-	-	30.3c
				EC$_e$		
III A	<30%	4.7ab	7.3a	10.0a	12.3c	10.0c
III B	30-45%	3.7a	6.2ab	5.3b	6.7a	8.8bc
III B	45-60%	5.7b	8.0ac	4.7bc	10.2bc	7.0ab
III C & II	>60%	5.3b	8.6ac	9.2ac	7.2ab	-
I	-	-	-	-	-	7.3a

[†] See Appendix 1.6 for a description of carbonate layers.

Within each land unit, values followed by the same letter are not significantly different at $P \leq 0.05$ (one way analysis of variance - two sample t test).

In the Minnipa-Wudinna unit, higher boron tended to be associated with less induration. IIIA carbonate layers had significantly more boron than the other layers and similarly, IIIB carbonate layers (30-45% calcrete fragments) had more boron than IIIB carbonate layers with 45-60% calcrete fragments and class IIIC and II carbonates.

The Buckleboo unit alone was characterised by class I carbonate which has "few, if any, visible calcrete fragments" (Wetherby and Oades 1975). Class I carbonate contained more boron than class IIIB (45-60% calcrete fragments), IIIC or II carbonates,which were not different from one another. As with the Minnipa-Wudinna unit, subsoil boron tended to increase in concentration with a decreasing proportion of calcrete fragments. Apart from relationships within individual land units, there were no general relationships between carbonate layers and high boron concentrations common to all land units. In general, the carbonate layers associated with high boron in individual land units tended to exhibit higher EC_e s, although again there were no relationships between carbonate layer and EC_e common to all land units.

Relationships between soil boron, EC_e and texture.

In all but the Minnipa-Wudinna and Buckleboo units, soil textures recorded were limited to the range sandy loams to fine sandy clay loams (Table 5.8). Clays also occurred in the Minnipa-Wudinna and Buckleboo units, where significant ($P \leq 0.05$) differences occurred between boron concentrations in these two texture groups. In both units, the lighter textured group contained less boron than the heavier clays.It should be noted that in the random selection of sampling sites, areas of the siliceous Moomba Sands (Firman 1978, Wetherby 1980) which do occur in these two units and which appear to be generally low in extractable boron, were not represented by chance.

The clays were more saline than the lighter textured soils at Minnipa- Wudinna, but at Buckleboo the clays contained significantly less salt than the coarser textured group.

Table 5.8. Relationships between mean extractable boron (mg kg^{-1}), EC_e (dS m^{-1}), and textural classes in each land unit.

Textural class	Cungena	Nunjikompita	Land unit Minnipa-Wudinna	Penong	Buckleboo
			Boron		
Sands	-	-	-	-	-
Loams	$8.2^{\dagger}$	$11.7^{\dagger}$	22.1a	$25.7^{\dagger}$	21.1a
Clays	-	-	33.0b	-	33.9b
			EC_e		
Sands	-	-	-	-	-
Loams	$4.7^{\dagger}$	$7.3^{\dagger}$	8.0a	$9.7^{\dagger}$	9.2a
Clays	-	-	11.3b	-	7.4b

† Sands and clays were not found at this site.

Within each land unit, values followed by the same letter are not significantly different at $P \leq 0.05$ (one way analysis of variance - two sample t test).

Relationships between Soil boron, EC_e and topography

Each site in the survey was located on a 1:50,000 topographical map and the altitude estimated in metres above sea level. In all land units other than Nunjikompita, the range in metres between the highest and lowest sites was divided into four approximately equal groups. At Nunjikompita, where the terrain was relatively flat, the elevation of all sites was divided into just two classes.

At Penong, Minnipa-Wudinna and Buckleboo, there were significant ($P \leq 0.05$) relationships between extractable boron and altitude above sea level, with extractable boron increasing in the more elevated portions of these land units. At Penong and Buckleboo, extractable boron almost doubled between the lowest and highest areas. For these land units, topographical information (in conjunction with data on geological formations)) may be a particularly useful tool in the prediction of where high boron is likely to occur in the subsoil.

While significant differences between elevation and EC_e were recorded in the same three land units and also at Nunjikompita, EC_e increased with elevation only at Penong and Nunjikompita.

Table 5.9 Relationships between mean extractable subsoil boron (mg kg^{-1}), EC_e (dS m^{-1}), and elevation in the landscape (metres above sea level) within each land unit.

Land Unit	Elevation	Boron	EC_e
Penong	77-86	17.5 a	5.6 a †
	87-95	18.5 a	5.1
	96-104	25.9 b	8.2 b
	105-114	33.3 c	14.4 c
Nunjikompita	46-50	11.9 a	6.9 a
	51-56	11.3 a	8.0 b
Cungena	45-55	7.7 a	4.1 a
	56-65	-	-
	66-75	9.6 a	5.8 a
	76-85	7.6 a	4.7 a
Minnipa-Wudinna	153-165	20.5 a	6.8 ab
	166-178	23.2 bc	10.1 c
	179-191	24.9 cd	7.8 b
	192-203	25.9 bd	5.1 a
Buckleboo	190-218	21.6 a	7.4 a
	219-246	21.0 a	8.1 ab
	247-274	28.2 b	8.7 b
	275-302	41.5 c	7.7 a

† Within any land unit, values followed by the same letter are not significantly different $P \leq 0.05$ (one way analysis of variance - two sample t test).

Conclusions

It may be concluded from the data that within the limits imposed by an 80% confidence interval, most of the soils within the mapping unit comprising Cungena and Nunjikompita do not contain, over a large area, quantities of soil boron which are likely to be hazardous to wheat production. Conversely, the Buckleboo and Minnipa-Wudinna units contain concentrations of boron which are likely to be toxic to wheat over a large proportion of the land unit The wide range of boron concentrations at Penong extended from the nutritionally adequate to the highest values recorded in the survey. Individual pits had boron concentrations in excess of 100 mg kg^{-1}. The data indicate a notable lack of uniformity in the Penong unit. In all land units, the highest concentrations of boron occurred at about 0.8-0.9 m in the subsoil.

Only the Buckleboo unit contained sub-soils which were consistently saline. Otherwise, saline and non saline subsoils occurred to some extent in all units, with some extremely high EC_e s (>10 dS m^{-1}) recorded at Nunjikompita, Minnipa-Wudinna and Penong.

There were no generally universal diagnostic indicators which could be used in the field to separate subsoils which are likely to present a boron or salt hazard to wheat from those which are not. However, within land units, some easily recognised topographical and subsoil features could be useful in recognising where higher concentrations of boron are likely to occur. At Minnipa-Wudinna for instance, elevation in the landscape, the presence of IIIA carbonate layers, the reddish phase of the Wiabuna Formation or subsoils of heavy texture may give such an indication. At Buckleboo, elevation in the landscape, the presence of Blanchetown Clay, class I or IIIA carbonate layers, or subsoils of heavy texture may be useful indicators of higher soil boron. Topographical information may also be of value at Penong in predicting higher soil boron.

With respect to recognising where higher EC_e s may occur in the subsoil, the only indicators which may have some value are likely to be the presence of subsoils of heavy texture at Minnipa-Wudinna and conversely, lighter texture at Buckleboo, where the reddish phase of the Wiabuna Formation is also likely to be more saline than the Blanchetown Clay. Topographical factors may be useful at Penong or Nunjikompita.

The coefficients of variation and confidence intervals for boron or salt data for each unit are calculated from the mean square for the highest level of the design, the "primary sampling unit". It is therefore important that a large number of primary sampling units are included in the design, a problem in the design used in this survey. The width of a confidence interval is partially dependent on the value for t relevant to the number of degrees of freedom for the primary sampling unit, and in this survey, with only two sectors, the high value for t has contributed strongly to the wide confidence intervals.

However, the survey was designed originally to provide as much information as possible about the distribution of boron and salt within the constraints of time and cost where previously there was virtually no information. This objective was achieved as the estimation of the variance components has clearly indicated how more precise estimates of mean boron and salt concentrations may be obtained by concentrating the survey effort at different levels of the sampling strata. Where the largest variance components have been identified, more intense sampling may now be concentrated at the expense of those strata with low or negligible variance components.

The Penong unit may serve as an example in this respect. As table 5.3 shows, almost half of the total variance in soil boron occurred at the sector level. A consideration of the data showed that mean extractable boron concentrations in the two sectors were 18.3 and 32.7 mg kg^{-1}. Based on the data presented here, a more intensive survey of the Penong unit has now been made (B. Hughes, pers. comm.) and it is apparent that the sector containing the higher concentrations of boron (and salt) could be identified by different soil characteristics and to some extent by vegetation. Another distinguishing feature is the common occurrence of bare patches where, particularly in dry seasons, salt rises to the surface and plant life is unable to persist. These patches are known colloquially as "magnesia patches" and the surface soil often exhibits an EC_e in excess of 40 dS m^{-1}. Although the discussion of this is not considered to be within the scope of this chapter, it is of interest that a separate mapping unit has now been identified as a result of the survey.

The land units in this study represent an association of soils which have been grouped together on the basis of landform and geological characteristics. A further source of variation within each unit may be variation in salinity or boron due to differences in soils. No attempt has been made in this discussion to consider this source of variation as it was considered that a detailed examination of soils was beyond the scope of the initial project. However, it is intended that this aspect will be considered in more detail in further studies.

6.0 COMPACTION OF VIRGIN SOIL BY MECHANIZED AGRICULTURE ON UPPER EYRE PENINSULA

6.1 Introduction

In the dryland farming system of southern Australia, normal tillage depth does not reach 0.1 m and soil compaction below that depth is likely to remain unless specifically treated with deep tillage implements. Agricultural machinery with relatively light axle loads may cause serious compaction problems below the depth of normal tillage. Dexter *et al.* (1988) measured soil pressures beneath the wheels of tractors on wet soils at two sites on Upper Eyre Peninsula, South Australia. The pressure beneath the wheels was measured at 0.1 s intervals as the tractor, towing an implement in the "transport" position, was driven on undisturbed soil at a speed of 0.7 m s^{-1}. Significant pressures were transmitted at both sites to depths of at least 0.3 m, on soils that were already considered to be strong.

To assess the cumulative compactive effects of 75 years of agricultural operations, a series of penetrometer resistance measurements were made at the same two sites on Upper Eyre Peninsula as used by Dexter *et al.* (1988) where large areas of virgin soil, never previously subject to wheeled traffic, lie interspersed with cereal cropping areas. Penetrometer resistances were also recorded before and after the passage of wheels on both virgin and cultivated soil.

6.2 Materials and Methods

The soil types at the two sites have been described in the Appendix (1.2 and 1.5). Full details of axle loadings, tyre data and ground pressures for the machinery used in the following experiments are recorded in Chapter 7.

Experiment 1

An area of virgin soil at Minnipa which had not been exposed to grazing domestic animals or to the passage of vehicles was subjected to one and five passages respectively of an International 1486 tractor. Penetrometer resistances were recorded before the passage of the tractor and afterwards in the soil beneath the wheelmark of the front and inner rear wheels. Measurements were taken about 0.5 m apart from opposite sections of the tracked and nontracked areas. Recordings were made at 0.5 m intervals along the wheel track and eight recordings were taken from each section. Soil gravimetric water contents were also measured immediately afterwards at 0.1 m depth intervals to 0.5 m using a 50 mm thin walled tube sampler. There were five replications of soil water measurements.

Experiment 2

In a second experiment, two areas of virgin soil lying adjacent to cultivated areas were selected as 'typical' in terms of soil type, at both Minnipa and Cungena. Twenty recordings were made at random from areas of 10 m x 10 m in the virgin and adjacent cultivated areas, no more than 10 m apart. Soil gravimetric water contents were measured immediately afterwards and were replicated four times. Penetrometer resistances at each depth interval were analysed by the two sample t-test. Only those depth intervals at which there were no missing values were compared. (Missing values occurred where soil strength exceeded the capacity of the penetrometer.) Also, data comparing virgin and cultivated areas are presented only for those instances in which the soil water content of the virgin soil was less than in the corresponding cultivated area. Because soil strength increases rapidly as the soil dries, it was considered that where the virgin soil was drier, a significant reduction in soil strength below that of the cultivated area would in fact be even greater at an equivalent water content.

Penetrometer measurements were made in mid-winter during August, when the soil is wetter than at any other time of the season in this environment.

6.3 Results and Discussion

Experiment 1

Penetrometer resistances measured in the virgin soil before and after the passes of wheels are shown in Figures 6.1 and 6.2.

A single pass of the tractor did not significantly increase soil strength at any depth, ($P \leq 0.05$) (Fig. 6.1), but five passes of the tractor significantly increased soil strength from the surface to 0.27 m (Fig. 6.2). Soil water contents are given in Table 6.1a. Water retention characteristics at three matric potentials (-10 kPa, -100 kPa and -1.5 MPa) determined for the Minnipa soil are shown in Figure 6.3. Soil water potentials in the virgin soil at Minnipa were close to -100 kPa between the surface and 0.3 m but were between -100 kPa and -1.5 MPa below that depth at the time of sampling.

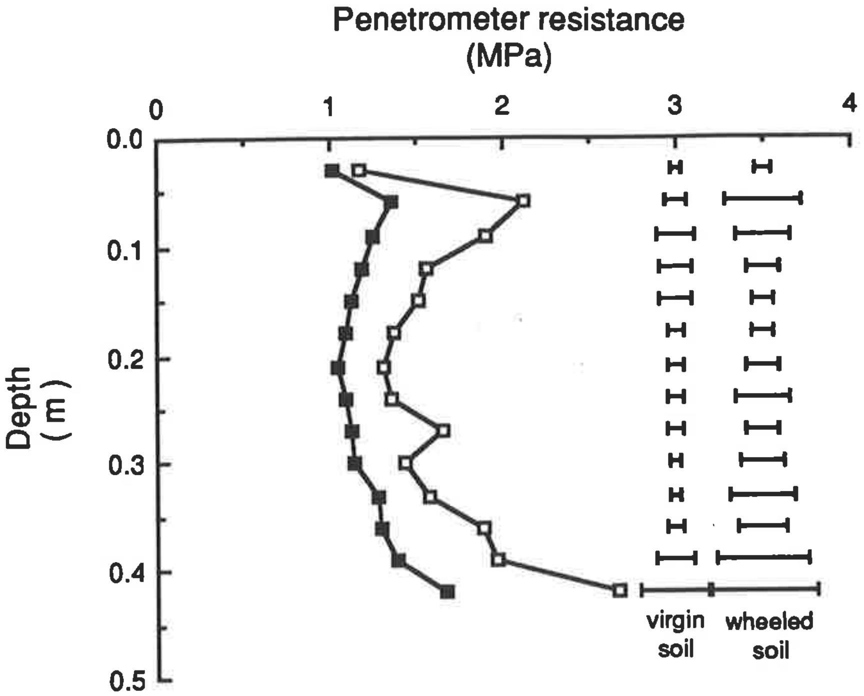


Fig. 6.1. Penetrometer resistance profiles at Minnipa in virgin soil (■) and after one pass of wheels (❑). Error bars show standard errors of the means.

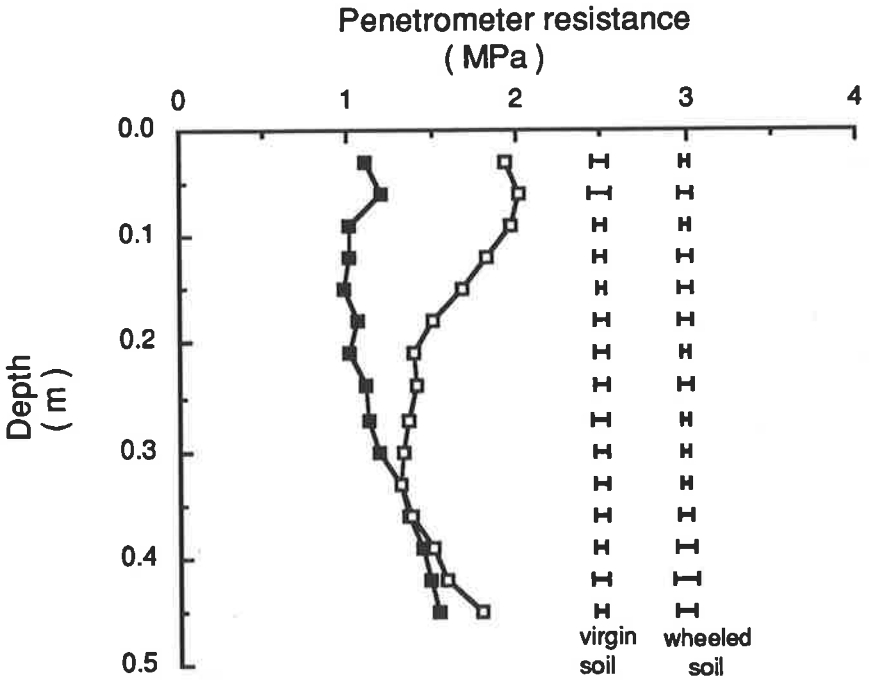


Fig. 6.2. Penetrometer resistance profiles at Minnipa in virgin soil (■) and after five passes of wheels (❑). Error bars show standard errors of means.

Table 6.1. Gravimetric water contents (kg kg^{-1}) at the times of the experiments

(a) Virgin soil at Minnipa

Depth (m)	Water content
0.0-0.1	0.105
0.1-0.2	0.133
0.2-0.3	0.139
0.3-0.4	0.131
0.4-0.5	0.108

(b) Virgin and cultivated soil at Minnipa

Depth	Water content			
	Field N3		Field N6	
(m)	virgin	cultivated	virgin	cultivated
0.0-0.1	0.088	0.100	0.069	0.081
0.1-0.2	0.115	0.123	0.104	0.110
0.2-0.3	0.129	0.138	0.147	0.149
0.3-0.4	0.148	0.159	0.143	0.146
0.4-0.5	0.138	0.144	0.134	0.136

(c) Virgin and cultivated soil at Cungena

Depth	Water content			
	John's field		Gum's field	
(m)	virgin	cultivated	virgin	cultivated
0.0-0.1	0.130	0.128	0.059	0.092
0.1-0.2	0.080	0.155	0.085	0.122
0.2-0.3	0.074	0.125	0.084	0.186
0.3-0.4	0.086	0.098	0.080	0.120
0.4-0.5	0.088	0.093	0.072	0.110

These results indicate that a small number of passes of a medium sized tractor (total mass 7,610 kg) compacted the soil to a considerable depth below the normal depth of tillage in relatively dry soil. In the absence of ameliorative processes such as freezing and thawing, swelling and shrinking, the compaction is likely to remain indefinitely.

Coefficients of variation calculated on the data presented in Figure 6.2 are shown in Figure 6.4. Since variability or spatial heterogeneity of soil properties is synonymous with soil structure (Dexter 1988) these reductions in coefficients of variation potentially indicate a corresponding deterioration of structural stability of the soil.

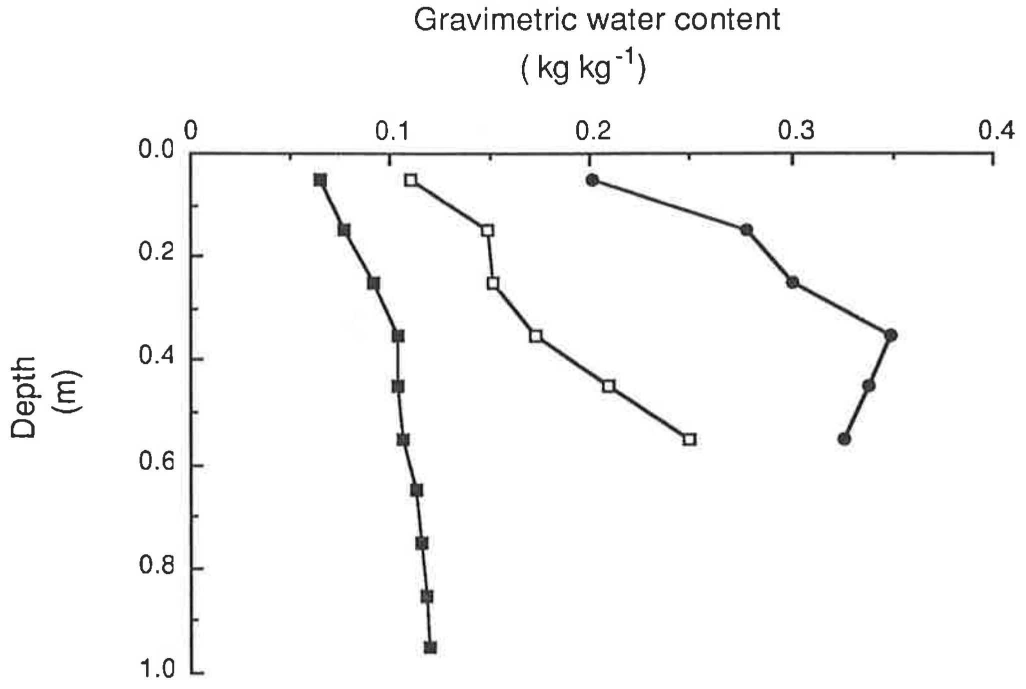


Fig. 6.3. Depth distribution of soil water holding capacities at Minnipa for matric water potentials of -1.5 MPa (■), -100 kPa (□) and -10 kPa (●).

Experiment 2

The areas used for measurement at Minnipa were in open grassy plains within conservation reserves, immediately adjacent to cultivated land, with uniform soil types and topography. Comparative penetrometer measurements are shown in Figures 6.5 and 6.6 Soil water contents are shown in Table 6.2b. Coefficients of variation for the data in Figure 6.6 are shown in Figure 6.7.

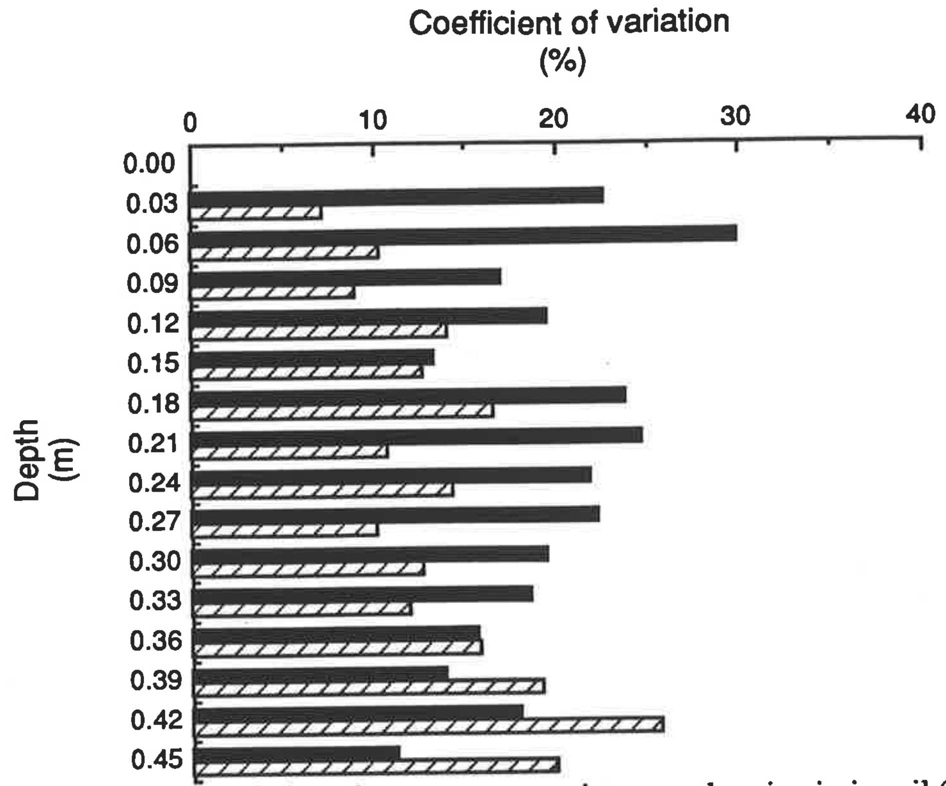


Fig. 6.4. Coefficients of variation of penetrometer resistance values in virgin soil (■) and after five passes of wheels (▨) at Minnipa.

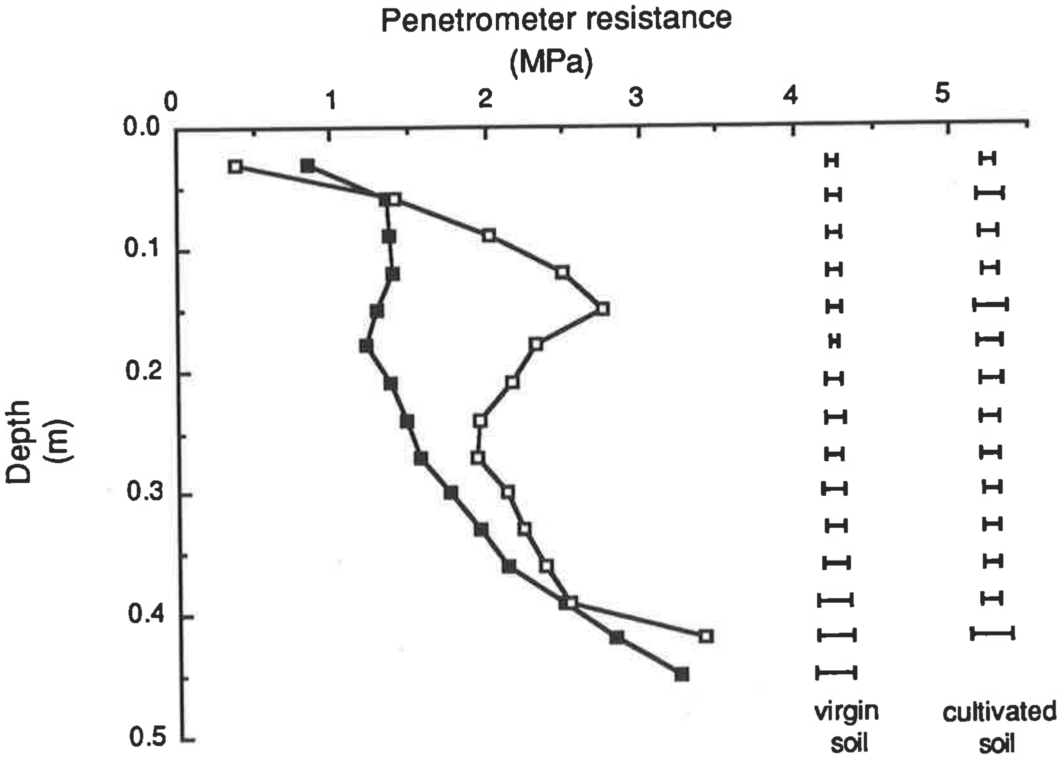


Fig. 6.5. Penetrometer resistance profiles for virgin soil (■) and for an adjacent area of soil regularly cultivated over a period of about 75 years in field N3 at Minnipa (□). Error bars show standard errors of the means.

Soil water contents at a given depth were similar at both sites although at each depth soil in the cultivated area was slightly wetter. The soil water potential in field N3 was close to -100 kPa to 0.4 m and between -1.5 MPa and -100 kPa between 0.4-0.5 m. In field N6, the soil water potential was close to -1.5 MPa in the surface 0.1 m, but was similar to the N3 water profile to 0.5 m. Coefficients of variation for the N6 field site are shown in Figure 6.7.

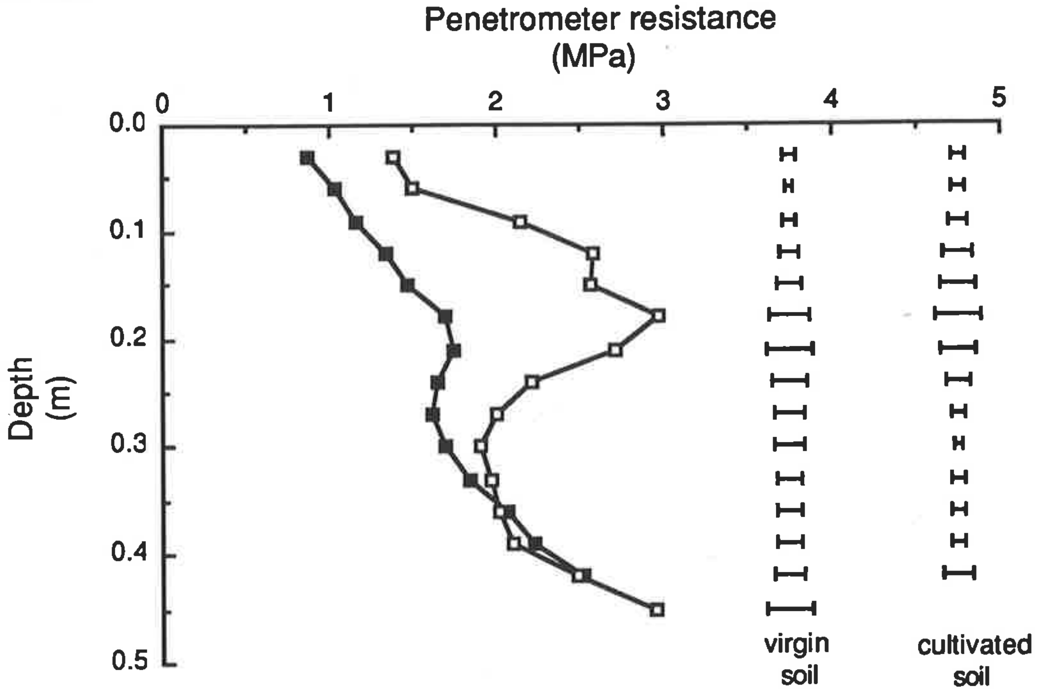


Fig 6.6. Penetrometer resistance profiles for virgin soil (■) and for an adjacent area of soil regularly cultivated over a period of 75 years in field N6 at Minnipa (□). Error bars show standard errors of the means.

The results show that at Minnipa the effect of cultivation was towards significantly increasing soil strength, in one instance (Figure 6.6), to a depth of 0.24 m and in the other (Figure 6.5) to 0.33 m. The penetrometer profiles of the cultivated soils in both fields were similar, with a maximum value at 0.15-0.18 m. The history of agriculture on Eyre Peninsula is relatively short, with the area having been opened for agricultural development only 75 years ago. It is assumed that the compaction process has been insidious, in the absence of ameliorative processes such as freezing and thawing and swelling and shrinking, although the use of machinery with axle loads exceeding 4000 kg began only in the previous decade. However, when the data shown in Figure 6.2 are considered, relatively few passes of a tractor were able to alter the soil strength profile significantly to a considerable depth.

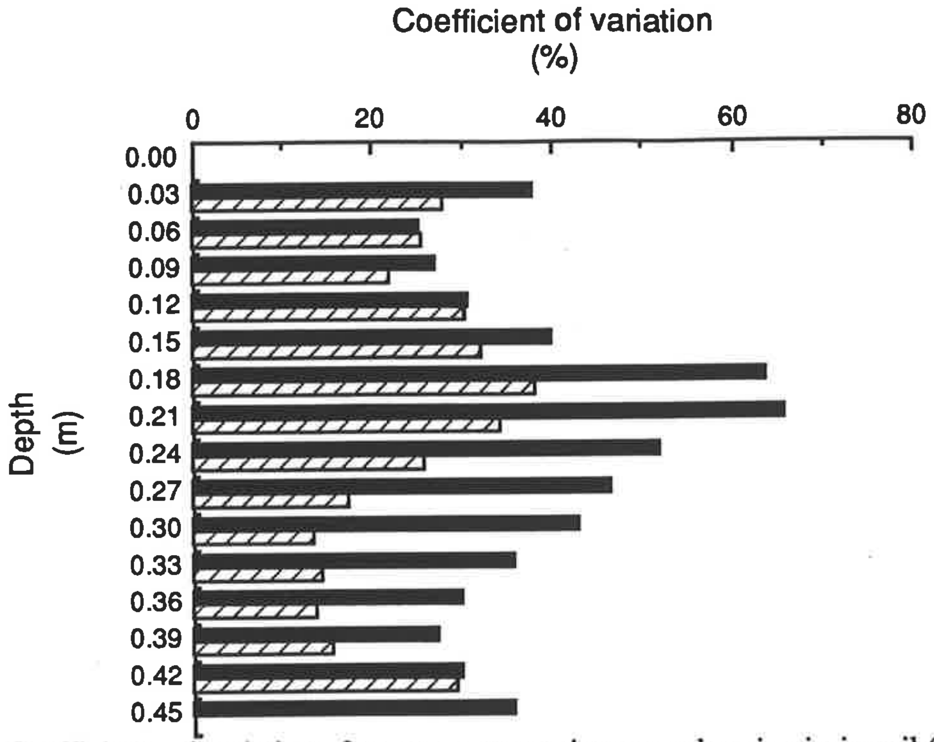


Fig. 6.7. Coefficients of variation of penetrometer resistance values in virgin soil (■) and for an adjacent area of soil regularly cultivated over a period of 75 years in field N6 at Minnipa (▨). CV values were not calculated where missing values occurred.

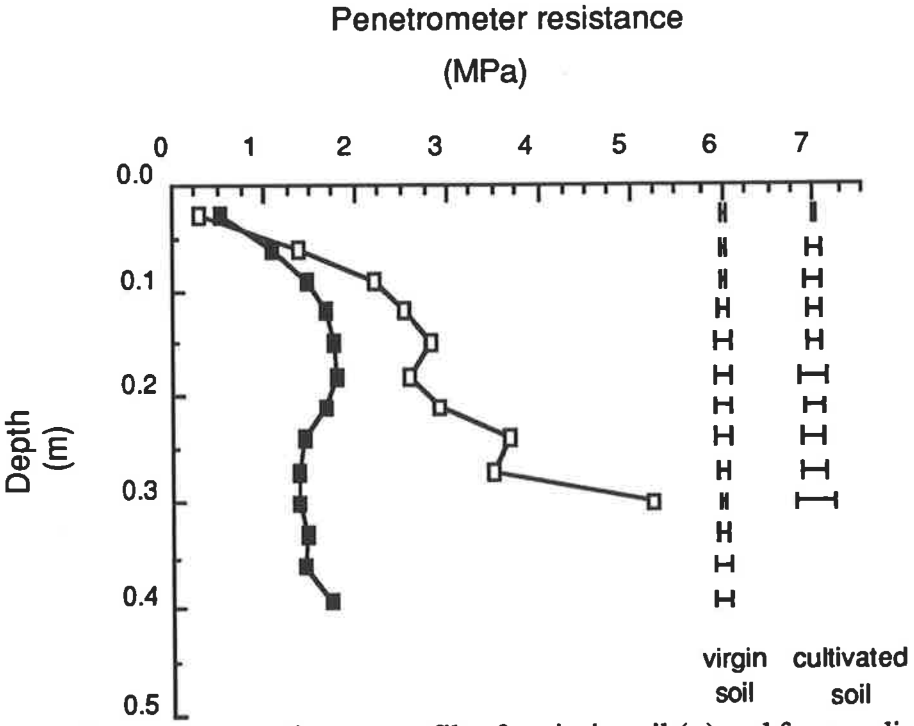


Fig.6.8. Penetrometer resistance profiles for virgin soil (■) and for an adjacent area of soil regularly cultivated over a period of about 70 years in John's field, Cungena (□). Error bars show standard errors of the means.

At Cungena, sites were chosen where uncultivated areas of land occurred within cultivated fields. These areas had been subject to the grazing of sheep. The results of the penetrometer studies are given in Figures 6.8 and 6.9.

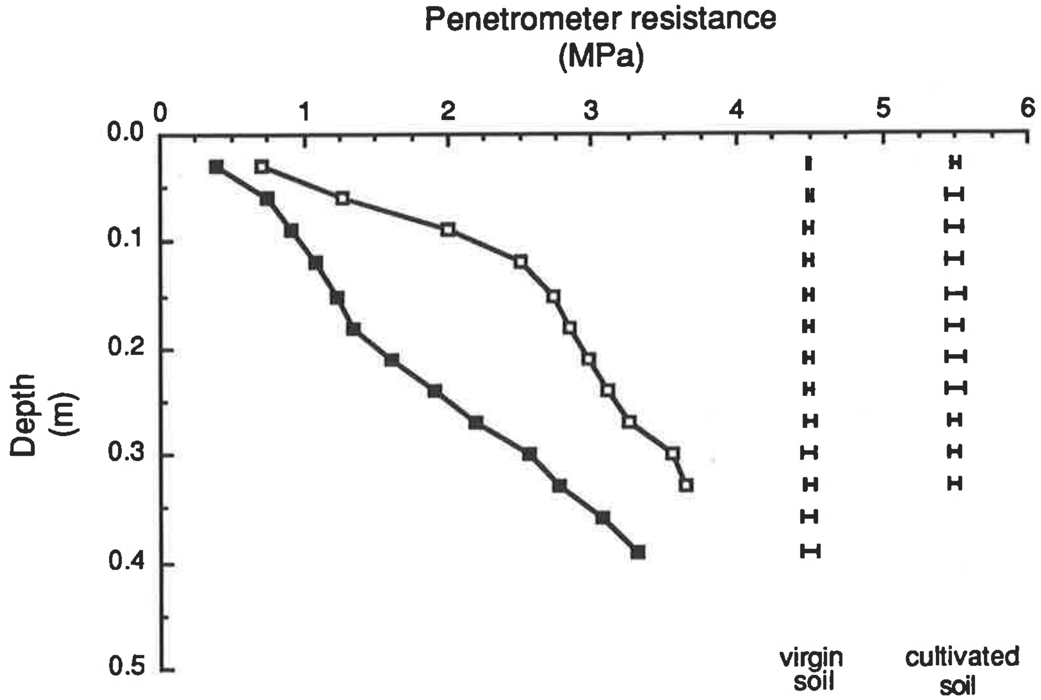


Fig. 6.9. Penetrometer resistance profiles for virgin soil (■) and for an adjacent area of soil regularly cultivated over a period of about 70 years in Gum's field, Cungena (❑). Error bars show standard errors of the means.

In Figure 6.8, the cultivated soil was too strong to allow all 10 attempted penetrations to extend deeper than 0.3 m. Nevertheless, the virgin soil was significantly weaker to that depth at least. The soil was in some instances stronger than the capacity of the instrument in the cultivated soil, and it may be that this difference in strength extended to below the depth to which measurement was possible. In Figure 6.9, the soil in both virgin and cultivated areas became increasingly stronger with depth but the cultivated soil was significantly stronger to 0.33 m at least.

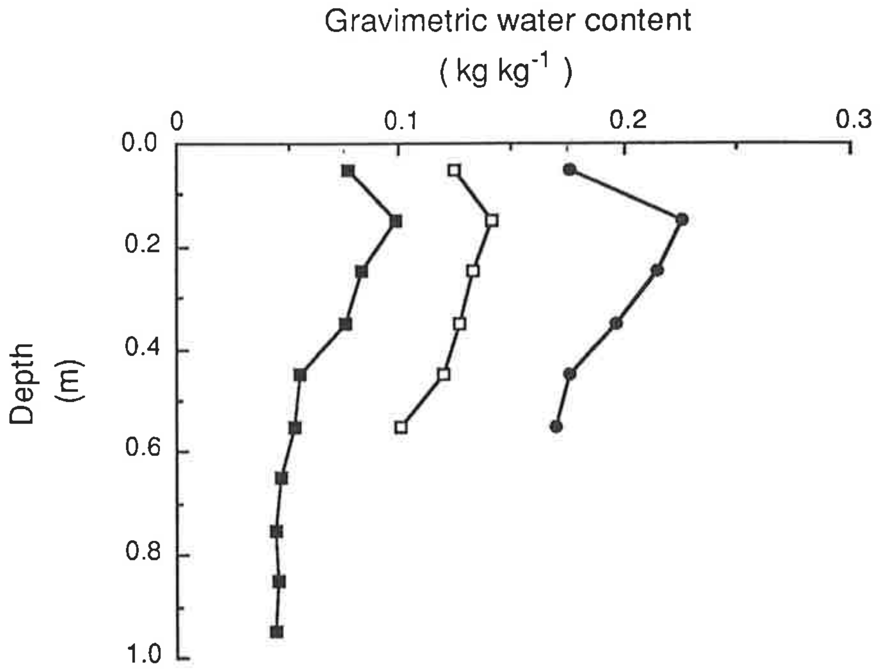


Fig. 6.10. Depth distribution of soil water holding capacities at Cungena for matric water potentials of -1.5 MPa (■), -100 kPa (□) and -10 kPa (●).

A larger tractor had been used at this site than at Minnipa in normal field operations, and although the ground pressures of the rear and front wheels were greater at Minnipa, the Cungena tractor had a much wider wheel track (1.26 m) compared with the Minnipa tractor (0.98 m) and a greater axle loading (7,610 kg total mass at Minnipa, 11,840 kg at Cungena). This suggests that the compactive effect of the Cungena tractor may have extended over a wider area, and deeper into the subsoil. The virgin soil at the site at which the data for Figure 6.9 were collected was quite strong, although the soil was very dry (Table 6.1c), considerably drier than the cultivated field soil. This emphasises the significant differences recorded. Water retention characteristics of the Cungena soil at matric potentials of -10 kPa, -100 kPa and -1.5 MPa for the Cungena sites are shown in Figure 6.10. Soil water at the two fields in the undisturbed soil was at a matric potential of about -1.5 MPa. In the cultivated soils, the matric potential was within the range -10 kPa to -1.5 MPa.

6.4 Conclusions

The data indicate that at both sites, soil which had been subject to farm vehicular traffic had over a period of years become significantly stronger than adjacent virgin soil to a depth of between 0.2 and 0.3 m. Only five passes of a medium sized tractor (7,610 kg) were sufficient, in relatively dry conditions, to increase the strength of virgin soil to a depth of 0.27 m. The reduction in coefficient of variation of soil penetrometer resistance values observed as a result of wheel traffic and arable agriculture indicate a deterioration in soil structure as compared with the virgin soil.

In this marginal cereal growing environment, the cost of continuous deep tillage to reverse the effects of compaction is likely to be prohibitive. The use of controlled traffic techniques should be considered, and certainly, further research is warranted. The properties of the adjacent virgin soils provide important reference soil conditions against which the effects of mechanized agriculture can be compared.

7.0 TRAFFIC INTENSITY ON ARABLE LAND ON UPPER EYRE PENINSULA

7.1 Introduction

Most soil compaction research has been carried out in North America and northern Europe where high proportions of the areas of arable fields are covered every year by the wheels of machines. Soane (1970, 1975) reported that, in Britain, the traditional method of seedbed preparation for cereals resulted in 0.91 of the area being covered by wheels, and in Sweden Eriksson *et al.* (1974) reported that the total area of wheel tracks produced each year in cereal fields may be larger than the area of the field by a ratio of up to five. Håkansson (1985a) measured ratios in the range three to 5.5.

The pattern of the wheel tracks produced is neither random nor organised but depends on the pattern of field working in combination with the wheel spacings of various machines. The wheel spacings of agricultural machines are not standardised and tend to vary over the range of machines used by a given farmer.

Håkansson (1985a) used the term "traffic intensity" to integrate the total amount of field traffic. The annual traffic intensity is obtained by multiplying the mass of each vehicle in tonnes (t) by the distance which it travels (km) per unit area of field (ha) and summing this over all passes of all vehicles over the year. For typical Swedish farms, he obtained values of traffic intensity in the range 110-230 t km ha^{-1}.

In the northern hemisphere, spring sowing of crops occurs when the soil is at field capacity after the previous winter, and harvest often takes place in autumn when the soil is becoming wet as winter approaches. Harvest is often followed by ploughing and the sowing of winter cereals. The majority of potentially compactive machinery operations then, occur when the soil is moist, and more susceptible to compaction.

In the drier cereal growing areas of southern Australia, seedbed preparation and sowing occur when only the upper part of the soil profile has been wet by autumn rains. The depth of wet soil at sowing tends to decrease as the cereal growing areas become more marginal. Harvest usually takes place on hard, dry soil. Crop spraying is the only mechanical operation which takes place when the whole root zone is moist and susceptible to compaction. Even though few operations are performed when the whole soil profile is most susceptible to compaction, it is evident that compaction has become a serious impediment to efficient root growth in many areas, possibly because the normal depth of tillage is comparatively shallow. The types and amounts of field traffic on two sites in South Australia were quantified.

7.2 Materials and Methods

The sites were chosen on Upper Eyre Peninsula at Minnipa and Cungena.

Farms in this region tend to be large (2000 ha or more), but not all of the area is cropped every year. A survey of 33 farms done by the South Australian Department of Agriculture (Wynter *et al.* 1981) showed an average annual cropped area of 840 ha and an average tractor PTO power of 120 kW. Both of these figures are likely to have increased since 1981. Average field size is about 100 ha.

The farming system at the two properties is typical of that in the region. Fields are cropped about every second year. The other, non-cropped, part of the rotation is a legume-based pasture which is grazed by sheep. Typical rotations are:

wheat-pasture (i.e. a two-year rotation),
wheat-barley-pasture-pasture (i.e. a four-year rotation),
wheat-oats-pasture-pasture (i.e. a four-year rotation), or
wheat-barley-pasture (i.e. a three-year rotation).

For the cropping part of the rotation (i.e. wheat, barley or oats), the sequence of operations is typically as follows:

1) seed-bed preparation (April-May),
2) sowing (May-June, as early as possible),
3) spraying of herbicides:
    i) pre-sowing (preferably in early May) for grass or broad spectrum weed control, and usually incorporated in the soil, and/or
    ii) post-emergence (in June-August) from the 2-leaf stage of the crop up to early tillering;
4) harvest (October-November).

At Minnipa, there are usually two spraying operations (May and July), whereas at Cungena there is usually only one (July).

The pastures are self-sown from the seed reserves remaining in the soil from previous pastures. Ideally, pastures are legume dominant although they often constitute a minor component. Pasture legumes are typically *Medicago* (medic) species (e.g. *Medicago truncatula* at Minnipa and *Medicago littoralis* at Cungena). The seeds of medic have a hard coat, and only a proportion (e.g. 10-25%) of the seed reserves germinate in a given year. Pastures are sprayed in winter or more commonly in spring to reduce the proportion of grasses which can act as hosts for pathogens of cereal crops. The spraying-out of grasses from the pasture phase therefore significantly reduces the carry-over of diseases from one cereal crop to the next. The pastures die during the hot, dry summer. Details of the legume pasture part of the crop rotation have been discussed in detail by Puckridge and French (1983).

7.3 Field working patterns

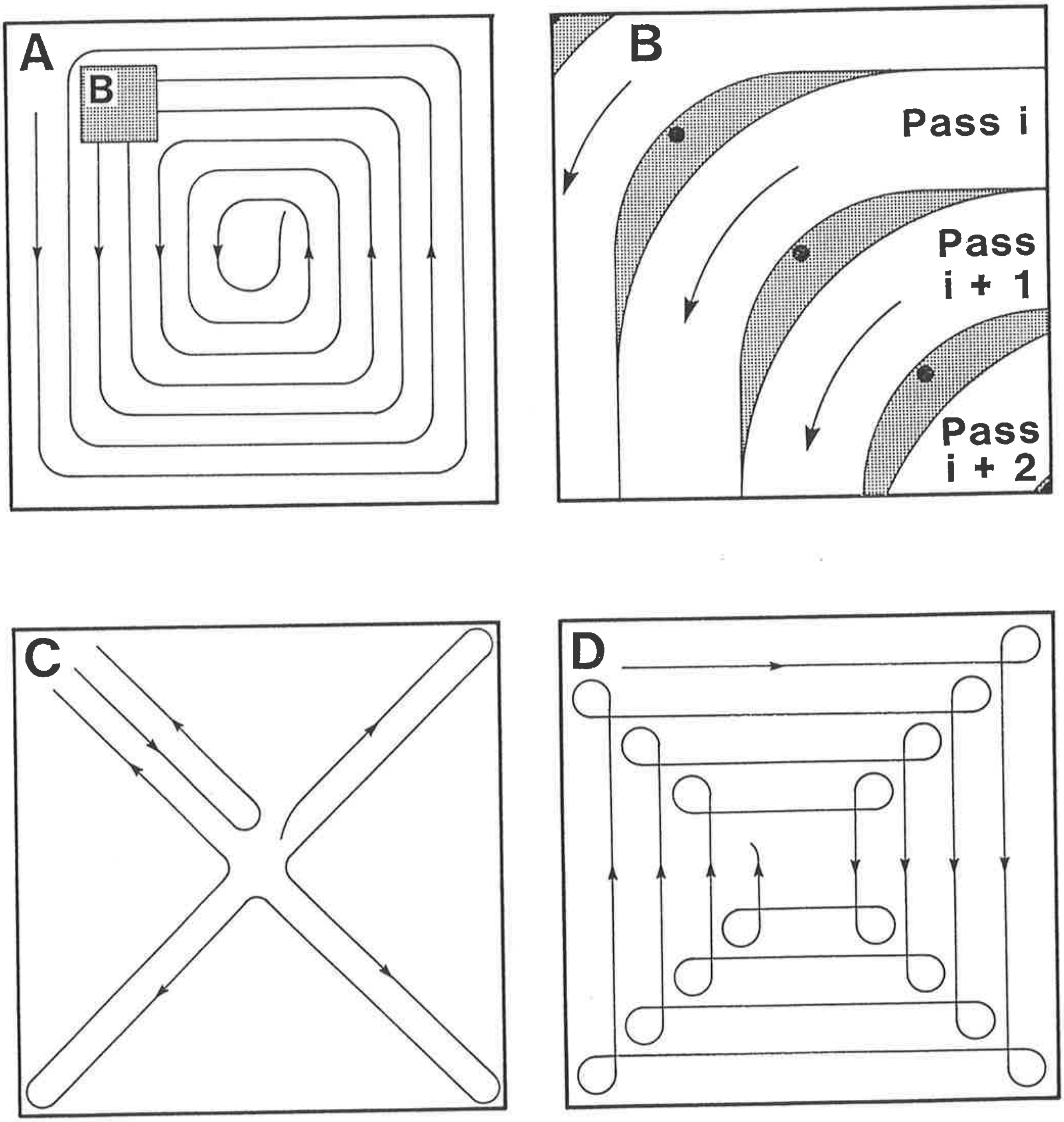
The patterns of field working are shown in Fig.7.1. This figure is not to scale, and more passes are required around a field to cover it than are shown. Also, not shown in Fig.7.1 are the fire breaks. These are required by law to be a vegetation-free strip of at least 2 m width running completely around the edge of each field to prevent the spread of fires.

Tillage and seeding operations are traditionally done anti-clockwise as shown in Fig.7.1A. This practice originated with asymmetrical tillage implements such as mould-board ploughs and disc-ploughs which moved soil from left-to-right (when looking in the direction of travel). Such implements had to travel anti-clockwise so that the untilled soil could be turned into the empty furrow remaining from the previous pass. Nowadays, ploughs are used only infrequently, and the tillage implements most commonly used have symmetrical arrays of tines with symmetrical feet and are known as scarifiers or cultivators. Similar implements fitted with air fans, seed-boxes, metering equipment and seed-tubes are known as airseeders. However, the tradition of anti-clockwise tillage persists.

In negotiating corners, headlands are left untilled or unsown as shown in Fig.7.1.B. When the centre of the field is reached the operator then works a pattern of diagonals as shown in Fig.7.1.C to fill-in these headlands. This practice means that some parts of the field on the diagonals are double tilled and sown at double rates. The normal sowing rate (with a single pass) is 120 plants m^{-2}. Spraying operations also tend to be done anti-clockwise.

Harvesting is done clockwise as shown in Fig.7.1.D. Although many harvesters are symmetrical these days, this tradition follows from the time of horse- or tractor-drawn harvesters. These were generally constructed with the cutter bar on the right-hand-side and had to be pulled by horses or tractors operating on the left on areas which had already been cut.

Fig. 7.1 Typical field working patterns in southern Australia. Tillage and sowing are usually done anti-clockwise around the field (A). This leaves un-tilled and un-seeded headlands (B). Each dot in B near the edge of a pass represents the centre of the turning circle of the previous pass. The remaining headlands are worked along the diagonals (C). Harvesting is usually done clockwise (D).


A
B
B
Pass i
Pass i + 1
Pass i + 2
C
D

During sowing, the truck (or tractor and trailer) carrying seed and fertilizer is parked at suitable places along the diagonal from the corner of the field containing the gate. The hoppers for seed and fertilizer on the sowing equipment are filled as it comes around to that diagonal.

7.4 Characterisation of wheel traffic

The machinery types used at Minnipa and Cungena are given in Tables 7.1 and 7.2. For each machine, these tables give the tyre sizes, ply ratings, inflation pressures, mean contact areas, mean wheel loads, and mean contact pressures.

Contact areas were measured in the field with the machines stationary. Talcum powder was puffed around the tyre-soil interface and then the machine was driven away. A piece of transparent polythene sheet was then placed on the soil surface and the inside boundary of the band of talcum powder was traced around with a felt-tipped pen and was assumed to represent the contact area. The area was measured later in the laboratory with a planimeter.

Mean wheel loads were measured either on a weigh bridge or with portable scales ("TELUB AB" weighing plate model 10T). Mean contact pressures were obtained by dividing the mean wheel loads by the mean contact areas. Maximum contact pressures between wheels and the soil were not measured in this work but were shown previously to be around 1.6 times the mean contact pressure (Dexter *et al.* 1988).

The widths of the wheel tracks in the field are given in Table 7.3. These were measured on the soil surface with a rule after the machines had travelled past.

Table 7.1. Machinery types used at Minnipa with wheel and tyre specifications.

A. *Tractor*: International 1486 (2 wheel drive) (124 kW engine power)

Rear tyres:	Dual:	Inner -	24.5-32	10 Ply	Inflation pressure, 112 kPa
		Outer -	18.4-38	8 Ply	
Front tyres:			11.0-16	8 Ply	Inflation pressure, 280 kPa

Mean contact areas (each wheel)		
Front wheels (seeder hitched to tractor) (each wheel)		0.077 m^2
Rear wheels (each wheel)	Inner	0.29 m^2
	Outer	0.17 m^2
Mean wheel load (each wheel)	Front wheels	8.48 kN
	Rear wheels (Outer plus inner)	28.81 kN
Mean ground contact pressure (each wheel)		
	Front wheels	110.1 kPa
	Rear wheels	62.6 kPa

B. *Airseeder/Scarifier*: Connor Shea Scariseeder 48 row, 8.7 m width

			Inflation pressure
2 x Centre tyres	12.00-24	(10 ply)	300 kPa
2 x Outer tyres	8.25-20	(6 ply)	300 kPa
Mean contact areas		Centre wheels (each)	0.113 m^2
		Outer wheels (each)	0.077 m^2
Mean wheel load (seeder empty)		Centre wheels (each)	18.38 kN
		Outer wheels (each)	5.27 kN
Mean contact pressures		Centre wheel (each)	163.3 kPa
		Outer wheel (each)	68.8 kPa

C. *Harvester:* International 711 self propelled, 5.5 m comb

Front tyres	18.4-26	(12 ply)	280 kPa
Rear tyres	7.5-18	(8 ply)	315 kPa
Mean contact areas		Front wheels (each)	0.179 m^2
		Rear wheels (each)	0.047 m^2
Mean wheel load (empty grain bin)		Front wheels (each)	26.4 kN
		Rear wheels (each)	6.7 kN
Mean contact pressures		Front wheels (each)	147 kPa
		Rear wheels (each)	143 kPa

D. *Boompsray:* Toyota Landcruiser FJ45 Long wheel base, fitted with 1000 L spray tank. Boom width 13.9 m

Mean contact areas	Front wheels (each)	0.056 m^2
	Rear wheels (each)	0.058 m^2
Mean wheel load (tank full)	Front wheels (each)	4.5 kN
	Rear wheels (each)	11.8 kN
Mean contact pressures	Front wheels (each)	80.5 kPa
	Rear wheels (each)	203.6 kPa

Table 7.2. Machinery types used at Cungena with wheel and tyre specifications.

A. *Tractor:* Phoenix 3080 - articulated (4 wheel drive) (228 kW engine power)

Rear tyres	Dual	Inner	24.5-32	10 ply
		Outer	24.5-32	10 ply
Front tyres	Dual	Inner	24.5-32	10 ply
		Outer	24.5-32	10 ply
Inflation pressure		125 kPa - all tyres		
Mean contact area		each wheel	$0.21\ m^2$	

Mean wheel loads (each wheel)

Front wheels	Inner and outer	33.9 kN
Rear wheels	Inner and outer	24.1 kN
Mean ground contact pressure	Front wheels	79.6 kPa
	Rear wheels	56.6 kPa

B1. *Airseeder/Chisel plough:* "Fusion sabreseeder 5550" 15.35 m wide (0.3 m row spacing)

		Inflation pressure
2 Centre tyres (each)	14.9/13-26	350 kPa
2 Outer tyres on centre section each	14.9/13-26	350 kPa
2 Inner tyres on Wings (each)	14.9/13-26	350 kPa
2 Outer tyres on Wings (each)	14.9/13-26	350 kPa

Mean wheel load (each wheel)	2 Centre tyres (each)	21.56 kN
	2 Outer tyres on centre section (each)	18.52 kN
	2 Inner tyres on wings (each)	11.56 kN
	2 Outer tyres on wings (each)	10.19 kN
Mean contact area (all wheels)		$0.07\ m^2$
Mean ground contact pressure	2 Centre tyres (each)	308 kPa
	2 Outer tyres on centre section (each)	265 kPa
	2 Inner tyres on wings (each)	165 kPa
	2 Outer tyres on wings (each)	146 kPa

B2. *Grain hopper of airseeder:* 2 tyres 22.5-26 (10 ply)

Mean contact area (each wheel)	$0.225\ m^2$
Mean wheel load (each wheel)	29.84 kN
Mean ground contact pressure (each wheel)	132.6 kPa

C. *Harvester* as at Minnipa (Table 1)

D. *Boomspray* as at Minnipa (Table 1)

Table 7.3. Widths of wheeltracks made on bare cultivated soil.

	Each front wheel track width (m)		Each rear wheel track width (m)	
Minnipa				
A. Tractor	0.29		0.57	(Inner)
			0.41	(Outer)
B. Airseeder	0.28	(Inner)		
	0.17	(Outer)		
C. Harvester	0.42		0.18	
D. Boomspray	0.22		0.22	
Cungena				
A. Tractor	0.63	(duals)	0.63	(duals)
B1 Airseeder	0.28	(8 wheels)		
B2 Grain hopper	0.55			
C. Harvester	0.42		0.18	
D. Boomspray	0.22		0.22	

The pattern of wheel positions relative to the edge of the field are shown in Figs. 7.2 and 7.3. These show only the pattern within a single width of the widest machine used. The pattern will not repeat towards the centre of the field because the machine widths are not exact multiples of any particular width. In spite of this, the outside 13.9 m at Minnipa and 15.7 m at Cungena has been taken as representative of the traffic over the whole field.

The proportion of the field covered by wheel tracks in a cropping year is shown by the right-hand (black) bars in Figs. 7.2 and 7.3. This amounts to 48.3% at Minnipa and 46.7% at Cungena. Actually, these percentages would be slightly greater in practice because it is unlikely that the wheel tracks would follow each other exactly in the two or three successive tillage and seeding operations which use the same machinery.

The quantity of traffic is summarized in Tables 7.4 and 7.5. These tables show the distance in kilometres travelled by each machine per hectare of field worked. In a cropping year, the total traffic intensities were 60 and 65.2 t km ha^{-1} at Minnipa and Cungena, respectively.

In pasture years of the rotation, when only spraying is done, the total traffic intensity is only 2.4 t km ha^{-1}. Coverage of the soil by the hooves of grazing sheep has not been considered. A typical rotation with 50% cereal cropping and 50% pasture, gives mean annual traffic intensity values of 31.2 t km ha^{-1} at Minnipa and 33.8 t km ha^{-1} at Cungena.

Different parts of a field receive different amounts of traffic. This is illustrated in Table 7.6 where it is shown that, in a cropping year, up to seven wheel passes are possible over a given spot at Minnipa and up to 13 at Cungena. These figures are only approximate estimates because they assume that the wheels will pass in exactly the position calculated. In practice, this does not occur. On and near the field diagonals, the traffic levels are greater. These greater local levels have not been estimated.

The values in Table 7.6 can be used to calculate the total area of wheel tracks per unit area of field in a cropping year. The resulting ratios are 1.42 for Minnipa and 1.88 for Cungena.

The figures in Table 7.6 imply that at Minnipa and Cungena, 51.7% and 53.3% respectively of the field areas receive no wheeling. Whilst this is true in principle, a

Fig. 7.2 Wheel positions relative to the edge of the field at Minnipa. Actually, the "edge of the field" is the inside edge of the firebreak. Figures show mean values of ground contact pressure.

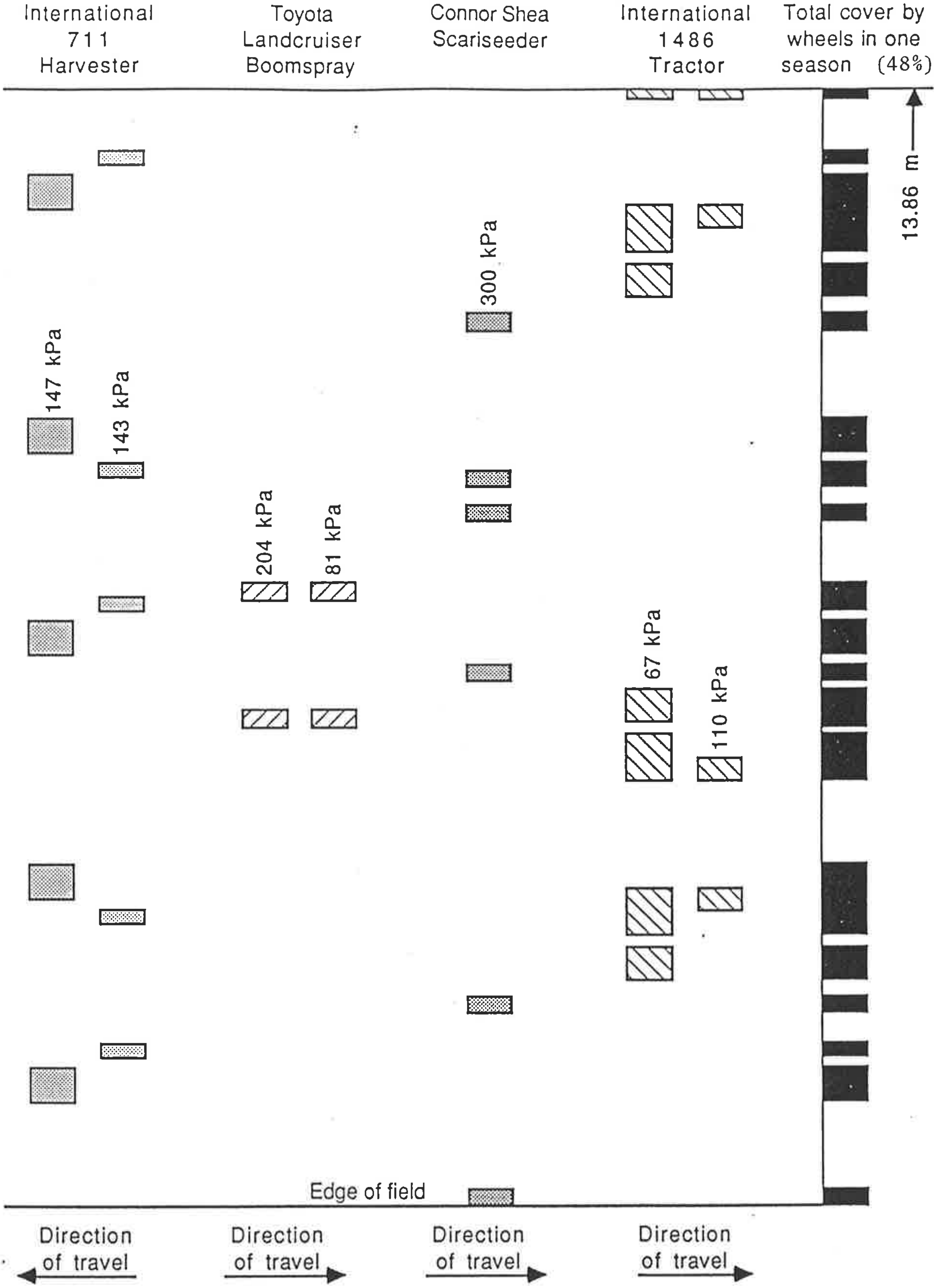
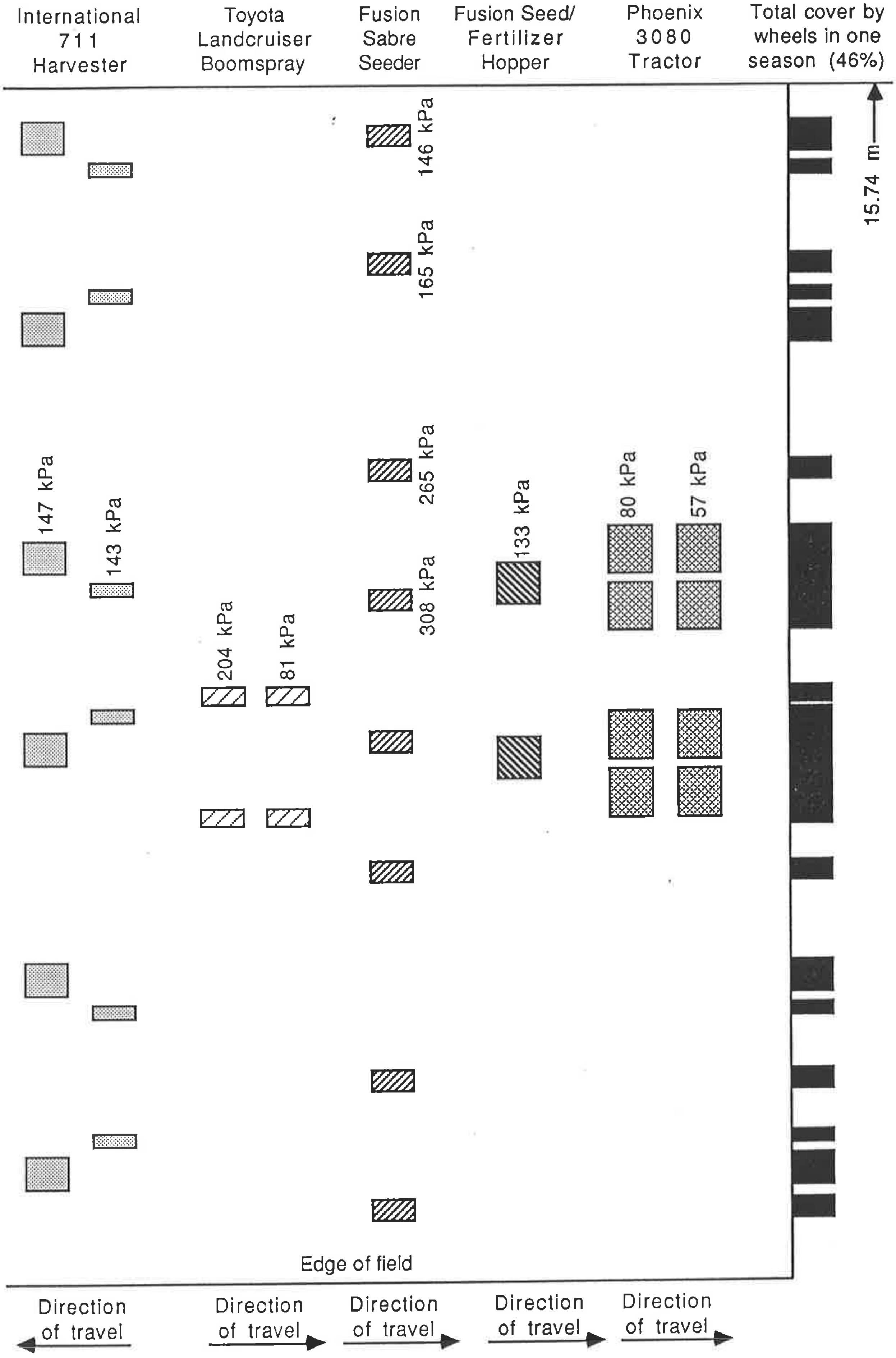

International 711 Harvester
Toyota Landcruiser Boomspray
Connor Shea Scariseeder
International 1486 Tractor
Total cover by wheels in one season (48%)
13.86 m
300 kPa
147 kPa
143 kPa
204 kPa
81 kPa
67 kPa
110 kPa
Edge of field
Direction of travel
Direction of travel
Direction of travel
Direction of travel

Fig. 7.3 Wheel positions relative to the edge of the field at Cungena. Actually, the "edge of the field" is the inside edge of the firebreak. Figures show mean values of ground contact pressure.


International 711 Harvester
Toyota Landcruiser Boomspray
Fusion Sabre Seeder
Fusion Seed/ Fertilizer Hopper
Phoenix 3080 Tractor
Total cover by wheels in one season (46%)
15.74 m
146 kPa
165 kPa
265 kPa
308 kPa
147 kPa
143 kPa
204 kPa
81 kPa
133 kPa
80 kPa
57 kPa
Edge of field
Direction of travel
Direction of travel
Direction of travel
Direction of travel
Direction of travel

number of factors ensure that the whole field area becomes wheeled and compacted over the years. These factors include, slight positional variations with each separate tillage operation, variable width of the firebreaks from year to year, and changes in farm machinery every few years to new models which may have different widths and wheel spacings.

Table 7.4. Traffic intensity at Minnipa (t km ha^{-1}) for one season's operations for a wheat crop.

Operation	Machine	Mass (t)	km ha^{-1}	t km ha^{-1}
1st Scarifying	Tractor	7.610	1.149	14.29
	Scariseeder	4.825		
2nd Scarifying	Tractor	7.610	1.149	14.29
	Scariseeder	4.825		
Seeding	Tractor	7.610	1.149	14.29
	Scariseeder	4.825		
Boomspray (pre-sowing)		3.300	0.722	2.40
(post-sowing)		3.300	0.722	2.40
Harvesting		6.770	1.818	12.31
Total for 1 season				59.98

Table 7.5. Traffic intensity at Cungena (t km ha^{-1}) for one season's operations for a wheat crop.

Operation	Machine	Mass (t)	km ha^{-1}	t km ha^{-1}
1st Scarifying	Tractor	11.84	0.635	15.53
	Chisel Plough	12.62		
2nd Scarifying	Tractor	11.84	0.635	15.53
	Chisel Plough	12.62		
Seeding (including hopper)		30.55	0.635	19.40
Boomspray		3.30	0.722	2.40
Harvesting		6.77	1.818	12.31
Total for 1 season				65.17

Table 7.6. Percentages of the areas of fields at Minnipa and Cungena covered by wheels *n* times in a cropping year.

Number of wheelings, *n*	Minnipa	Cungena
1	17.2	17.3
2	-	-
3	21.4	10.2
4	0.7	2.5
5	-	1.5
6	5.1	7.1
7	3.9	1.8
8	-	-
9	-	1.7
10	-	2.3
11	-	-
12	-	0.8
13	-	1.5
Total coverage (%)	48.3	46.7

7.5 Conclusions

The values obtained from the properties at Minnipa and Cungena do not differ widely, and the mean values may be considered. In a cropping year, the total area of wheel tracks of farm vehicles is equal to 165% of the area of the field but only about 47.5% of the field is actually covered with wheels. In a pasture year only about 3.2% is covered. The average traffic intensity is 62.6 t km ha^{-1} in a cropping year and 2.4 t km ha^{-1} in a pasture year. This gives a mean annual traffic intensity of 32.5 t km ha^{-1}.

These figures indicate that traffic amount and intensity is much lower in the semi-arid, environment of southern Australia than has been reported for Europe. In spite of this, problems associated with soil compaction appear to be increasing steadily (Western Australian Department of Agriculture 1985, Ellington 1986). The effects of compaction are therefore more likely to be due to the absence of mechanisms which tend to undo the effects of compaction than due to abnormally high values of field traffic intensity.

In the areas considered, there is no freezing and thawing of water which could loosen the soil. There is wetting and drying, but the clay contents of the soils are often not high enough to give significant swelling and shrinking. Earthworm activity is very low. Tillage deeper than a few centimetres is not practical in many areas for a variety of reasons. These include: the presence of rocks or tree roots in the sub-soil, the need to avoid bringing undesirable (e.g. sodic) sub-soil to the surface, and also the requirement to keep the seed reserves of the legume pastures in the top few centimetres of soil.

Reducing the amount and intensity of traffic or keeping traffic from the cropped parts of the field would reduce the steady increase in the adverse effects of soil compaction. Ways of achieving this which are being investigated include the use of controlled traffic or fixed (permanent) wheel tracks perhaps with the use of gantries (Taylor 1986, Hilton and Bowler 1986). However, it is difficult to integrate these approaches into systems involving grazed pastures.

Other possible approaches to the problem include the development of improved forms of sub-surface tillage which could be useful in some areas, and the development of "biological tillage". Improvements through biological tillage could involve the introduction of exotic species of earthworms which are more active in dry conditions and/or the use of plants having root systems which are better able to penetrate compacted soil (Elkins *et al.* 1977, Jakobsen and Dexter 1988).

8.0 TILLAGE AND COMPACTION EFFECTS ON SOIL PROPERTIES, ROOT GROWTH AND YIELD OF WHEAT DURING DROUGHT ON UPPER EYRE PENINSULA

8.1 Introduction

The rate of root growth, rooting density and rooting depth are reduced by soil compaction (Greacen *et al.* 1968, Taylor and Ratliff 1969, Russell 1977). These effects tend to be more pronounced in drought (Fiskell *et al.* 1968). In semi arid environments, the ability of the plant to absorb subsoil water is likely to be seriously reduced by the limits to root penetration imposed by soil compaction. However, some compaction may be beneficial in loose soil (Raghavan *et al.* 1979, Ohu and Folorunso 1989). Jakobsen and Dexter (1987) developed a computer model which showed that on already strong sandy loam soils on Upper Eyre Peninsula, wheat yield could increase in some circumstances as soil density increased because the impedance to root growth and water uptake could prevent the early depletion of soil water leading to a greater deficit later in the season.

When treating soil compaction by deep tillage, the aim is to enhance root growth and improve air and water movement through the soil by breaking up the compacted layer without inversion or mixing of the soil layers. However, compaction after deep tillage may induce soil densities equal to or greater than before treatment (Ellington 1986).

Little improvement in root growth may be expected if factors other than mechanical impedance are limiting (Swain 1975). In semi-arid climates, the availability of water in the subsoil may have a large effect in controlling root penetration. Although the supply of soil water may not be improved by the tillage (Ellington 1987), Bennie and Botha (1986) demonstrated an improvement in water use efficiency after deep tillage.

At two sites on Upper Eyre Peninsula, penetrometer data indicate an insidious soil compaction problem below normal tillage depth (Dexter *et al.* 1988). As little information was available concerning the effects of tillage below normal cultivation depth (0.05-0.08m) in the cereal growing areas with less than 350 mm annual rainfall, an experiment was conducted to test the hypothesis that deeper tillage would reduce soil strength, improve the root growth of wheat and alter the soil water regime in the root zone in comparison with tillage to normal depth, thus resulting in yield increases.

In a second experiment, a further hypothesis was tested - viz. that soil tilled below the normal depth of cultivation would, after relatively few passes of a tractor, assume a soil strength equal to or greater than soil tilled to normal depth. As a result, root growth, soil water contents and grain yields would not differ between treatments.

The experiments were conducted on Upper Eyre Peninsula at Minnipa in 1987 and at Cungena in 1987 and 1988. Complete site details are given in the Appendix (1.3, 1.4 and 1.5).

8.2 Tillage experiments

8.2.1 Experimental design and treatments

The experiments had simple randomised block designs with four replicates of three tillage treatments. Tillage was carried out using an "Alfarm 270" chisel plough in soil with a water potential close to the wilting point (-1.5 MPa) to depths of 0.30m, 0.15m or 0.05m (the normal depth of cultivation). The machine had a total width of 2.5m with eight tynes, each 0.05 m wide. Plots were 40 m long at Minnipa and 20 m at Cungena. Treatments were carried out in November, 1986 at Cungena and Minnipa, and in February 1988 at Cungena. The tillage was done in dry soil to reduce the possibility of the operation itself having a compactive effect, which may occur in sandy loam soils sensitive to shear stress (Jakobsen and Greacen 1985).

Table 8.1. Summary of tillage treatments applied at the two sites in 1987 and 1988.

Tillage depth (m)	Minnipa 1987	Cungena 1987	Cungena 1988
0.05 (control)	$M_{87}T_{0.05}$	$C_{87}T_{0.05}$	$C_{88}T_{0.05}$
0.15	$M_{87}T_{0.15}$	$C_{87}T_{0.15}$	$C_{88}T_{0.15}$
0.30	$M_{87}T_{0.30}$	$C_{87}T_{0.30}$	$C_{88}T_{0.30}$

After two further cultivations to normal depth following opening rains, plots were sown at 0.18 m row spacing at Minnipa on 3 June, 1987, and at Cungena on 19 July, 1987 and 10 June, 1988. Plots were sown at Minnipa with the wheat cultivar Aroona and at Cungena with the cultivar Schomburgk at 50 kg ha^{-1}. Basal fertilizer was 15 kg ha^{-1} nitrogen and 10 kg ha^{-1} phosphorus, applied as ammonium sulphate and diammonium phosphate.

8.2.2 Soil measurements

Water retention characteristics were determined for the soil profiles in 1987. For potentials of -100 kPa and -1.5 MPa, samples were dried from saturation on pressure plate apparatus. For water potentials of -10 kPa, samples were drained from saturation on "porosity 4" sintered glass funnels. Gravimetric water contents at the three potentials for the soil profile at Minnipa are shown in Fig. 8.1.a., and for Cungena in Fig. 8.1.b.

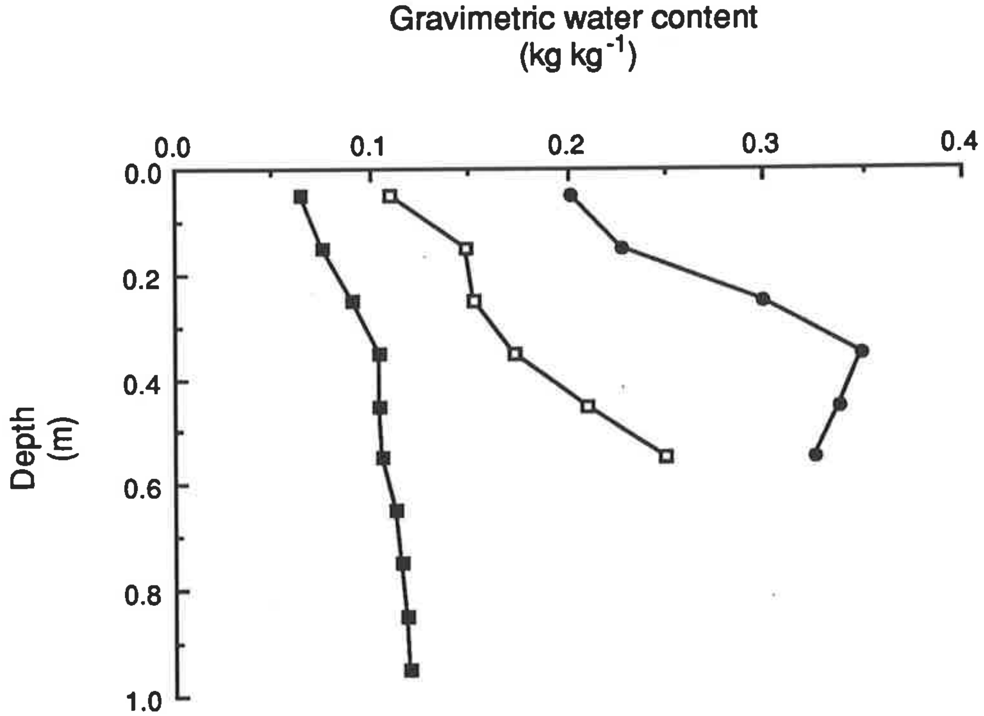


Fig. 8.1.a. Water retention characteristics of the soil profile at Minnipa. Gravimetric water contents are shown for matric water potentials of -1.5 MPa (■), -100 kPa (□) and -10 kPa (●).

At Minnipa in 1987, an hydraulically operated thin walled tube sampler with hardened cutting tip (diameter 50 mm) was used to collect four cores to a depth of 0.6 m at random from a 4 m length at the end of each plot, on 12 July at crop growth stage Feekes 1.3 (Large 1954). Cores were segmented at 0.1 m intervals, bulked, mixed and subsampled to measure gravimetric water contents.

At Cungena, the same procedure was adopted on 11 August, 1987 with the plants at Feekes stage 1, and in 1988 on 19 June, just before emergence.

Penetrometer resistances were recorded at each site immediately after core sampling. A Bush recording penetrometer (Anderson *et al.* 1980) was used. The penetrometer had a cone of 12.6 mm diameter and a total enclosed angle of 30°.

Penetration resistance was measured at 0.03 m depth increments to 0.45 m. Sites for measurement were selected at random and 10 measurements were taken in each plot.

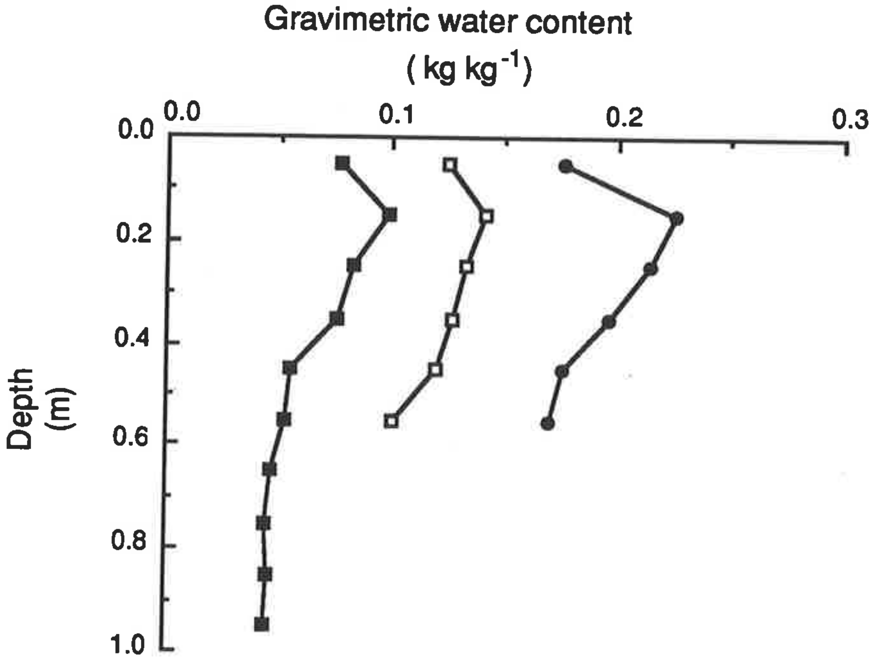


Fig. 8.1.b. Water retention characteristics of the soil profile at Cungena. Gravimetric water contents are shown for matric water potentials of -1.5 MPa (■), -100 kPa (□) and -10 kPa (●).

At Minnipa on 10 October, 1987, (Feekes stage 11.2) six cores to 1 m were taken at random from a 2 m length of plot. Cores were segmented in 0.1 m intervals and bulked for each plot, mixed and sub-sampled for the determination of gravimetric water content and root length density. Root lengths per unit mass of soil were determined on dry samples using a line intersect method (Tennant 1975, Hignett 1976).

At the conclusion of the experiment at Minnipa, a pit was dug at the site and 20 clods taken from each 0.1 m depth interval between 0.3 m and 1 m. Bulk densities were determined using the Saran resin coating method (Brasher *et al.* 1966). These values were compared with bulk densities measured from soil cores taken at anthesis at an adjacent site.

At Cungena at anthesis in both 1987 and 1988, it was not possible to sample the dry sandy soil using a tube sampler, and a method similar to that described by Oussible and Crookston (1987) was adopted. Samples for water content and rooting density determinations were taken by pressing steel cylinders (0.076 in diameter and 0.06 m long) horizontally into the walls of pits dug in the centre of each plot.

Root length density, soil water content and penetrometer resistances at anthesis were determined as at Minnipa, except that at Cungena in 1988, the 0.3-0.4 m, 0.5-0.7 m and 0.8-0.9 m depth intervals were not sampled for roots.

The measurement of bulk density from the tilled layers using the steel cylinders was unsatisfactory and in these experiments, bulk densities were measured only below 0.3 m from a single control plot in separate measurements of four replications.

Grain yields were measured at the conclusion of the season with a small plot harvester (Wintersteiger).

8.2.3 Analysis and treatment of data

Data on gravimetric water content, penetrometer resistance, and root length density were subjected to analysis of variance for the soil profile as a whole and for each 0.1 m depth interval separately.

Because soil strength at depth often exceeded the capacity of the penetrometer (7 MPa), large numbers of missing values occurred particularly at anthesis, with consequent skewing of the distribution of the results. Medians thus were used in preference to means. Where the number of missing values in 10 attempted penetrations at any depth exceeded four, no median was calculated. For cases where there were missing values at some depths but not at others, medians were used at all depths to allow comparison between penetrometer resistances over the entire depth of measurement. Where there were no missing values, coefficients of variation were calculated to indicate the variability. An example is shown in Fig. 8.5.

8.2.4 Results and discussion

Rainfall data for Minnipa (1987) and Cungena (1987 and 1988) are shown in Fig. 8.2.

The 1987 season was a severe drought (annual rainfall was 269 mm at Minnipa and 196 mm at Cungena), although the 1988 season was even drier (163 mm at Cungena).

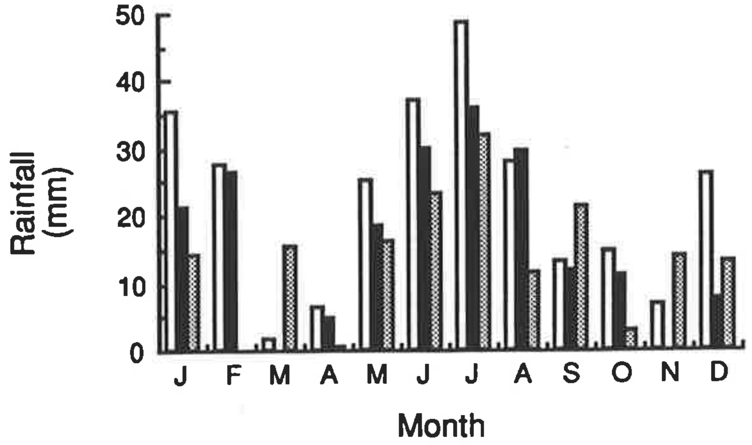


Fig. 8.2. Monthly rainfall at Minnipa in 1987 (□), Cungena in 1987 (■) and Cungena in 1988 (▨).

8.2.4.1 Soil water contents

Minnipa 1987

There were no significant differences in soil water content between treatments at Minnipa in July or on 10 October (when the crop was at the soft dough stage (Feekes 11.2)). (Appendix 8.1, 8.4).

There was a trend in July for the $M_{87}T_{0.30}$ plots to be slightly drier to a depth of 0.6 m while in October the whole soil profile in each treatment was close to the -1.5 MPa water potential.

Cungena 1987, 1988

Soil water data for Cungena in 1987 are shown in Table 8.2.

Table 8.2. Mean gravimetric soil water contents (kg kg^{-1}) on 11 August 1987, at Cungena..

Depth (m)	$C_{87}T_{0.30}$	$C_{87}T_{0.15}$	$C_{87}T_{0.05}$	LSD (0.05)
0.0-0.1	0.144	0.144	0.144	0.007
0.1-0.2	0.161	0.166	0.171	0.014
0.2-0.3	0.152	0.156	0.161	0.010
0.3-0.4	0.141	0.134	0.138	0.012
0.4-0.5	0.105	0.106	0.112	0.009
0.5-0.6	0.078	0.082	0.089	0.008

Table 8.3. Mean gravimetric soil water contents (kg kg^{-1}) at anthesis, 1987 at Cungena.

Depth (m)	$C_{87}T_{0.30}$	$C_{87}T_{0.15}$	$C_{87}T_{0.05}$	LSD (0.05)
0.0-0.1	0.026	0.023	0.019	0.024
0.1-0.2	0.083	0.091	0.097	0.023
0.2-0.3	0.087	0.089	0.089	0.020
0.3-0.4	0.077	0.084	0.093	0.009
0.4-0.5	0.071	0.083	0.087	0.013
0.5-0.6	0.069	0.070	0.080	0.011
0.6-0.7	0.063	0.063	0.069	0.010
0.7-0.8	0.060	0.059	0.063	0.010
0.8-0.9	0.063	0.058	0.064	0.015
0.9-1.0	0.070	0.079	0.067	0.017

The $C_{87}T_{0.30}$ treatment had significantly drier soil than the control at only one depth interval (0.5-0.6 m) although there was a trend for the deeper tilled plots to be slightly drier than the control below 0.1 m. This suggests enhanced, or at least more efficient (in terms of water extraction) root growth (Oussible and Crookston 1987) in the deeper tilled soil. (The possibility of extra water loss over the previous summer from the deeper tilled plots was discounted because soil water measurements taken near sowing in 1988 showed no significant differences between treatments at that time. Appendix 8.2)

Water contents measured at Cungena at anthesis in 1987 are shown in Table 8.3, and in 1988 in Table 8.4.

The $C_{87}T_{0.30}$ treatments were drier than the control from 0.3-0.6 m ($P \leq 0.05$).

Table 8.4. Mean gravimetric soil water contents (kg kg^{-1}) at anthesis, 1988 at Cungena.

Depth (m)	$C_{88}T_{0.30}$	$C_{88}T_{0.15}$	$C_{88}T_{0.05}$	LSD (0.05)
0.0-0.1	0.058	0.069	0.062	0.027
0.1-0.2	0.082	0.097	0.101	0.025
0.2-0.3	0.086	0.099	0.106	0.018
0.3-0.4	0.087	0.094	0.104	0.017
0.4-0.5	0.087	0.088	0.093	0.010
0.5-0.6	0.084	0.084	0.087	0.006
0.6-0.7	0.081	0.079	0.084	0.003
0.7-0.8	0.082	0.078	0.081	0.006
0.8-0.9	0.083	0.080	0.081	0.008
0.9-1.0	0.071	0.083	0.107	0.048

In 1988, a significant difference in water contents ($P \leq 0.05$) occurred between 0.2 and 0.4 m and 0.6 and 0.7 m, although there was a trend for the water content to be less with increasing depth of tillage in the upper 0.7 m of the profile.

8.2.4.2 Penetrometer resistances

Penetrometer resistances of the soil early in the growing season in 1987, are shown as functions of depth and tillage treatments in Figs. 8.3 and 8.4.

Minnipa 1987.

At Minnipa (Fig. 8.3), $M_{87}T_{0.30}$ plots were significantly weaker between 0.12 and 0.27 m compared with the other treatments. Soil in the $M_{87}T_{0.15}$ treatments was not significantly different from the control at any depth within the range of tillage. This may be a function of the narrowness of the tynes and tyne spacing not having been sufficiently close for effective loosening. By anthesis, the soil was so strong that measurements were not possible below 0.12 m (the capacity of the penetrometer was 7 MPa). (Appendix 8.5).

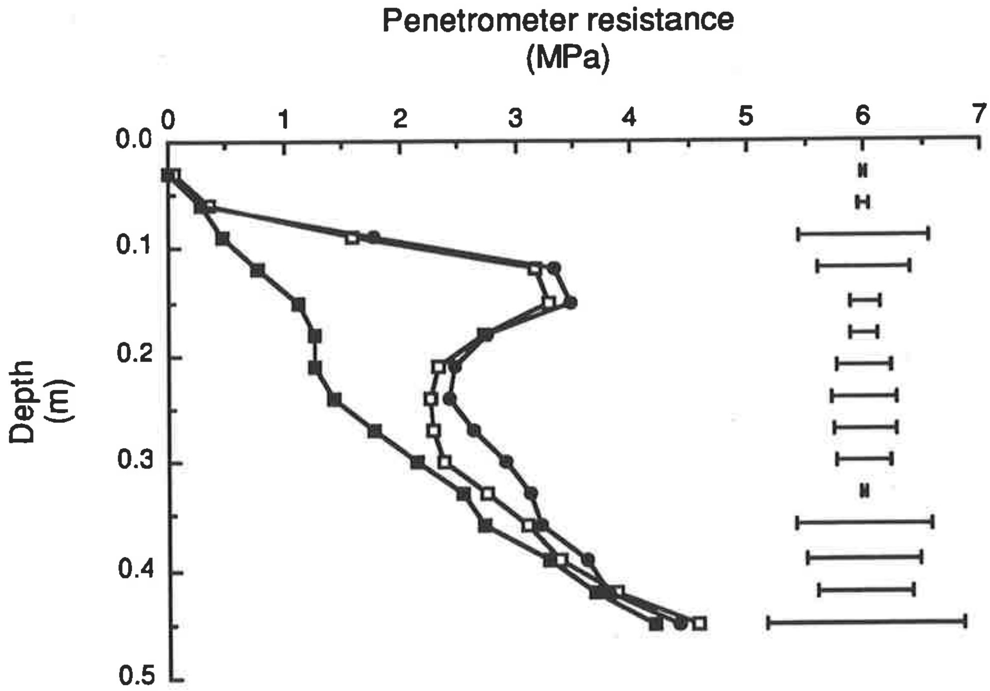


Fig. 8.3. Penetrometer resistance as a function of depth and tillage treatment on 12 July, 1987 at Minnipa. LSD bars at each depth interval are for P=0.05. $M_{87}T_{0.30}$ (■), $M_{87}T_{0.15}$ (□), $M_{87}T_{0.05}$ (●)

Cungena 1987

At Cungena in 1987, tillage significantly weakened the soil from below 0.1 m to approximately tillage depth when penetrometer resistance was measured on 11 August. Coefficients of variation calculated on this data (where no missing values occurred) are shown in Fig. 8.5. At anthesis, strength below 0.06 m was very high even in the deeper

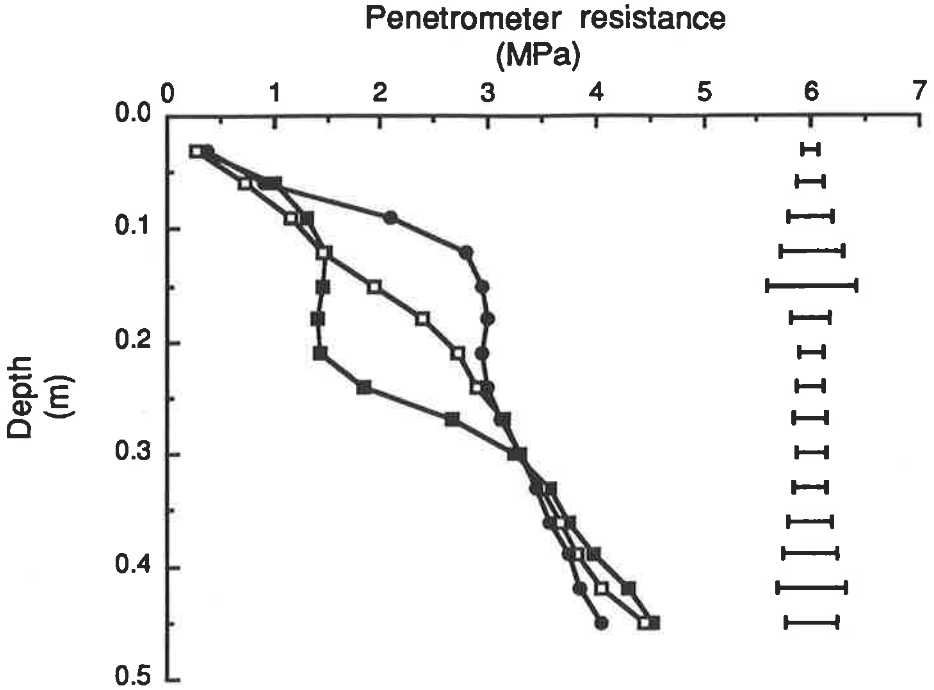


Fig. 8.4. Penetrometer resistance as a function of depth and tillage treatment on 11 August, 1987 at Cungena, LSD bars at each depth interval are for P=0.05. $C_{87}T_{0.30}$ (■), $C_{87}T_{0.15}$ (□), $C_{87}T_{0.05}$ (●).

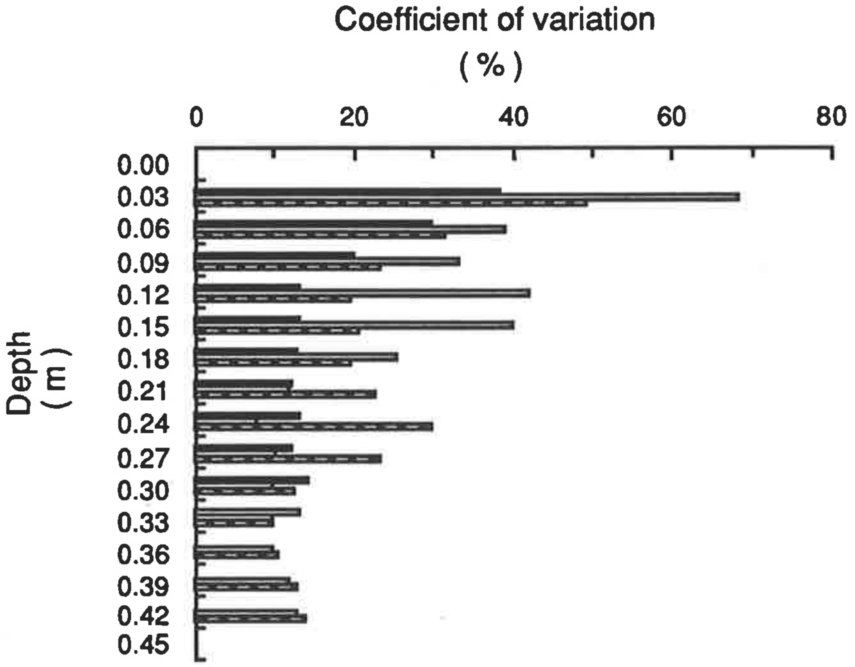


Fig. 8.5. Coefficients of variation of penetrometer resistance values as a function of depth and tillage treatment on 11 August, 1987 at Cungena. CV values were not measured where missing values occurred. $C_{87}T_{0.30}$ (■), $C_{87}T_{0.15}$ (□), $C_{87}T_{0.05}$ (▨).

tilled soil, although the $C_{87}T_{0.30}$ soil remained significantly weaker than the $C_{87}T_{0.05}$ soil between 0.09 and 0.21 m ($P \leq 0.1$). (Appendix 8.6).

Cungena 1988

In 1988, subsoil was so dry on 19 June that significant differences in soil strength ($P \leq 0.05$) occurred only between 0.9 and 0.18 m depth and no recordings at all were possible below 0.30 m. However, the effects of tillage on soil strength were still evident at anthesis (Appendix 8.3, 8.7).

8.2.4.3 Root length density

Minnipa 1987

No significant differences as a result of the treatments occurred at Minnipa except in the 0.6-0.7 m depth interval where the $M_{87}T_{0.15}$ treatment produced slightly more roots than the $M_{87}T_{0.30}$ treatment. The results are shown in Fig. 8.6.

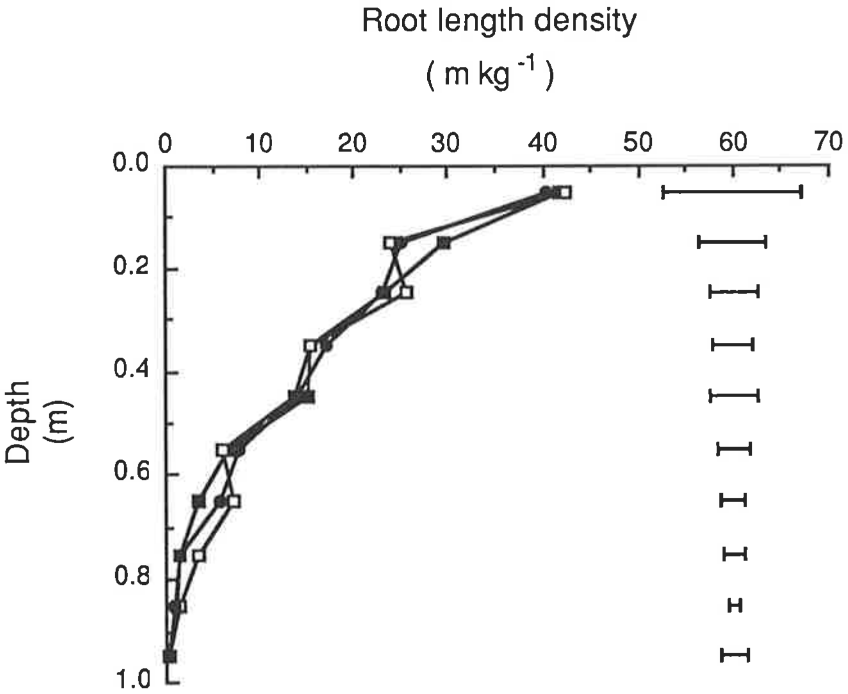


Fig. 8.6. Root length density of wheat as a function of depth and tillage treatment at anthesis, 1987 at Minnipa. LSD bars at each depth interval are for P=0.05. $M_{87}T_{0.30}$ (■), $M_{87}T_{0.15}$ (□), $M_{87}T_{0.05}$ (●).

Cungena 1987

Root length densities for the tillage experiment at Cungena in 1987 are shown in Fig. 8.7. There was a trend for the deeper tilled soil to have more roots than the control between 0.1 and 0.5 m, although a significant difference ($P \leq 0.05$) occurred only at the 0.4-0.5 m depth interval.

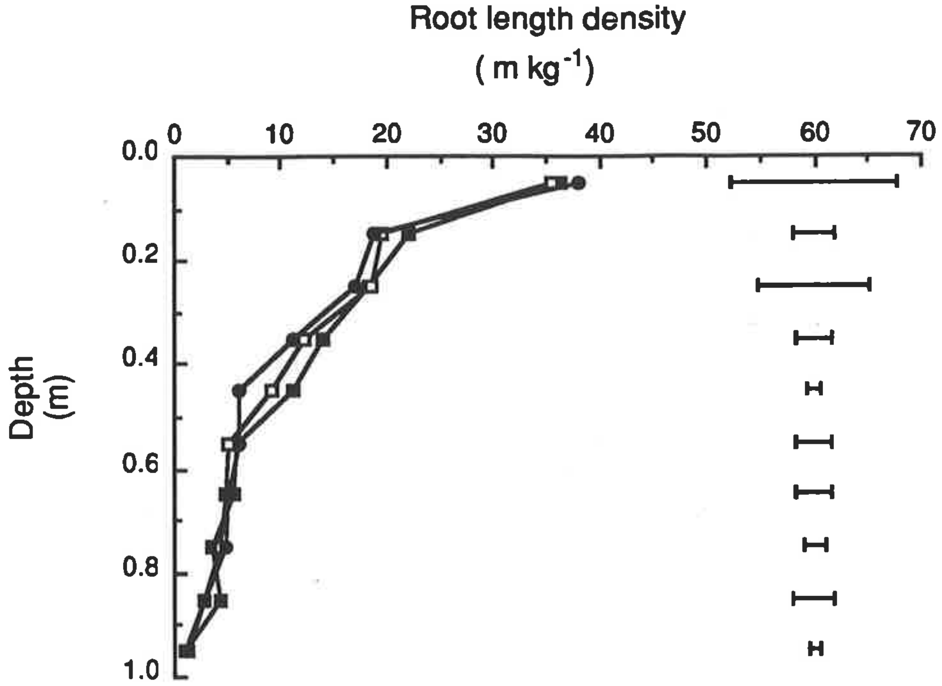


Fig. 8.7. Root length density of wheat as a function of depth and tillage treatment at anthesis, 1987 at Cungena. LSD bars at each depth interval are for P=0.05. $C_{87}T_{0.30}$ (■), $C_{87}T_{0.15}$ (□), $C_{87}T_{0.05}$ (●).

This trend appears to be reflected in the soil water contents at anthesis with the $C_{87}T_{0.30}$ treatment having less water than the control between 0.3 and 0.6 m. (Table 8.3) The increase in mean water extraction from this zone in the $C_{87}T_{0.30}$ plots was 3.2 mm more than the control ($C_{87}T_{0.05}$) during the period 11 August to 17 October. The rainfall in that period was 76.5 mm.

Cungena 1988

At Cungena in 1988, rooting densities were not measured for all depth intervals. Again, a significant difference in rooting density was recorded in the 0.4-0.5 m depth interval, with both deeper tillage treatments having more roots than the control. (Appendix 8.8).

In general, deeper tilled soil tended to be drier between 0.1 and 0.7 m at anthesis than the control soil, although significant differences ($P \leq 0.05$) between $C_{88}T_{0.30}$ and the control soil occurred only in the 0.2-0.4 and 0.6-0.7 m depth intervals.

Rooting depth

Hamblin and Tennant (1987) reported that despite large differences in total root length per unit ground area (L_a) between cereals and grain legumes, water losses from the soil over the growing season were similar. They concluded that maximum rooting depth was better correlated with soil water loss from the profile than with rooting density. They also noted that dead root material from previous crops presented identification problems with current root material and that distinguishing between the two was a greater source of error than was often acknowledged. Similar difficulties were encountered in this experiment.

Forrest *et al.* (1985) conducted a survey of the physical characteristics of important wheat growing soils in eastern Australia and adopted as a criterion for depth of rooting, that depth at which the rooting density fell below 0.5 m kg^{-1}. Using their criterion, all treatments at Minnipa in 1987 had a maximum rooting depth of 0.9-1 m. At Cungena in 1987, all treatments in both experiments had a maximum rooting depth of at least 1 m.

In 1988, maximum rooting depth at Cungena was generally between 0.5 and 0.7 m in all treatments.

8.2.4.4 Bulk density

Bulk densities at each site between 0.3 and 1.0 m are shown in Table 8.5.

Table 8.5. Bulk densities (kg m^{-3}) between 0.3 and 1.0 m.measured at Minnipa 1987 and at Cungena 1987, 1988

Depth (m)	Minnipa 1987		Cungena 1987	Cungena 1988
0.3-0.4	1226	(1400) *	1290	1360
0.4-0.5	1233	(1450)	1330	1410
0.5-0.6	1291	(1420)	1350	1420
0.6-0.7	1308	(1490)	1410	1450
0.7-0.8	1303	(1550)	1440	1360
0.8-0.9	1280	(1550)	1420	1440
0.9-1.0	1319	(1600)	1430	1330

* means in brackets were measured from soil clods (Brasher *et al.* 1966)

Bulk densities measured below 0.3 m from soil cores did not appear to be excessive at any site (Jones 1983).

8.2.4.5 Grain yields

Grain yields for each site and season are shown in Table 8.6. The $C_{87}T_{0.30}$ and $C_{88}T_{0.30}$ treatments produced significantly higher grain yields ($P \leq 0.05$) than the other treatments at Cungena. Grain yields were higher in the deeper tilled soil in 1988 than in 1987. Although 1988 was drier, sowing was possible much earlier in 1988 because of the rainfall distribution, and yields reflect this.

Table 8.6. Grain yields (kg ha^{-1}).

Year	Site	Treatment	Yield
1987	Minnipa	$M_{87}T_{0.30}$	723
		$M_{87}T_{0.15}$	886
		$M_{87}T_{0.05}$	761
		LSD (0.05)	193
	Cungena	$C_{87}T_{0.30}$	330
		$C_{87}T_{0.15}$	263
		$C_{87}T_{0.05}$	285
		LSD (0.05)	43
1988	Cungena	$C_{88}T_{0.30}$	399
		$C_{88}T_{0.15}$	315
		$C_{88}T_{0.05}$	272
		LSD (0.05)	59

8.2.5 General discussion and conclusions

Minnipa 1987

Although tillage with a chisel plough to depths below the normal depth of tillage at Minnipa had no measurable effect on water use, root growth or grain yield, there was a trend for the $M_{87}T_{0.30}$ soil to be slightly drier at all depths to 0.6 m in July. This may have been due to enhanced root growth in the six weeks after sowing. While it is possible for roots to have grown to that depth in the time in ideal conditions, penetrometer resistances in excess of 4 MPa (Fig. 8.3) were measured for all treatments at 0.45 m and sufficient continuous pore space of sufficient size would have been necessary to allow the roots to have penetrated to that depth in six weeks. (Tennant (1976) measured maximum root depths of only 0.15-0.3 m six weeks after sowing in Western Australia.)

It is possible that the comparatively low grain yield in the $M_{87}T_{0.30}$ treatments at Minnipa was caused by rapid early root growth drying out the soil quickly (Ellington 1986), and a lack of adequate following rain. Another possibility is that the greater clay content at depths greater than 0.1 m resulted in a rather cloddy structure in the 0.1-0.3 m depth layer after tillage to 0.3 m. Research in a variety of seasons is needed to test these hypotheses. Soil strength as indicated by a penetrometer was reduced by tillage to 0.3 m, but tillage to 0.15 m did not remove a hard pan below normal tillage depth (0.05 m) - the loosening effect of deeper tillage was not measurable in dry soil at anthesis. Nevertheless, roots were able to penetrate in all treatments to 0.9 m at least. Root data from an earlier experiment at Minnipa were compared with a computer simulated profile (Jakobsen and Dexter 1988) and it was concluded that the field data could only be explained by the roots having found a considerable number of low resistance pathways. In any event, the soil at Minnipa below 0.6 m contained a high concentration of boron and was alkaline-saline (Appendix 1.3) - both parameters likely to affect root growth below that depth (see Chapter 4).

Cungena 1987, 1988

Soil strength was reduced considerably by deeper tillage at Cungena and the effects were still measurable at anthesis. Root growth was enhanced to a small degree below 0.3 m.

A computer model developed by Jakobsen and Dexter (1987) for Cungena in 1987, was used to simulate root growth. The maximum rooting depth without deep tillage, was estimated to be 0.75 m. All plots had a maximum measured rooting depth of at least 1 m, suggesting that roots were able to find low resistance pathways into the subsoil. Tillage to 0.3 m enhanced water extraction by plants and increased grain yield, although the increase in yield in a single season was not sufficient to cover the cost of the operation. (The subsoil at the 1988 site was alkaline-saline (United States Salinity Laboratory Staff 1954) below 0.7 m depth (Appendix 1.5)). Further research is needed to establish the effects of deeper tillage in wetter seasons.

8.3 Recompaction experiments

In the normal course of field operations on the Upper Eyre Peninsula, large tractors with dual wheels may be expected to pass three to four times over approximately the same areas of a field each cropping season. Where treatment of compaction by tillage occurs in late spring or autumn in the pasture phase of the rotation, as it normally would, recompaction may occur in the following few months as the soil is prepared for sowing. The recompaction experiments attempted to simulate this process.

8.3.1 Experimental treatments

The experiments were conducted at Cungena only, in 1987 and 1988. The design and layout were identical to the tillage experiments which were conducted at adjacent sites, but all plots were recompacted just before sowing by four passes of a Phoenix 3080 four wheel drive tractor. The tractor had a mass of 11,800 kg and was fitted with dual wheels. Each wheel was fitted with 24.5 x 32 x 10 ply tyres inflated to 125 kPa. Mean ground contact pressure of the front wheels was 79.6 kPa and of the rear wheels 56.6 kPa. The tractor was driven at about 1.5 m s^{-1}, which is the normal speed of travel for field workings. The width of the dual wheels was equal to the distance between the inner surfaces of the inside wheels so that plots could be completely covered by wheels. A summary of the treatments applied is shown in Table 8.7.

Table 8.7. Summary of treatments applied at Cungena in 1987 and 1988.

Tillage depth before recompaction (m)	1987	1988
0.05 (control)	$C_{87}T_{0.05}R$	$C_{88}T_{0.05}R$
0.15	$C_{87}T_{0.15}R$	$C_{88}T_{0.15}R$
0.30	$C_{87}T_{0.30}R$	$C_{88}T_{0.30}R$

8.3.2 Soil measurements

Soil water content to 0.5 m was measured in 0.1 m intervals (with four replications) at the times of recompaction in 1987 and 1988. Otherwise, the measurements taken were the same as those in the tillage experiments and the same methods of data analyses were employed.

8.3.3 Results and discussion

8.3.3.1 Soil water contents

Cungena 1987

In 1987, the soil water potential at the time of recompaction was close to -100 kPa to a depth of 0.5 m and in 1988, similar to the -1.5 MPa water retention profile below 0.1 m (Appendix 8.16). In the top 0.1 m of soil, the soil water potential was -100 kPa.

Measurements of gravimetric soil water contents taken on 11 August, 1987 (three weeks after sowing), are shown in Table 8.8.

Table 8.8. Mean gravimetric soil water contents (kg kg^{-1}) on 11 August, 1987 at Cungena.

Depth (m)	$C_{87}T_{0.30}R$	$C_{87}T_{0.15}R$	$C_{87}T_{0.05}R$	LSD (0.05)
0.0 - 0.1	0.142	0.142	0.138	0.008
0.1 - 0.2	0.160	0.159	0.164	0.006
0.2 - 0.3	0.144	0.144	0.153	0.008
0.3 - 0.4	0.120	0.127	0.131	0.010
0.4 - 0.5	0.095	0.103	0.106	0.009
0.5 - 0.6	0.072	0.083	0.087	0.009

The significant differences ($P \leq 0.05$) measured between the $C_{87}T_{0.30}R$ and $C_{87}T_{0.05}R$ treatments suggest that the enhanced removal of water from the deeper tilled soil at some depths in the tillage experiment was not affected by recompaction.

Soil water contents at anthesis in 1987 are shown in Table 8.9. Recompaction in 1987 did not appear to affect the uptake of water when the tillage and recompaction experiments are considered, as the water contents in both experiments were similar at anthesis, and the $C_{87}T_{0.30}R$ soil was significantly drier than the $C_{87}T_{0.05}R$ soil in the 0.3 - 0.6 m depth intervals.

Table 8.9. Mean gravimetric soil water contents (kg kg^{-1}) at anthesis, 1987 at Cungena.

Depth (m)	$C_{87}T_{0.30}R$	$C_{87}T_{0.15}R$	$C_{87}T_{0.05}R$	LSD (0.05)
0.0-0.1	0.040	0.040	0.049	0.060
0.1-0.2	0.077	0.081	0.082	0.014
0.2-0.3	0.075	0.088	0.085	0.011
0.3-0.4	0.071	0.091	0.093	0.017
0.4-0.5	0.068	0.083	0.080	0.012
0.5-0.6	0.068	0.077	0.079	0.007
0.6-0.7	0.068	0.070	0.072	0.009
0.7-0.8	0.067	0.063	0.067	0.009
0.8-0.9	0.070	0.060	0.068	0.019
0.9-1.0	0.067	0.062	0.065	0.013

Cungena 1988

In 1988 there were no differences between treatments in soil water contents, whether measured nine days after sowing, on 19 June, or at anthesis (Appendix 8.9, 8.11). However, there were significant reductions in water content at anthesis in some depth intervals in the tillage experiment in 1988 at Cungena.

8.3.3.2 Penetrometer resistances

Cungena 1987

Similar differences in penetrometer resistances between treatments as occurred in the tillage experiments were observed in the recompaction experiments in both 1987 and 1988, but absolute differences were less and the recompacted soil tended to be stronger, suggesting that all treatments were affected by recompaction. However, the deeper tilled treatments were more affected (Fig. 8.8). At depths below 0.39 m, $C_{87}T_{0.30}R$ soil was significantly stronger than the $C_{87}T_{0.05}R$ soil. Because the same trend occurred in the tillage experiment, (Fig. 8.4) it is likely that this is a function of the water status of the soil at this depth interval since the mean water content of the $C_{87}T_{0.30}R$ soil was significantly less ($P \leq 0.05$) than the $C_{87}T_{0.05}R$ soil. It is unlikely that the tractor used for recompaction would have compacted the soil at 0.39 m.

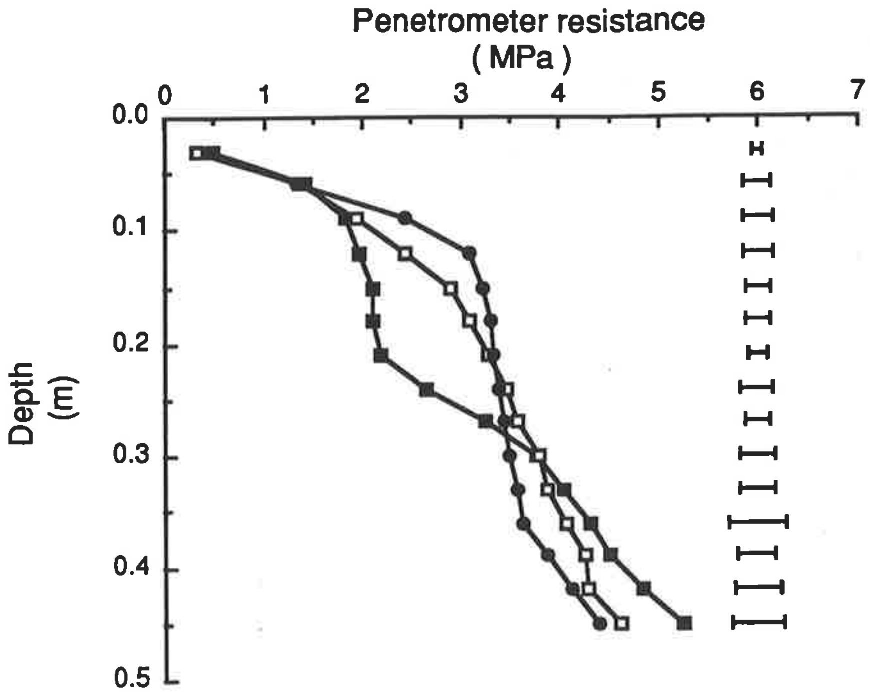


Fig. 8.8. Penetrometer resistance as a function of depth and tillage treatment on 11 August, 1987 at Cungena. LSD bars at each depth interval are for $P=0.05$. $C_{87}T_{0.30}R$ (■), $C_{87}T_{0.15}R$ (□), $C_{87}T_{0.05}R$ (●).

Penetrometer measurements were not possible at anthesis below 0.15 m and there were no significant differences between treatments above this depth (Appendix 8.12). The results indicate a large increase in soil strength over the season .

Cungena 1988

The data for penetrometer resistance measured on 19 June at Cungena are not presented (Appendix 8.10), but no measurements were possible below 0.24 m for any treatment because the soil was too strong. Soil strength changes induced by deeper tillage were not completely reversed by recompaction, although again absolute differences between the deeper tilled soil and the controls appeared to be generally less in the recompacted experiment than in the corresponding tillage experiment. In the 1988 recompaction experiment, the soil was much drier than in 1987 below 0.1 m at the time of recompaction. However, comparison of the penetrometer data (Appendix 8.7, 8.13) between the tillage and recompaction experiments at anthesis suggests that much of the soil loosening effect of the tillage treatments was reversed by recompaction. (Soil water contents between 0.1-0.4 m were actually slightly higher in the $C_{88}T_{0.30}R$ treatment than the $C_{88}T_{0.30}$ treatment at anthesis, (Appendix 8.11, Table 8.4) so soil water content differences do not explain the higher soil strength profile in the former).

8.3.3.3 Root length density

Root length densities were not significantly different between treatments in either year (Appendix 8.15). Maximum rooting depths (Forrest *et al.* 1985) were similar to those attained in the tillage experiments.

8.3.3.4 Grain yields

Grain yields from the recompaction experiments in 1987 and 1988 are shown in Table 8.10.

Table 8.10. Grain yields (kg ha^{-1}).

Year	Treatment	Yield
1987	$C_{87}T_{0.30}R$	338
	$C_{87}T_{0.15}R$	285
	$C_{87}T_{0.05}R$	300
	LSD (0.05)	56
1988	$C_{88}T_{0.30}R$	313
	$C_{88}T_{0.15}R$	280
	$C_{88}T_{0.05}R$	279
	LSD (0.05)	67

There were no significant yield differences between treatments in either year, and it is suggested that the effects of recompaction were able to remove the yield advantage conferred by deeper tillage, even in dry seasons.

8.3.4 General discussion and conclusions

Changes in soil water content at anthesis similar to those produced by deeper tillage in the tillage experiment occurred in the recompaction experiment in 1987. Otherwise, other differences evident in the tillage experiments (e.g. rooting density and grain yields) were not reproduced in the recompaction experiments. Deeper tilled soil appeared to be more susceptible to the effects of recompaction (in terms of increasing soil strength) than control soil. The effect of four passes of wheels of a large (11,800 kg) tractor was to remove the yield benefits induced by tillage to 0.3 m in both years. Research is needed to measure the effects of recompaction in wetter seasons when the soil is more susceptible to compaction. The effects of deeper tillage in this environment are not likely to be lasting under the current tillage systems operating and it appears that alternative approaches such as direct drilling or controlled traffic systems, need to be considered.

The fact that roots were able to penetrate to considerable depths in these soils of high strength suggests the presence of biopores or low resistance pathways. Bulk densities measured below 0.3 m were not excessive and in fact were generally close to values considered by Jones (1983) to be optimal for root growth. This may, in part, account for the ability of roots to penetrate the subsoil, despite high penetrometer resistances.

9.0 GENERAL DISCUSSION

The ability of wheat plants to produce to their potential in a given environment depends on the availability of adequate soil water throughout the growing season. In times of surface drought the availability of water in the subsoil may be critical in maintaining growth rates. In semi-arid environments, root penetration is often a direct function of water penetration (Tennant 1976a). Where roots are prevented from reaching subsoil reserves, yields may be severely reduced (Tennant 1976a). While it is important that roots have access to subsoil reserves, it is also important that rapid root growth to depth does not dry the subsoil too rapidly, inducing a later water deficit at critical growth stages (Passioura 1972, Meyer 1976).

In many parts of Upper Eyre Peninsula, the penetration of wheat roots into subsoils below a depth of 0.5 m is often limited, as many inspections of pit faces over several years have shown. Estimations of the mean wet soil depth (wetting front) at Minnipa and Cungena for instance are about 1.1 and 0.9 m respectively (B. Jakobsen pers. comm.). As a result, not all subsoil water is used by the crop and it is likely that growth and yields are restricted as a consequence.

An adverse chemical environment in the subsoil may affect plant growth either directly by toxic effects on roots or shoots or indirectly by salinity lowering the osmotic potential of the soil water.

The initial field experiment conducted in 1986 was designed to assess the ability of wheat roots to penetrate and extract water from the subsoil in conditions where adequate water was available at the start of the season. Soil strength was reduced considerably by irrigation at the beginning of the season, but even at a matric potential close to -100 kPa, soil strength was likely to have restricted root growth rates to some degree, in the absence of pathways of low mechanical resistance (Dexter 1987, Jakobsen and Dexter 1988). The application of irrigation water increased the maximum rooting depth (Forrest et al. 1985) of wheat from 0.70 to 1.15 m.

A large amount of salt was removed from the irrigated soil between sowing and anthesis. At anthesis the soil water content in both treatments was similar. In 1988, measurements from the experimental area indicated that the previously irrigated soil was still non saline (< 4 dS m^{-1}). The growth of oats on this soil at anthesis was significantly greater in terms of shoot production and the soil was significantly drier below 0.3 m than in the control soil. By harvest more water had been removed from the non-saline subsoil but yields did not differ. Again it is hypothesised that plants which were able to withdraw more water from a non saline subsoil and produce more dry matter were then subject to a critical water deficit after anthesis.

The 1986 data show a greater uptake of boron (as indicated by concentrations of boron in the grain) from the irrigated soil coincident with deeper rooting and higher water use. While irrigated and control plants probably suffered from boron toxicity, it is likely that the irrigated plants were affected to a greater degree. It is interesting to note that the model of Jakobsen and Dexter (1987) predicted a rooting depth of 1.35 m compared with a measured depth of 0.70 m in the control soil. However, the prediction was made in terms of soil physical and water parameters only; possible effects of boron and salinity were not considered in the model.

The initial investigation demonstrated that the growth of wheat at this site was influenced by soil strength, boron and salinity, and further research was undertaken to study the role of each in determining root growth and yield.

The survey of the boron and salinity status of parts of Upper Eyre Peninsula was undertaken to determine the potential hazard to cereals, determine the variability of the distribution of boron and salinity, and examine the possibility of diagnosing high boron and salinity from associated soil factors. The survey was restricted to four of the agriculturally important mapping units and was designed to provide as much information as possible from an extensive area (about 300,000 arable ha) where little information had previously been available.

Of the total area surveyed, it was concluded that about 100,000 ha (the area comprising the Cungena and Nunjikompita land units) were unlikely to present a serious hazard of boron toxicity to wheat, although it is likely that some proportion of the Nunjikompita unit would contain subsoils of sufficiently high extractable boron to reduce the yield of wheat to some degree.

In the remaining 200,000 ha comprising the Penong, Minnipa-Wudinna and Buckleboo land units, boron toxicity could be expected to occur to varying degrees of severity. The latter two units contained consistently high concentrations. The Penong unit contained a wide range of boron concentrations with some extremely high values. Following this survey and analysis of the results, further more detailed work undertaken by B. Hughes (pers. comm.) has resulted in the identification of a distinct and separate land unit.

Salt was more variable than boron and only at Buckleboo were subsoils consistently saline. A more efficient and detailed assessment of salinity could be carried out in the Minnipa-Wudinna, Nunjikompita and Penong units, based on the breakdown of variance components as a guide to where to concentrate the greatest survey effort, and using the rapid field assessment techniques outlined by Rhoades *et al.* (1988 a,b,c, 1990).

Within individual land units, the identification of textural classes, individual carbonate layers and geological formations may be useful in indicating where boron particularly and to some degree salinity, are likely to be hazardous to wheat production. At Penong, Minnipa-Wudinna and Buckleboo, the elevation of the landscape appears to be a useful indicator of where high extractable boron is likely to occur in the subsoil. Many of the elevated areas are distinguished by granitic inselbergs. It is interesting to note that the reddish phase of the Wiabuna Formation appears to be associated with these outcrops, (K. Wetherby, pers. comm.) and that the Blanchetown Clay occurs closer to the surface in the more elevated areas - both of these geological formations tend to contain high concentrations of extractable boron.

Boron and salt at concentrations representative of field values common to Upper Eyre Peninsula were added to subsoil in the pot experiment. The least amount of added boron (20 mg kg^{-1} soil, which corresponded to 13.4 mg $CaCl_2$ extractable boron kg^{-1} soil at the end of the experiment) produced a grain yield equal to 75% of the control, while the highest addition (73 mg boron kg^{-1} soil, which corresponded to 37.6 mg $CaCl_2$ extractable boron kg^{-1} soil at the end of the experiment) yielded only 48% of the control. The effect of boron was greater on grain yield than on total dry weight of shoots. Conversely, added salt had a greater effect on dry weight of shoots than on grain yield. The mean dry weight of shoots at the highest salt treatment (75 mmol$_c$ kg^{-1} soil) was 59% of the control, while the mean dry weight of grain was 69% of the control.

Root growth was significantly affected by both salinity and boron, with boron having the greater effect. At the highest boron addition, few roots penetrated more than 0.1 m into the treated subsoil. All added salt and boron treatments significantly reduced root growth in the basal layer. This has important implications for the ability of plants to use subsoil water in the field, as water use may be related to depth of rooting (Hamblin and Tennant 1987). In wet seasons, plants may be able to obtain sufficient water from the topsoil and upper subsoil to maintain optimum growth, but in dry seasons they may suffer water stress if either salt or boron or both inhibit or even prevent root growth in the lower subsoil. Even where roots do penetrate the lower subsoil the plants may take up larger amounts of potentially toxic ions - as occurred in the 1986 field experiment. In the pot experiment, water use efficiency was significantly reduced by increasing boron, both in terms of total shoot weight and grain yield, with the more pronounced effect on grain yield. Salinity had little effect on the water use efficiency of grain production but increasing salinity progressively reduced water use efficiency in terms of total dry matter.

While this data may not be applied directly to the field, it may be concluded that the presence of boron and salt in the subsoil at concentrations commonly measured in the survey are likely to have a considerable influence in reducing wheat yields. The difficulties in predicting critical values of extractable boron in field soils have been discussed by Cartwright *et al.* (1984). The extent to which yields are limited will be a function of the depth at which maximum concentrations occur, rooting patterns (shallow rooted cultivars may avoid taking up boron from the deeper parts of the subsoil), tolerance of the cultivar and seasonal conditions. There appears to be little value in attempting to increase the rooting depth of wheat in these environments in cultivars which are intolerant to salt or boron.

Wheel induced soil compaction has become a serious problem throughout the agricultural areas of the world. Where virgin uncultivated soils occur in conjunction with cultivated soils, the opportunity for comparison is presented as the virgin soils provide vital reference soil conditions for measuring the cumulative compactive effects of arable agriculture.

The agricultural regions of Upper Eyre Peninsula were first extensively developed for agriculture after about 1910 although the clearing of native vegetation for agriculture has continued until the 1980's. Thus agriculture has been practised for only a relatively short time. Nevertheless, agricultural operations at two sites were shown to have significantly increased soil strength to a depth of 0.2-0.3 m. Where a medium sized tractor was driven five times over virgin soil (which was relatively dry and more resistant to compaction than it would be when wet), soil strength was increased significantly to a depth of 0.27 m. Where coefficients of variation were calculated from the penetrometer resistance data, the reduction in coefficients of variation associated with wheel traffic and arable agriculture indicate a deterioration in soil structure compared with the virgin soil.

Soil compaction in Europe and North America has been associated with high values of field traffic intensity (e.g. Håkansson 1985a). Very little data are available concerning field traffic intensity in southern Australia where seasonal conditions and crop rotations are quite different from those in which arable agriculture is practised in the northern hemisphere. The major agricultural operations in South Australia, particularly in the low rainfall cereal growing areas are normally carried out when only the upper part of the soil profile has been wet by autumn rains. Nevertheless, compaction of the soil has occurred as a result of agricultural operations on Upper Eyre Peninsula as the comparative penetrometer data in which virgin and cultivated soils were studied shows. The amount and intensity of traffic is much lower in this semi-arid environment than in Sweden, for example, Håkansson (1985a). Soil compaction in southern Australia is likely to be due more to the absence of mechanisms which reverse compaction than to high values of field traffic intensity.

Attempts to ameliorate soil compaction by tillage with a narrow tyned chisel plough to depths of 0.15 m and 0.30 m were not effective in a drought year at Minnipa. It is hypothesised that tillage to 0.3 m may have countered any beneficial effect of reduced soil strength by allowing roots to rapidly dry out the soil early in the growing season. It is also possible that the greater clay content below 0.1 m resulted, after tillage to 0.3 m, in a rather cloddy structure not conducive to root growth. Research in a variety of seasons is needed to test this hypothesis. Tillage to 0.15 m did not remove a hard pan below normal tillage depth, possibly due to the narrowness of the tynes and tyne spacing having been too wide for effective loosening of the soil to that depth. It is possible that tillage with a machine fitted with preceding shallow tynes and correctly designed wings (Spoor and Godwin 1978) may have improved the performance of the machine.

Tillage with a chisel plough at Cungena resulted in enhancement of root growth and water extraction below tillage depth. Grain yields in both seasons were increased by tillage to 0.3 m. However, similar increases in root growth and yield were not evident in the recompaction experiments, suggesting that the beneficial effects of deep tillage were quickly negated by the recompaction process. The effects of recompaction would be likely to be more severe in wetter seasons. The effects of any tillage methods which promote root growth into the subsoil need to be carefully assessed in environments where rapid early root growth may induce a water deficit later in the season, or where high boron and/or salinity occur in the subsoil. Henderson (1989) suggested that deep tillage should not be practised in Western Australia in the absence of substantial subsoil water recharge from summer rains and good seasonal opening rains, unless compaction was severe.

The current farming systems on Eyre Peninsula are based on relatively low costs per hectare over a relatively large number of hectares - the mean area sown to wheat annually on each farm is about 1,000 ha. Consequently, cyclical deep tillage with a chisel plough to reverse the effects of soil compaction is likely to be prohibitively expensive. The development of improved and more efficient subsurface tillage systems (e.g. "slit tillage" (Elkins *et al.* 1983) may have advantages where subsurface calcrete is not a problem. Controlled traffic systems or the use of permanent tracks and gantries (Taylor 1986, Hilton and Bowler 1986) should be investigated in this environment. Alternatively, "biological tillage" - the use of plants with roots able to penetrate compact subsoils - should be investigated. Such plants are able to leave "biopores" - low resistance pathways - through which later crops are able to gain access to the subsoil (Talha *et al.* 1974, Elkins *et al.* 1977).

Excessive soil strength is a well documented cause of restricted root growth. It is readily apparent that penetrometer resistances in the vicinity of 4-5 MPa which occurred commonly in field soils at both Minnipa and Cungena are likely to impose serious restrictions on the penetration of roots into the subsoil in this environment (Ehlers *et al.* 1983). Jakobsen and Dexter (1988) showed that if the Minnipa soil, with a penetrometer resistance of 4-5 MPa, were free of low resistance pathways, the end result would be a root system limited to a depth of less than 0.3 m. When simulated root profiles were compared with measured root data from Minnipa, it was concluded that a "substantial fraction" of roots in the measured profile had found pathways of low mechanical resistance. Biopores were shown to enhance root penetration significantly, although the authors cautioned that deeper root penetration could adversely affect yield if rapid early root growth in dry climates such as those at Minnipa and Cungena were to deplete subsoil water reserves.

At both sites, bulk densities measured below 0.3 m were not excessive and did not differ greatly from optimum values proposed by Jones (1983). Jakobsen and Dexter (1987) showed that the yield of wheat at Minnipa could actually be increased by increasing soil density in some circumstances.

Most of the agricultural areas of Upper Eyre Peninsula have been used for agricultural operations for about 75 years. It is possible that root channels left by the dominant *Eucalyptus* species provide some assistance to root growth - these channels have often been observed in the field. The gradual disappearance of these pathways may have serious implications for the future. The ability of roots to find these pathways is also likely to be reduced by steadily increasing soil strength. Research is needed to evaluate the role of biopores in aiding root penetration in this environment. It appears that increasing soil strength presents an insidious problem over the entire arable area of Eyre Peninsula (about 2,000,000 ha), a problem which is likely to increase unless addressed, as preventing the problem will be much cheaper than attempting to reverse it.

However, where they occur, high boron and salt concentrations at present probably constitute the most serious impediment to the growth of wheat. The arable area likely to constitute a boron hazard to wheat on Upper Eyre Peninsula, estimated from the survey, is about 200,000 ha. The possible hazards in other mapping units are unkown but it is likely that a considerable hazard exists. Hirsch and Manton (1989) conducted a survey of barley leaf diseases throughout South Australia and included symptoms of boron toxicity. The estimated affected area on Eyre Peninsula was 112,800 ha (the whole area was not surveyed) and in the State 289,200 ha. There is justification for breeding resistant cultivars. It is probably no accident that the wheat cultivar Halberd, which was found to be boron tolerant (Paull *et al.* 1986), is still widely grown on Upper Eyre Peninsula after nearly 25 years. Because of the costs involved, it is unfortunate that little attention has been paid to root growth in plant breeding but in view of the effects of boron on the growth of roots, some assessment of root performance should be included in cultivar testing programmes where high concentrations of boron occur in the subsoil.

10.0 APPENDIX

Table 1.1. Mean monthly rainfall and pan evaporation at Minnipa.

Month	Rainfall (mm)	Pan evaporation (mm)
January	12	344
February	20	287
March	15	242
April	18	160
May	36	110
June	41	67
July	45	77
August	42	100
September	32	134
October	26	193
November	20	257
December	18	328
Annual total	325	2299

Table 1.2. Minnipa 1986 site.

A. Soil description

Depth (m)	Colour (Munsell Chart)	Texture	Carbonate layers*	Fine earth carbonates (reaction to 1M HCl†)
0.00-0.08	5YR4/4	Loam	-	M
0.08-0.24	5YR4/6	Sandy clay loam	-	H
0.24-0.30	7.5YR5/6	Clay loam	III B/C	VH
0.30-0.60	7.5YR5/6	Clay loam	III A	VH
0.60-1.30	7.5YR 5/6	Light clay	IIIA/Qpo	VH
1.30-1.70	5YR5/6	Medium clay	Qpo/Qph	VH

B. Some soil properties

Depth (m)	pH (1:5 soil:water)	EC_{e25} (saturated paste extract) (dS m^{-1})	Boron (mannitol extraction) (mg kg^{-1})
0.0-0.1	8.5	0.9	1.9
0.1-0.2	8.5	1.1	1.9
0.2-0.3	8.6	1.1	2.1
0.3-0.4	-	2.0	4.4
0.4-0.5	8.9	5.2	9.6
0.5-0.6	-	6.5	16.9
0.6-0.7	-	4.5	22.0
0.7-0.8	9.7	7.0	27.8
0.8-0.9	-	5.5	33.3
0.9-1.0	-	6.0	24.7
1.0-1.1	9.7	5.2	36.0

* For description of carbonate layer and geological classification, see Table 1.6 (Appendix).

† See Table 1.7 (Appendix).

Table 1.3. Minnipa 1987 site.

A. Soil description

Depth (m)	Colour (Munsell Chart)	Texture	Carbonate layers*	Fine earth carbonates (reaction to 1M HCl†)
0.00-0.10	5YR3/4	Sandy loam	-	S
0.10-0.35	5YR4/6	Sandy clay	-	S
0.35-0.50	5YR5/6	Light clay	III B	VH
0.50-0.75	5YR6/6	Light medium clay	IIIA/Qpo	VH
0.75-1.30	5YR 6/6	Light medium clay	Qph	VH
1.30-1.70	5YR7/6	Light medium clay	Qph	VH

B. Some soil properties

Depth (m)	pH (1:5 soil:water)	EC_{e25} (saturated paste extract) (dS m^{-1})	Boron (mannitol extraction) (mg kg^{-1})
0.0-0.1	7.7	2.7	0.9
0.1-0.2	8.4	1.9	1.2
0.2-0.3	8.4	1.7	1.5
0.3-0.4	8.4	1.6	2.4
0.4-0.5	8.6	1.9	3.9
0.5-0.6	9.1	3.6	9.7
0.6-0.7	9.3	7.5	29.5
0.7-0.8	9.3	4.1	14.5
0.8-0.9	9.3	6.5	20.4

Table 1.4. Cungena 1987 site.

A. Soil description

Depth (m)	Colour (Munsell Chart)	Texture	Carbonate layers*	Fine earth carbonates (Reaction to 1M HCl†)
0.0-0.1	7.5YR4/4	Sandy loam	-	VH
0.1-0.3	7.5YR4/4	Fine sandy loam	-	VH
0.3-0.4	7.5YR4/4	Fine sandy loam	III B	VH
0.4-0.8	7.5YR5/6	Sandy loam	III A/Qpo	VH
0.8-1.0	5YR5/8	Sandy clay loam	Qpo	VH

B. Some soil properties

Depth (m)	pH (1:5 soil:water)	EC_{e25} (saturated paste extract) ($dS\ m^{-1}$)	Boron (mannitol extraction) ($mg\ kg^{-1}$)
0.0-0.1	8.4	1.2	0.7
0.1-0.2	8.5	1.3	1.0
0.2-0.3	8.7	1.1	1.1
0.3-0.4	8.7	0.9	1.1
0.4-0.5	8.8	0.9	1.2
0.5-0.6	8.9	0.9	1.3
0.6-0.7	-	0.6	3.0
0.7-0.8	-	0.8	4.2
0.8-0.9	-	1.0	3.6

Table 1.5. Cungena 1988 site.

A. *Soil description*

Depth (m)	Colour (Munsell Chart)	Texture	Carbonate layers*	Fine earth carbonates (Reaction to 1M HCl†)
0.00-0.10	10YR3/3	Sandy loam	-	VH
0.10-0.60	10YR5/4	Sandy loam	-	VH
0.60-1.00	10YR6/4	Sandy loam	III A/Qpo	VH
1.00-1.25	7.5YR6/6	Sandy loam	III A/Qpo	VH

B. *Some soil properties*

Depth (m)	EC_{e25} (saturated paste extract) (dS m^{-1})	Boron (mannitol extraction) (mg kg^{-1})
0.0-0.1	1.2	2.4
0.1-0.2	1.0	3.1
0.2-0.3	1.2	3.3
0.3-0.4	1.4	2.9
0.4-0.5	1.8	4.8
0.5-0.6	2.5	6.5
0.6-0.7	3.4	8.8
0.7-0.8	4.3	8.9
0.8-0.9	6.1	10.0
0.9-1.0	8.2	12.0

Table 1.6. Carbonate layers as classified by Wetherby and Oades (1975).

Class	Description
I	Fine carbonate in reddish clay, few if any calcrete fragments present. Boundary with topsoil diffuse.
II	Sheet or boulder calcrete, very hard and usually banded with pinkish colour. Concretions common in layer just above the calcrete.
IIIA	Compact yellowish mixture of finely divided carbonate and sand, containing less than 30% calcrete fragments. Texture ranges from sandy loam to sandy clay loam.
IIIB	As for IIIA carbonate, except that calcrete fragments account for 30-60% of the layer.
IIIC	As for IIIA carbonate, except that calcrete fragments account for greater than 60% of the layer.
Qpo*	Wiabuna Formation - aeolian sandy loam to light clay with moderate amounts of fine earth carbonates. Carbonate layers IIIA, IIIB or IIIC are usually found near the top of the formation.
Qph*	Blanchetown Clay – red to greenish sandy clays and clays with occasional sandy seams.
Qpbu*	Upper Member Bridgewater Formation - unconsolidated calcareous sand composed of wind sorted fractured shells.

*After Firman (1978) and Wetherby (1980).

Table 1.7. Fine earth carbonates – Wetherby (1990).

	Reaction to 1M HCl	Fine earth carbonates (%)
N (Nil)	No effervescence	< 1.5
S (Slight)	Effervescence just visible	< 1.5
M (Moderate)	Effervescence easily visible	1.5 - 8
H (High)	Strong effervescence	1.5 - 8
VH (Very high)	Violent effervescence	> 8

Table 3.1. Penetrometer resistances (MPa) measured at anthesis, 1986 at Minnipa

Depth (m)	Control	Irrigated	Significance ($P \leq 0.05$)
0.03	0.25	0.36	NS
0.06	0.62	0.84	NS
0.09	0.83	0.91	NS
0.12	1.91	2.21	NS
0.15	3.97	4.02	NS
0.18	5.27	4.09	NS
0.21	-	-	
0.24	-	-	
0.27	-	-	
0.30	-	-	
0.33	-	-	
0.36	-	-	
0.39	-	-	
0.42	-	-	
0.45	-	-	

Table 3.2. Mannitol extractable boron (mg kg^{-1}) and EC_{e25} (dS m^{-1}) for soil from the control and irrigated plots at anthesis, 1986 at Minnipa.

Depth (m)	Boron Control	Boron Irrigated	Boron LSD (0.05)	EC_{e25} Control	EC_{e25} Irrigated	EC_{e25} Significance ($P \leq 0.05$)
0.0-0.1	1.9	2.0	0.7	0.9	1.0	0.05
0.1-0.2	1.9	1.7	0.8	1.1	1.1	0.2
0.2-0.3	2.1	1.8	0.6	1.1	1.2	0.5
0.3-0.4	4.4	2.5	7.9	2.0	1.1	2.5
0.4-0.5	9.6	4.8	15.9	5.2	1.3	4.8
0.5-0.6	16.9	12.5	31.6	6.5	2.2	5.7
0.6-0.7	22.0	22.3	31.5	4.5	1.5	6.3
0.7-0.8	27.8	19.5	12.1	7.0	1.8	7.6
0.8-0.9	33.3	36.7	12.7	5.5	2.0	3.7
0.9.1.0	24.7	38.7	6.6	6.0	1.8	6.0
1.0-1.1	36.0	29.3	8.7	5.2	1.9	3.9
1.1-1.2	35.3	39.7	18.6	-	-	-

Appendix 5.1 The stratigraphy of the soils of Upper Eyre Peninsula (Wetherby 1990)

STRATIGRAPHY OF E.P.

Moornaba (Molineaux) Sand

The parallel sandridges of Eyre Peninsula, normally found superimposed over a flat to rolling topography containing class II or IIIA, B, C carbonate layers in aeolian sediments of inland origin

Lowan Sand

The jumbled sandridges of Eyre Peninsula

Siliceous

Overlies recent alluvial deposits (Pooraka Formation), tertiary sediments or basement rock

Calcareous

Overlies flat to rolling topography containing class II or IIIA, B, C carbonate layers in aeolian sediments of marine (Bridgewater Formation) origin.

//

B2K horizon (class IV carbonate) associated with the Peebinga Pedoderm

//

Wiabuna (Woorinen) Formation. Rolling topography of aeolian origin

Siliceous

Formed from materials of inland origin

Calcareous

Formed from materials associated with the marine Bridgewater Formation

Pooraka Formation - Outwash fans and plains surrounding basement highs

///

Relict 2B2t of Loveday Pedoderm///////////////

Callabonna Clay (Reddish)//////////////////////////

Coomunga Clay (Yellow)////////////////////////////

///

//

Relict 2B2K horizon associated with the Loveday Pedoderm (class IIIA, B,C)//////////////////

//

Upper Bridgewater Formation - marine/aeolian origin

//

Relict 3B2K horizon (soft phase class II) associated with the Bakara Pedoderm

//

Lower Bridgewater Formation - marine/aeolian origin

inland the soft (Bakara) phase of class II carbonate is often found directly on top of the hard (Ripon) phase of class II carbonate and both appear to have formed in aeolin sediments of inland origin

//

Relict 4B2K horizon (hard phase class II) associated with Ripon Pedoderm

//

Blanchetown Clay

///

When Blanchetown Clay forms the land surface 2B2K horizons are often present - (class I) Loveday Pedoderm

///

Tertiary sediments (often ferruginous)

Avondale Clay

Table 8.1. Mean gravimetric water contents (kg kg^{-1}) on 12 July, 1987 at Minnipa (tillage experiment).

Depth (m)	$M_{87}T_{0.30}$	$M_{87}T_{0.15}$	$M_{87}T_{0.05}$	Significance ($P \leq 0.05$)
0.0-0.1	0.069	0.076	0.071	NS
0.1-0.2	0.095	0.099	0.098	NS
0.2-0.3	0.117	0.128	0.129	NS
0.3-0.4	0.132	0.138	0.141	NS
0.4-0.5	0.140	0.143	0.143	NS
0.5-0.6	0.138	0.139	0.139	NS

Table 8.2. Mean gravimetric water contents (kg kg^{-1}) on 19 June, 1988 at Cungena (tillage experiment).

Depth (m)	$C_{88}T_{0.30}$	$C_{88}T_{0.15}$	$C_{88}T_{0.05}$	Significance ($P \leq 0.05$)
0.0-0.1	0.190	0.185	0.178	NS
0.1-0.2	0.140	0.128	0.123	NS
0.2-0.3	0.083	0.084	0.081	NS
0.3-0.4	0.074	0.073	0.070	NS
0.4-0.5	0.071	0.070	0.067	NS
0.5-0.6	0.072	0.069	0.068	NS

Table 8.3. Penetrometer resistances (MPa) measured on 19 June, 1988 at Cungena (tillage experiment).

Depth (m)	$C_{88}T_{0.30}$	$C_{88}T_{0.15}$	$C_{88}T_{0.05}$	Significance ($P \leq 0.05$)
0.03	0.38	0.45	0.46	NS
0.06	0.78	0.82	0.97	NS
0.09	0.96	1.16	1.90	0.25
0.12	1.01	1.58	2.78	0.63
0.15	1.18	2.70	3.66	0.66
0.18	1.48	3.99	4.53	0.76
0.21	2.14	4.64	4.66	NS
0.24	4.01	4.37	4.92	NS
0.27	5.22	5.37	5.30	NS
0.30	6.12	-	-	NS
0.33	-	-	-	-
0.36	-	-	-	-
0.39	-	-	-	-
0.42	-	-	-	-
0.45	-	-	-	-

Table 8.4. Mean gravimetric water contents (kg kg^{-1}) at anthesis, 1987 at Minnipa (tillage experiment).

Depth (m)	$M_{87}T_{0.30}$	$M_{87}T_{0.15}$	$M_{87}T_{0.05}$	Significance ($P \leq 0.05$)
0.0-0.1	0.067	0.064	0.065	NS
0.1-0.2	0.069	0.068	0.071	NS
0.2-0.3	0.079	0.078	0.078	NS
0.3-0.4	0.086	0.086	0.098	NS
0.4-0.5	0.086	0.088	0.089	NS
0.5-0.6	0.096	0.092	0.094	NS
0.6-0.7	0.101	0.097	0.102	NS
0.7-0.8	0.111	0.108	0.111	NS
0.8-0.9	0.117	0.115	0.116	NS
0.9-1.0	0.120	0.120	0.120	NS

Table 8.5. Penetrometer resistances (MPa) measured at anthesis, 1987 at Minnipa (tillage experiment).

Depth (m)	$M_{87}T_{0.30}$	$M_{87}T_{0.15}$	$M_{87}T_{0.05}$	Significance ($P \leq 0.05$)
0.03	0.18	0.15	0.25	NS
0.06	0.69	0.62	0.78	NS
0.09	1.31	1.78	3.95	NS
0.12	2.45	6.00	4.22	3.0
0.15	-	-	-	-
0.18	-	-	-	-
0.21	-	-	-	-
0.24	-	-	-	-
0.27	-	-	-	-
0.30	-	-	-	-
0.33	-	-	-	-
0.36	-	-	-	-
0.39	-	-	-	-
0.42	-	-	-	-
0.45	-	-	-	-

Table 8.6. Penetrometer resistances (MPa) measured at anthesis, 1987 at Cungena (tillage experiment).

Depth (m)	$C_{87}T_{0.30}$	$C_{87}T_{0.15}$	$C_{87}T_{0.05}$	Significance ($P \leq 0.05$)
0.03	0.07	0.06	0.08	NS
0.06	0.71	0.44	0.84	NS
0.09	2.29	2.16	3.09	0.75
0.12	3.42	3.79	4.91	NS
0.15	3.77	4.66	5.22	NS
0.18	3.76	4.36	5.37	NS
0.21	3.89	4.71	4.79	0.33
0.24	4.53	4.95	4.93	NS
0.27	5.26	4.83	4.91	NS
0.30	5.21	4.97	5.09	NS
0.33	5.29	4.85	5.10	NS
0.36	5.28	4.95	5.30	NS
0.39	5.78	5.12	5.26	NS
0.42	5.98	5.16	5.26	NS
0.45	5.18	5.06	5.30	NS

Table 8.7. Penetrometer resistances (MPa) measured at anthesis, 1988 at Cungena (tillage experiment).

Depth (m)	$C_{88}T_{0.30}$	$C_{88}T_{0.15}$	$C_{88}T_{0.05}$	Significance ($P \leq 0.05$)
0.03	0.19	0.17	0.25	NS
0.06	0.37	0.42	0.59	0.14
0.09	0.78	1.26	2.44	0.94
0.12	0.95	2.24	4.23	1.14
0.15	1.20	3.64	5.20	1.06
0.18	1.34	4.75	5.37	0.69
0.21	1.72	5.41	5.65	0.78
0.24	3.11	6.00	5.12	0.37
0.27	4.36	6.00	5.07	NS
0.30	5.70	6.44	5.44	NS
0.33	-	-	-	-
0.36	-	-	-	-
0.39	-	-	-	-
0.42	-	-	-	-
0.45	-	-	-	-

Table 8.8. Root length densities (m kg^{-1}) measured at anthesis, 1988 at Cungena (tillage experiment).

Depth (m)	$C_{88}T_{0.30}$	$C_{88}T_{0.15}$	$C_{88}T_{0.05}$	Significance ($P \leq 0.05$)
0.0-0.1	44.3	19.1	28.1	NS
0.1-0.2	15.2	19.2	15.8	NS
0.2-0.3	5.9	5.0	4.8	NS
0.3-0.4	-	-	-	-
0.4-0.5	1.4	1.7	0.8	0.6
0.5-0.6	-	-	-	-
0.6-0.7	-	-	-	-
0.7-0.8	0.4	0.5	0.3	NS
0.8-0.9	-	-	-	-
0.9-1.0	0.2	0.2	0.1	NS

Table 8.9. Mean gravimetric water contents (kg kg^{-1}) on 19 June 1988, at Cungena (recompaction experiment).

Depth (m)	$C_{87}T_{0.30}R$	$C_{87}T_{0.15}R$	$C_{87}T_{0.05}R$	Significance ($P \leq 0.05$)
0.0-0.1	0.191	0.187	0.183	NS
0.1-0.2	0.135	0.135	0.139	NS
0.2-0.3	0.084	0.081	0.087	NS
0.3-0.4	0.071	0.072	0.069	NS
0.4-0.5	0.067	0.068	0.065	NS
0.5-0.6	0.066	0.067	0.064	NS

Table 8.10. Penetrometer resistances (MPa) measured on 19 June, 1988 at Cungena (recompaction experiment).

Depth (m)	$C_{88}T_{0.30}R$	$C_{88}T_{0.15}R$	$C_{88}T_{0.05}R$	Significance ($P \le 0.05$)
0.03	0.81	0.73	0.84	NS
0.06	1.55	1.27	1.66	NS
0.09	1.59	1.32	2.11	0.33
0.12	1.61	1.72	2.82	0.41
0.15	1.85	2.81	3.61	0.81
0.18	2.32	4.06	4.20	0.89
0.21	3.22	4.76	4.54	0.51
0.24	4.57	5.22	5.87	1.06
0.27	-	-	-	-
0.30	-	-	-	-
0.33	-	-	-	-
0.36	-	-	-	-
0.39	-	-	-	-
0.42	-	-	-	-
0.45	-	-	-	-

Table 8.11. Mean gravimetric water contents (kg kg^{-1}) measured at anthesis, 1988 at Cungena (recompaction experiment.)

Depth (m)	$C_{88}T_{0.30}R$	$C_{88}T_{0.15}R$	$C_{88}T_{0.05}R$	Significance ($P \le 0.05$)
0.0-0.1	0.054	0.044	0.062	NS
0.1-0.2	0.083	0.089	0.099	NS
0.2-0.3	0.090	0.091	0.100	NS
0.3-0.4	0.095	0.088	0.095	NS
0.4-0.5	0.091	0.091	0.086	NS
0.5-0.6	0.088	0.083	0.086	NS
0.6-0.7	0.084	0.079	0.082	NS
0.7-0.8	0.082	0.079	0.082	NS
0.8-0.9	0.083	0.087	0.087	NS
0.9-1.0	0.084	0.083	0.083	NS

Table 8.12. Penetrometer resistances (MPa) measured at anthesis, 1987 at Cungena (recompaction experiment).

Depth (m)	$C_{87}T_{0.30}R$	$C_{87}T_{0.15}R$	$C_{87}T_{0.05}R$	Significance ($P \leq 0.05$)
0.03	0.15	0.33	0.18	NS
0.06	3.25	3.73	3.12	NS
0.09	4.58	5.31	5.06	NS
0.12	5.31	5.22	5.50	NS
0.15	5.67	5.51	5.83	NS
0.18	-	-	-	-
0.21	-	-	-	-
0.24	-	-	-	-
0.27	-	-	-	-
0.30	-	-	-	-
0.33	-	-	-	-
0.36	-	-	-	-
0.39	-	-	-	-
0.42	-	-	-	-
0.45	-	-	-	-

Table 8.13. Penetrometer resistances (MPa) measured at anthesis, 1988 at Cungena (recompaction experiment).

Depth (m)	$C_{88}T_{0.30}R$	$C_{88}T_{0.15}R$	$C_{88}T_{0.05}R$	Significance ($P \leq 0.05$)
0.03	0.28	0.37	0.40	NS
0.06	3.24	2.31	2.68	NS
0.09	4.19	3.94	4.20	NS
0.12	3.57	4.37	5.35	0.89
0.15	3.27	5.26	5.65	1.30
0.18	3.70	5.50	4.60	NS
0.21	4.40	5.49	4.94	NS
0.24	5.27	5.31	5.29	NS
0.27	5.66	5.66	5.66	NS
0.30	-	-	-	-
0.33	-	-	-	-
0.36	-	-	-	-
0.39	-	-	-	-
0.42	-	-	-	-
0.45	-	-	-	-

Table 8.14. Root length densities (m kg^{-1}) measured at anthesis, 1987 at Cungena (recompaction experiment).

Depth (m)	$C_{87}T_{0.30}R$	$C_{87}T_{0.15}R$	$C_{87}T_{0.05}R$	Significance ($P \leq 0.05$)
0.0-0.1	30.9	29.5	32.7	NS
0.1-0.2	20.9	22.1	21.2	NS
0.2-0.3	17.8	16.1	14.7	NS
0.3-0.4	11.8	12.4	11.6	NS
0.4-0.5	7.8	9.1	7.0	NS
0.5-0.6	3.8	5.4	3.9	NS
0.6-0.7	3.2	3.5	2.9	NS
0.7-0.8	3.1	2.9	2.6	NS
0.8-0.9	1.8	1.5	2.4	NS
0.9-1.0	0.8	1.0	1.2	NS

Table 8.15. Root length densities (m kg^{-1}) measured at anthesis, 1988 at Cungena (recompaction experiment).

Depth (m)	$C_{88}T_{0.30}R$	$C_{88}T_{0.15}R$	$C_{88}T_{0.05}R$	Significance ($P \leq 0.05$)
0.1-0.1	32.2	37.5	33.8	NS
0.1-0.2	17.1	16.2	14.1	NS
0.2-0.3	5.0	6.0	4.9	NS
0.3-0.4	-	-	-	-
0.4-0.5	1.0	1.1	0.7	NS
0.5-0.6	-	-	-	-
0.6-0.7	-	-	-	-
0.7-0.8	0.4	0.3	0.4	NS
0.8-0.9	-	-	-	-
0.9-1.0	0.1	0.2	0.2	NS

Table 8.16. Gravimetric water contents (kg kg^{-1}) measured at the time of recompaction, 1987 and 1988 at Cungena.

Depth (m)	1987	1988
0.0-0.1	0.149	0.132
0.1-0.2	0.157	0.048
0.2-0.3	0.137	0.082
0.3-0.4	0.118	0.081
0.4-0.5	0.110	0.078

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TRAFFIC INTENSITY ON ARABLE LAND ON THE EYRE PENINSULA OF SOUTH AUSTRALIA

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Summary—Problems associated with soil compaction are being identified increasingly in southern Australia. This study of amounts and types of field traffic has been done in order to quantify some of the factors causing soil compaction. It is found that, in a cropping year, the proportion of the area covered by the wheels of farm vehicles is 47.5% and the total amount of traffic is 62.6 t km/ha (or 15.5 ton miles/acre). In a cropping year, the total area of wheel tracks per unit area of field is 1.65. Also the fields are cropped typically in only 50% of years with the other 50% of years being self-sown pastures involving negligible field traffic. Harvesting operations are done when the soil is dry and hard and not susceptible to compaction. The increase in problems resulting from soil compaction is therefore primarily associated with the absence of mechanisms which can reverse or undo any compaction. These mechanisms include soil swelling and shrinking, freezing and thawing cycles and earthworm activity. These processes which are important in maintaining a good soil structure in humid, temperate regions of the northern hemisphere are either absent or of negligible effect in the semi-arid, Mediterranean-type climatic region considered. Therefore, in spite of the relatively low levels of field traffic, there is a perpetual, insidious increase in soil compaction and associated problems.

INTRODUCTION

COMPACTION of agricultural soils by the wheels of machinery has long been recognized. Compaction is the process of increasing the soil density, and this gives rise to: reduction of air-filled porosity; reduction of hydraulic conductivity; and increased soil strength. These effects in turn can result in: increased incidence of root diseases of crops; water-logging, run-off and erosion; increased energy requirement for tillage; and reduced rates of root growth and reduced crop yields. The processes of compaction and its consequences have been considered in some detail [1–7].

Most of the work on soil compaction has been done in fairly high latitudes in North America and northern Europe. In the mechanized farming systems used in these areas, high proportions of the areas of arable fields are covered every year by the wheels of machines: Soane [1, 8] reported that, in Britain, the traditional method of seedbed preparation for cereals (after an earlier ploughing) involved: fertilizer distribution, harrowing twice, sowing and rolling. These five operations resulted in 0.91 of the area being covered by wheels.

On fields used for cereal production in Sweden, Eriksson *et al.* [2] reported that the total area of wheel tracks produced each year (including ploughing) may be larger than

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the area of the field by a ratio of up to 5, and Håkansson [3] measured ratios in the range 3–5.5.

In some experiments in The Netherlands on the effects of tillage and different levels of traffic on soil conditions and crop growth, Lumkes [9] measured total wheel track areas in the approximate range 1.25 to 3 times the area of the experimental plots. The lower end of this range was considered to be the minimum ratio which could be achieved.

The pattern of the wheel tracks produced is not random, but neither does it occur in any organized way. It depends on the pattern of field working in combination with the wheel spacings on the various machines. Wheel spacings are not standardized in agriculture and tend to be different on every machine used by a given farmer. The resulting pattern of wheel tracks have been described by Greacen and Sands [10] as "a systemised function of mechanical operations".

In order to sum-up or integrate the total amount of annual field traffic, Håkansson [3] has used the term "traffic intensity". The traffic intensity is obtained by multiplying the mass of each vehicle in tonnes (t) by the distance which it travels (km) per unit area of field (ha) and summing this over all the passes of all the vehicles over the year. The result is expressed in units of t km/ha (1 t km/ha = 0.248 ton miles/acre). For typical Swedish cereal farms, he obtained values of traffic intensity in the range 110–230 t km/ha.

In the humid, temperate climates of the northern hemisphere, the soil is moist for much of the year. The soil may be frozen for part of the winter (e.g. January, February) when no agricultural activities are performed, and at other times it may be too wet to support field traffic (e.g. December, March). Sowing of spring-sown crops takes place when the soil has drained to field capacity after the preceding winter (e.g. April, May). Harvest of many cereal crops takes place in the autumn (e.g. September, October) when the soil is becoming wet again with the approach of winter. Harvest is followed almost immediately by ploughing, and the sowing of winter cereals if these are to be grown. The soil may become dry and hard for a relatively short period in the summer (e.g. June, July) at a time when there are few machinery operations in the field except for crop spraying. Most of the main machinery operations are therefore performed whilst the soil is moist and very susceptible to compaction.

In southern Australia there is a Mediterranean-type climate with hot, dry summers (December–February) and cool, wet winters (June–August). The summers in this region are too hot and dry for crop growth without irrigation which is not possible in most areas because of the lack of suitable water supplies. The growing season therefore extends from autumn (e.g. May), through the winter, and up to harvest in the spring (e.g. November) and early summer (December). Tillage for seed-bed preparation and sowing is usually done when only the upper part of the soil profile has been wetted by autumn rains. Sometimes, the seeds are sown directly into completely dry soil so that they are ready to germinate and grow when the rain comes.

The hope and expectation is that further rains will sustain the seedlings, and that the zone of wetted soil will always extend deeper than the depth of rooting at the time. These requirements are not always met. Due to climatic variations within and between years, various problems can arise. These include a dry period following the rain which causes germination and this can result in severe retardation of the crop. Another not infrequent occurrence is that the crop may have used all of the plant-available-water in the soil profile before the onset of the grain-filling stage of crop growth, and after the rainy season has finished. This can lead to reasonable dry-matter yields but negligible grain yields. Droughts occur periodically.

In southern Australia, therefore, tillage and sowing are usually done when only the top part of the soil profile is moist and susceptible to compaction. Harvest is usually done when the whole soil profile is dry and hard. Usually, only spraying operations are done when the whole soil profile is moist and susceptible to compaction.

Even though few field operations are performed when the whole soil profile is moist and susceptible to compaction, it is evident that compaction has become a serious problem in many areas. It was therefore decided to quantify the types and amounts of field traffic on two farms in South Asutralia.

MATERIALS AND METHODS

Site details

Two sites were chosen both of which are on the north-western part of the Eyre Peninsula of South Australia. The two properties are at Minnipa (lat. 32°51′S, long. 135°09′E) and at Cungena (approximately 60 km NW of Minnipa). The soil at Minnipa is a loam and at Cungena it is a sandy loam. The soils at these two sites were described more fully in a previous paper on the transmission of pressure through soil beneath wheels [11].

The climate at both sites is of the semi-arid, Mediterranean type and rain-fed agriculture is practised. Mean monthly values of rainfall and pan evaporation at Minnipa are given in Table 1. It will be noticed that in no month does the average rainfall exceed the average pan evaporation. The mean annual rainfall at Cungena is less than at Minnipa being approximately 281 mm. Daily rainfall at Cungena, R_c, is approximately related to that at Minnipa, R_m, by

$$R_c = R_m\ (1.08 - 0.0012\,JD), \tag{1}$$

where JD is the Julian date (or day number) in the year. The discontinuity of equation (1) between days $JD = 365$ and $JD = 1$ is of no practical importance because negligible rainfall occurs in the period December–March. The pan evaporation at Cungena is probably similar to that at Minnipa.

Farms in this region tend to be large (2000 ha or more), but not all of the area is cropped every year. A survey of 33 farms done by the South Australian Department of Agriculture in 1981 showed an average annual cropped area of 840 ha and an average tractor PTO power of 120 kW. Both of these figures would probably have increased since 1981. Average field size is around 100 ha.

The farming system at the two properties is typical of that in the region. Fields are cropped in only about one-half of the years. The other, non-cropped, part of the rotation is a legume pasture which is grazed by sheep. Typical rotations are:

TABLE 1. MEAN MONTHLY VALUES OF RAINFALL AND PAN EVAPORATION AT MINNIPA

	Month												Annual Totals (mm)
	J	F	M	A	M	J	J	A	S	O	N	D	
Rainfall	12	20	15	18	36	41	45	42	32	26	20	18	325
Pan evaporation	344	287	242	160	110	67	77	100	134	193	257	328	2298

wheat–pasture (i.e. a 2-year rotation),
wheat–barley–pasture–pasture (i.e. a 4-year rotation),
wheat–oats–pasture–pasture (i.e. a 4-year rotation), or
wheat–barley–pasture (i.e. a 3-year rotation).

For the cropping part of the rotation (i.e. the wheat, barley or oats), the sequence of operations is typically as follows:

(1) seed-bed preparation (April–May),
(2) seeding (May–June, as early as possible),
(3) spraying which can be either or both of:
  (i) pre-sowing (preferably in early May) for grass or broad spectrum weed control. These herbicides are incorporated.
  (ii) post-emergence (in June–August) from the 2-leaf stage of the crop up to early tillering.
(4) harvest (October–November).

Some farmers still harrow after seeding, but this is now being done less frequently than formerly as it destroys the effects of the press-wheels which are being used increasingly to firm the soil around the seeds in the seed-rows (180 mm row spacing).

At Minnipa, there are usually two spraying operations (May and July), whereas at Cungena there is usually only one (July).

For the pasture phase, the pastures are self-sown from the seed reserves remaining from previous pastures. The pastures are leguminous and are typically medic species (e.g. *Medicago truncatula* at Minnipa and *Medicago littoralis* at Cungena). The seeds of medic have a hard coat, and only a proportion (e.g. 10–25%) of the seed reserves germinate in a given year. The requirement to spray a cereal crop is partly to kill any medic plants which have started to grow. Pastures are sprayed in winter or more commonly in spring to reduce the proportion of grasses which can act as hosts for pathogens (e.g. root rots) of cereal crops. The spraying-out of grasses from the pasture phase therefore significantly reduces the carry-over of diseases from one cereal crop to the next. The pastures are grazed at typically 1.2 sheep/ha. The pastures die during the hot, dry summer. Details of the legume pasture part of the crop rotation have been discussed in detail by Puckridge and French [12].

Field working patterns

The patterns of field working are shown in Fig. 1. This figure is not to scale, and more passes are required around a field to cover it than are shown. Not shown in Fig. 1 are the fire breaks. These are required by law to be a regularly-tilled and non-cropped strip of at least 2 m width running completely around the edge of each field to prevent the spread of fires.

Tillage and seeding operations are traditionally done anti-clockwise as shown in Fig. 1A. This practice originated with asymmetrical tillage implements such as mouldboard ploughs and disc-ploughs which moved soil from left-to-right (when looking in the direction of travel). Such implements had to travel anti-clockwise so that the untilled soil could be turned into the empty furrow remaining from the previous pass. Nowadays, ploughs are used only infrequently, and the tillage implements most commonly used have symmetrical arrays of tines with symmetrical feet and are known as scarifiers. Similar implements but fitted with seed-boxes, metering equipment and seed-tubes are known as scariseeders. However, the tradition of anti-clockwise tillage persists.

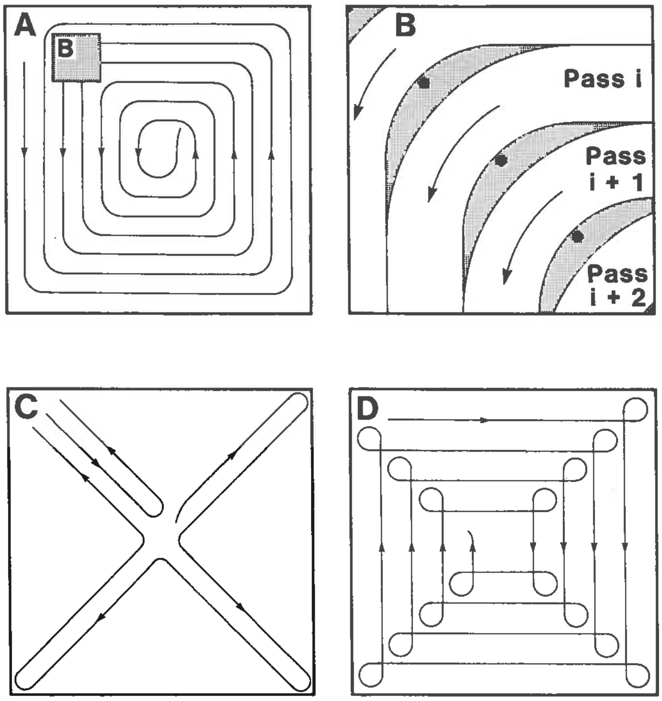

FIG. 1. Typical field working patterns in southern Australia. Tillage and seeding are usually done anti-clockwise round and round the field (A). This leaves un-tilled and un-seeded headlands (B). Each dot in B near the edge of a pass represents the centre of the turning circle of the previous pass. The remaining headlands are worked along the diagonals (C). Harvesting is usually done clockwise (D).

In going around the corners, headlands are left untilled or un-seeded as shown in Fig. 1B. When the operator has reached the centre of the field, he then works a pattern of diagonals as shown in Fig. 1C to fill-in these headlands. This practice means that some parts of the field on the diagonals get double the tillage and double the seeding rate. The normal seeding rate (with a single pass) is 120 plants/m^2.

Spraying operations also tend to be done anti-clockwise.

Harvesting is done clockwise as shown in Fig. 1D. Although many harvesters are symmetrical these days, this tradition follows from the time of horse- or tractor-drawn harvesters. These mostly had the cutter bar on the right-hand-side and had to be pulled by horses or tractors operating on the left on areas which had already been cut.

During seeding, the track or tractor and trailer carrying seed and fertilizer is parked at suitable places along the diagonal from the corner of the field containing the gate. The hoppers for seed and fertilizer on the seeding equipment are filled as it comes around to that diagonal. Likewise, the vehicle collecting grain at harvest is parked on the same diagonal, and the harvester hopper is emptied when the harvester comes around to that diagonal.

Characterization of wheel traffic

The machinery types used at Minnipa and Cungena are given in Tables 2 and 3. For

TABLE 2. MACHINERY TYPES USED AT MINNIPA WITH WHEEL AND TYRE SPECIFICATIONS

A. *Tractor*: *International* 1486 (*two wheel drive*) (124 *kW engine power*)						
Rear tyres:	Dual:	Inner -	24.5-32	10 ply		Inflation pressure, 112 kPa
		Outer -	18.4-38	8 ply		
Front tyres:			11.0-16	8 ply		Inflation pressure, 280 kPa
Mean contact areas (*each wheel*)						
Front wheels (seeder hitched to tractor) (each wheel)						0.077 m^2
Rear wheels (each wheel)					Inner	0.29 m^2
					Outer	0.17 m^2
Mean wheel load (each wheel)					Front wheels	8.48 kN
					Rear wheels(Outer plus inner)	28.81 kN
Mean ground contact pressure (each wheel)					Front wheels	110.1 kPa
					Rear wheels	62.6 kPa
B. *Airseeder/Scarifier*: *Connor shea scariseeder* 48 *row,* 8.7 *m width*						
						Inflation pressure
2 × Centre tyres			12.00-24	(10 ply)		300 kPa
2 × Outer tyres			8.25-20	(6 ply)		300 kPa
Mean contact areas					Centre wheels (each)	0.113 m^2
					Outer wheels (each)	0.077 m^2
Mean wheel load (seeder empty)					Centre wheels (each)	18.38 kN
					Outer wheels (each)	5.27 kN
Mean contact pressures					Centre wheel (each)	163.3 kPa
					Outer wheel (each)	68.8 kPa
C. *Harvester*: *International* 711 *Self propelled,* 5.5 *m comb*						
Front tyres			18.4-26	(12 ply)		280 kPa
Rear tyres			7.5-18	(8 ply)		315 kPa
Mean contact areas					Front wheels (each)	0.179 m^2
					Rear wheels (each)	0.047 m^2
Mean wheel load (empty grain bin)					Front wheels (each)	26.4 kN
					Rear wheels (each)	6.7 kN
Mean contact pressures					Front wheels (each)	147 kPa
					Rear wheels (each)	143 kPa
D. *Boomspray*: *Landcruiser FJ45 Long wheel base, fitted with* 1000 1 *spray tank. Boom width* 13.9 *m*						
Mean contact areas					Front wheels (each)	0.056 m^2
					Rear wheels (each)	0.058 m^2
Mean wheel load (tank full)					Front wheels (each)	4.5 kN
					Rear wheels (each)	11.8 kN
Mean contact pressures					Front wheels (each)	80.5 kPa
					Rear wheels (each)	203.6 kPa

each machine, these tables give the tyre sizes, ply ratings, inflation pressures, mean contact areas, mean wheel loads, and mean contact pressures.

Contact areas were measured in the field with the machines stationary. Talcum powder was puffed around the tyre/soil interface and then the machine was driven off. A piece of transparent polythene sheet was then placed on the soil surface and the inside boundary

TABLE 3. MACHINERY TYPE USED AT CUNGENA WITH WHEEL AND TYRE SPECIFICATIONS

A. Tractor: Phoenix 3080 *- articulated* (4 *wheel drive*) (228 *kW engine power*)					
Rear tyres:	Dual	Inner	24.5-32	10 ply	
		Outer	24.5-32	10 ply	
Front tyres:	Dual	Inner	24.5-32	10 ply	
		Outer	24.5-32	10 ply	
Inflation pressure	125 kPa - all tyres				
Mean contact area	each wheel			0.21 m^2	
Mean wheel loads (each wheel)					
Front wheels	Inner and Outer				33.9 kN
Rear wheels	Inner and Outer				24.1 kN
Mean ground contact pressure	Front wheels				79.6 kPa
	Rear wheels				56.6 kPa
B1. Airseeder/chisel plough: "*Fusion sabreseeder* 5550" 15.35 *m wide (*30 *cm row spacing*)					
					Inflation pressure
2 Centre tyres (each)			14.9/13-26		350 kPa
2 Outer tyres on centre section each			14.9/13-26		350 kPa
2 Inner tyres on wings (each)			14.9/13-26		350 kPa
2 Outer tyres on wings (each)			14.9/13-26		350 kPa
Mean wheel load (each wheel)	2 Centre tyres (each)				21.56 kN
	2 Outer tyres on centre section (each)				18.52 kN
	2 Inner tyres on wings (each)				11.56 kN
	2 Outer tyres on wings (each)				10.19 kN
Mean contact area (all wheels)					0.07 m^2
Mean ground contact pressure	2 Centre tyres (each)				308 kPa
	2 Outer tyres on centre section (each)				265 kPa
	2 Inner tyres on wings (each)				165 kPa
	2 Outer tyres on wings (each)				146 kPa
B2. Grain hopper of airseeder: 2 *tyres*					22.5-26 (10 ply)
Mean contact area (each wheel)					0.225 m^2
Mean wheel load (each wheel)					29.84 kN
Mean ground contact pressure (each wheel)					132.6 kPa
C. Harvester as at Minnipa (Table 1)					
D. Boomspray as at Minnipa (Table 1)					

of the band of talcum powder was traced around with a felt-tipped pen and was assumed to represent the contact area. The area was measured later in the laboratory with a planimeter.

Mean wheel loads were measured either on a weigh bridge or with portable scales ("TELUB AB" weighing plate model 10T). Mean contact pressures were obtained by dividing the mean wheel loads by the mean contact areas. Maximum contact pressures between wheels and the soil were not measured in this work but were shown previously to be around 1.6 times the mean contact pressure [11].

The widths of the wheel tracks in the field are given in Tables 4 and 5. These were measured on the soil surface with a ruler after the machines had travelled past.

The pattern of wheel positions relative to the edge of the field are shown in Figs 2

TABLE 4. WIDTHS OF WHEEL TRACKS MADE ON BARE CULTIVATED SOIL

	Each front wheel track width (m)		Each rear wheel track width (m)	
Minnipa				
A. Tractor	0.29		0.57 0.41	(Inner) (Outer)
B. Airseeder	0.28 0.17	(Inner) (Outer)		
C. Harvester	0.42		0.18	
D. Boomspray	0.22		0.22	
Cungena				
A. Tractor	0.63	(duals)	0.63	(duals)
B1. Airseeder	0.28	(8 wheels)		
B2. Grainhopper	0.55			
C. Harvester	0.42		0.18	
D. Boomspray	0.22		0.22	

TABLE 5. TRAFFIC INTENSITY AT MINNIPA (t km/ha) FOR ONE SEASON'S OPERATIONS

Operation	Machine	Mass (t)	km/ha	t km/ha
1st Scarifying	Tractor	7.610	1.149	14.29
	Scariseeder	4.825		
2nd Scarifying	Tractor	7.610	1.149	14.29
	Scariseeder	4.825		
Seeding	Tractor	7.610	1.149	14.29
	Scariseeder	4.825		
Boomspray (pre-sowing)		3.300	0.722	2.40
(post-sowing)		3.300	0.722	2.40
Harvesting		6.770	1.818	12.31
Total for one season				59.98

and 3. These show only the pattern within a single width of the widest machine used. The pattern will not repeat towards the centre of the field because the machine widths are not exact multiples of any particular width. In spite of this, the outside 13.9 m at Minnipa and 15.7 m at Cungena has been taken as representative of the traffic over the whole field.

The proportion of the field covered by wheel tracks in a cropping year is shown by the right-hand (black) bars in Figs 2 and 3. This amounts to 48.3% at Minnipa and 46.7% at Cungena. Actually, these percentages would be slightly greater in practice because it

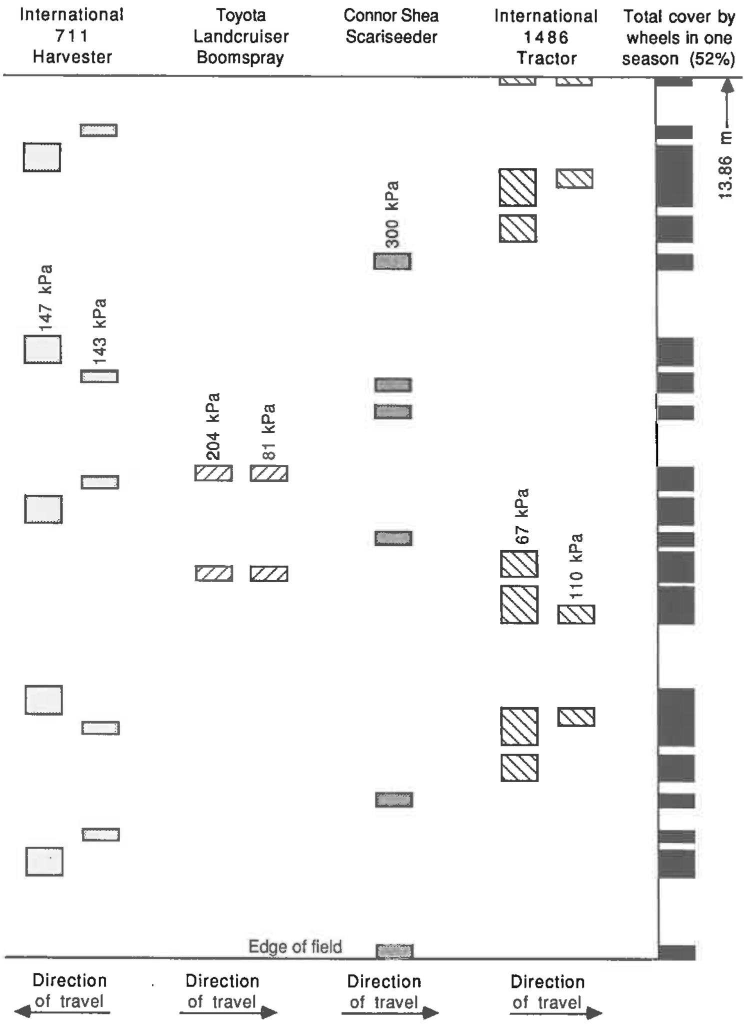

FIG. 2. Wheel positions relative to the edge of the field at Minnipa. Actually, the "edge of the field" is the inside edge of the firebreak. Figures show mean values of ground contact pressure.

is unlikely that the wheel tracks would follow each other exactly in the 2 or 3 successive tillage and seeding operations which use the same machinery.

The quantity of traffic is summarized in Tables 5 and 6. These tables show the distance in km travelled by each machine per ha of field worked. Also, the traffic intensity is expressed in t km/ha. In a cropping year, the totals are 60 and 65.2 t km/ha at Minnipa and Cungena, respectively.

In pasture years of the rotation, when only spraying is done, the total traffic intensity is only 2.4 t km/ha. Coverage of the soil by the hooves of grazing sheep has not been considered. If we assume a typical rotation with 50% cereal cropping and 50% pasture, then this gives mean annual traffic intensity values of 31.2 t km/ha at Minnipa and 33.8 t km/ha at Cungena.

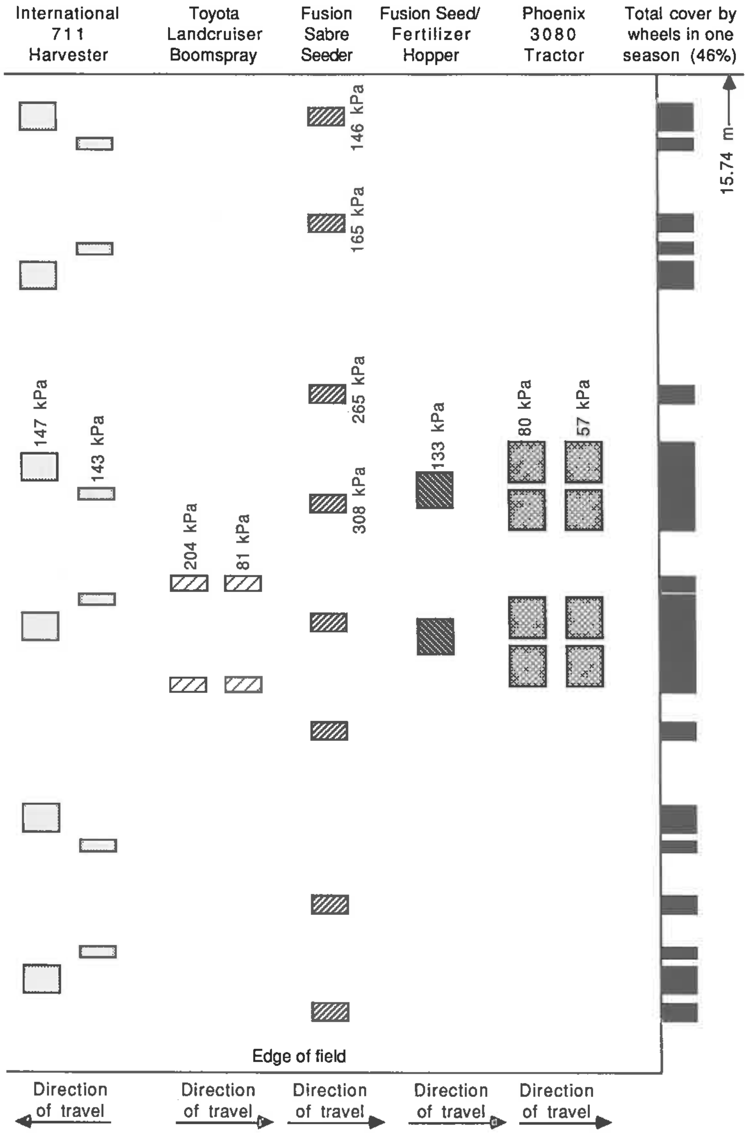

FIG. 3. Wheel positions relative to the edge of the field at Cungena. Actually, the "edge of the field" is the inside edge of the firebreak. Figures show mean values of ground contact pressure.

Different parts of a field receive different amounts of traffic. This is illustrated in Table 7 where it is shown that, in a cropping year, up to 7 wheel passes can occur over a given spot at Minnipa and up to 13 at Cungena. These figures are only approximate estimates because they assume that the wheels will pass in exactly the position calculated. Driver error will ensure that these figures are never attained exactly. On and near the field diagonals, the traffic levels are greater. These greater local levels have not been estimated.

The values in Table 7 can be used to calculate the total area of wheel tracks per unit

TABLE 6. TRAFFIC INTENSITY AT CUNGENA (t km/ha) FOR ONE SEASON'S OPERATIONS

Operation	Machine	Mass (t)	km/ha	t km/ha
1st Scarifying	Tractor	11.84	0.635	15.53
	Chisel plough	12.62		
2nd Scarifying	Tractor	11.84	0.635	15.53
	Chisel plough	12.62		
Seeding (incl. hopper)		30.55	0.635	19.40
Boomspray		3.30	0.722	2.40
Harvesting		6.77	1.818	12.31
Total for one season				65.17

TABLE 7. PERCENTAGES OF THE AREAS OF FIELDS AT MINNIPA AND CUNGENA COVERED BY WHEELS *N* TIMES IN A CROPPING YEAR

Number of wheelings, *N*	Minnipa	Cungena
1	17.2	17.3
2	—	—
3	21.4	10.2
4	0.7	2.5
5	—	1.5
6	5.1	7.1
7	3.9	1.8
8	—	—
9	—	1.7
10	—	2.3
11	—	—
12	—	0.8
13	—	1.5
Total coverage (%)	48.3	46.7

area of field in a cropping year. The resulting ratios are 1.42 for Minnipa and 1.88 for Cungena.

The figures in Table 7 imply that at Minnipa and Cungena, 51.7% and 53.3% respectively of the field areas receive no wheeling. Whilst this is true in principle, a number of factors ensure that the whole field area becomes wheeled and compacted over the years. These factors include driver error (as mentioned previously), variable width of the firebreaks from year to year, and changes in farm machinery every few years to new models which will almost certainly have different widths and wheel spacings.

CONCLUSIONS

The values obtained from the properties at Minnipa and Cungena are not very different, and so we shall consider the averages of these. In a cropping year, about 47.5% of the area of a field is covered with wheel tracks, whereas in a pasture year only about 3.2% is covered. The average traffic intensity is 62.6 t km/ha in a cropping year and 2.4 t km/ha in a pasture year. This gives a mean annual traffic intensity of 32.5 t km/ha.

The average value of the ratio of total area of wheel tracks per unit area of field is 1.65 in a cropping year.

These figures indicate that traffic amount and intensity is much lower in this semi-arid, Mediterranean-type climate in southern Australia than has been reported in northern Europe. In spite of this, problems associated with soil compaction appear to be increasing steadily. These effects of compaction are therefore more likely to be due to the absence of mechanisms which tend to undo the effects of compaction than due to abnormally high values of field traffic intensity.

In these areas considered, there is no freezing and thawing of soil water which could loosen the soil. There is wetting and drying, but the clay contents of the soils are often not high enough to give significant swelling and shrinking. Earthworm activity is very low. Tillage deeper than a few cm is not practical in many areas for a variety of reasons. These include: the presence of rocks or tree roots in the sub-soil, the need to avoid bringing undesirable (e.g. sodic) sub-soil to the surface, and also the requirement to keep the seed reserves of the legume pastures in the top few cm.

Reducing the amount and intensity of traffic or keeping the traffic off the cropped parts of the field would reduce the steady increase in the adverse effects of soil compaction. Ways of achieving this which are being investigated include the use of controlled traffic of fixed (permanent) wheel tracks perhaps with the use of gantries [13, 14]. However, it is difficult to integrate these approaches into systems involving grazed pastures.

Other possible approaches to the problem include the development of improved forms of sub-surface tillage which could be useful in some areas, and the development of "biological tillage". Improvements through biological tillage could involve the introduction of exotic species of earthworms which are more active in dry conditions and/or the use of plants having root systems which are better able to penetrate compacted soil [15, 16].

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PRESSURE TRANSMISSION BENEATH WHEELS IN SOILS ON THE EYRE PENINSULA OF SOUTH AUSTRALIA

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Summary—Pressure transmission beneath the wheels of moving agricultural vehicles was measured in two soils of economic importance on the Eyre peninsula of South Australia. The vertical component of soil pressure was found to decrease more rapidly with depth than predicted by the equation usually used in soil mechanics. Equations are proposed which provide much better descriptions of the experimental data. The results are discussed in terms of detailed measurements of soil penetrometer resistance, bulk density and water retention characteristics.

INTRODUCTION

LOADING of soil by the passage of a wheel increases the density (or compacts) the soil and increases its strength and hence penetration resistance. Compacted, strong soil can provide considerable impedance to the elongation of plant roots [1], and this can have a significant effect on the yield of crops [2].

The magnitude of these effects depends on the pressures or stresses which are applied to the soil by the vehicle wheels and on the way that these pressures are transmitted down the soil profile. Equations for pressure transmission in soil have been considered by a number of authors [3–5] and will not be considered in detail here. However we shall refer to the standard equation for the vertical component of pressure, σ_z, at a depth z in soil beneath the centre of a uniformly-loaded circular plate. This is obtained by using the results of Boussinesq [6] for the stress distribution arising from a point load on the surface of an elastic solid, modifying this with the stress-concentration factor (ν) of Griffith [7] and Froelich [8] which accounts to some extent for the fact that soil is not an ideal elastic solid, and integrating this over the area of the plate following the procedure of Newmark [9]. This gives:

$$\frac{\sigma_z}{\sigma_m} = (1 - (1 + (\frac{R}{z})^2)^{-\nu/2}). \tag{1}$$

Here, σ_m is the uniform contact pressure between the plate and the soil, R is the radius of the plate, and ν is the pressure concentration factor.

For an ideal, elastic material, $\nu = 3$. For uniform soil, ν can take increasing values as the soil becomes increasingly wet and weak. Soehne [3] proposed values of up to $\nu = 6$, but more recently Horn [10] has identified soils where effective values of ν can range from <1 to >10.

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In this paper, we report some measurements of pressure transmission beneath the wheels of agricultural vehicles under wet conditions in two important soil types on the Eyre peninsula of South Australia.

MATERIALS AND METHODS

Field sites

Experiments were carried-out at Minnipa and Cungena on the Eyre peninsula of South Australia. The site at Minnipa (lat. 32°51′S, long. 135°09′E) is approximately 400 km NW of Adelaide, the capital of South Australia. The site at Cungena is approximately 60 km NW of Minnipa. The climate at these sites is mediterranean. At Minnipa, the mean annual rainfall is 330 mm of which 262 mm falls in the growing season (May–November). At Cungena, the mean annual rainfall is only 0.85 of that at Minnipa, and is distributed slightly differently. Daily rainfall at Cungena, R_c, is approximately related to that at Minnipa, R_m, by

$$R_c = R_m\,(1.08 - 0.0012\mathrm{JD}) \tag{2}$$

where JD is the Julian Date (or day number) of the year. The discontinuity of equation (2) between days JD = 365 and JD = 1 is unimportant because negligible rainfall occurs in the period December–March.

The soil-landscapes on the Eyre peninsula have been described by Wright [11]. Minnipa falls in a Calcarenite plains sub-region and into unit DD7 (plains and swamps). Cungena falls in a Dunefields sub-region and into unit DD2 (plains and dunes). The DD7 and DD2 sub-regions are shown in Fig. 1. These regions are used for cereal production. The soils at the Minnipa and Cungena sites are fairly representative of cereal-growing soils in the respective sub-regions.

The soil at Minnipa is classified under Soil Taxonomy [12] as Calcixerollic xerochrept (loamy, mixed, thermic) and that at Cungena as Calcixerollic xerochrept (coarse loamy,

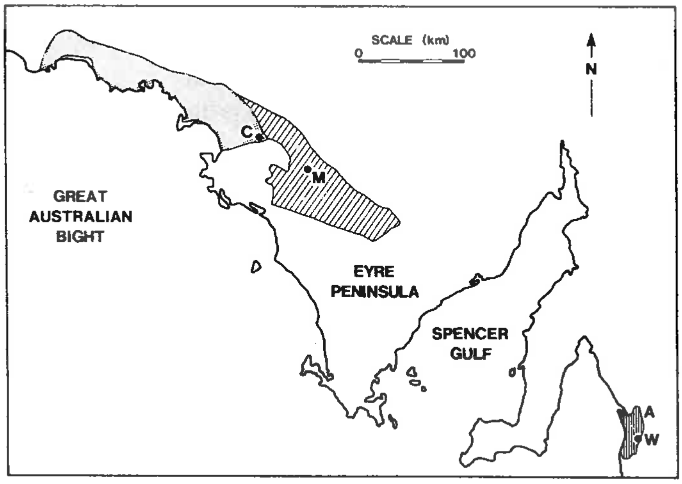

FIG. 1. Map showing the locations of Minnipa, M, and Cungena, C, relative to the Adelaide metropolitan area, A, which also contains the Waite Agricultural Research Institute, W. Dotted area shows soil-landscape type DD2 and the diagonally-hatched area shows soil-landscape type DD7.

FIG. 2. Experimental site at Cungena. The seeder with its wings up can be seen behind the tractor.

carbonatic, thermic). Under the Australian Factual Key system [13], both soils are Gc1.12. Some properties of the soils are given in Table 1.

The water retention characteristics of the soil profiles were determined. For water potentials of -100 kPa and -1.5 MPa, samples were dried from saturation on ceramic pressure plate extractors. For water potentials of -10 kPa, samples were drained from saturation on "porosity 4" sintered glass funnels. Profiles of gravimetric water content corresponding to these three potentials are given in Figs 3 and 4 for the Minnipa and Cungena sites, respectively.

TABLE 1. SOME PROPERTIES OF THE SOILS AT THE EXPERIMENTAL SITES

Depth (mm)	Texture	pH* (%)	ESP	$CaCO_3$ (%)
Minnipa				
0–70	light sandy clay loam	8.3	1	11
70–230	loam	8.6	2	13
230–520	clay loam	8.8	13	31
520–840	clay loam	9.4	22	34
840–1220	clay loam	—	—	34
Cungena				
0–50	sandy loam	8.4	1	—
50–150	light sandy clay loam	8.6	2	—
150–500	sandy loam	8.5	2	—
500–870	sandy loam	9.5	23	—

*Measured on 1:5 soil:water suspension

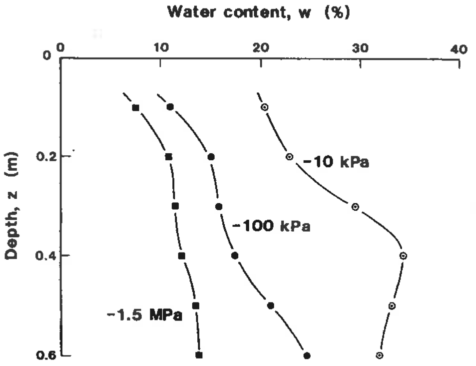

FIG. 3. Water-retention profiles at Minnipa.

The experiments reported here were carried-out in April 1987 at the end of the hot, dry summer period. Therefore, both sites were irrigated with sprinklers for several days before the measurements were made.

Soil measurements

Pits of about 0.75 m depth were dug in the experimental areas. The pits had vertical walls. Samples were collected from the pit walls for determination of gravimetric water content profiles. Volumetric water contents were also measured with a time-domain reflectometer [14] having twin probes of 150-mm length, 6.35-mm diameter and 50.8-mm separation (between centres). These probes were pushed horizontally into the vertical pit walls at the depths of the required measurements.

Soil strength was measured with an electronic recording penetrometer [15]. This had a cone of 12.6-mm diameter and a total enclosed angle of 30°. The penetration resistance was recorded at 30-mm depth increments. Soil strength profiles at the two sites were taken before and after the wheel passes. Additionally, a large number of soil strength profiles which were measured on different dates during 1986, when the soil was at a range of different water contents, were analysed. Soil bulk density profiles were measured with a high-resolution gamma-ray probe [16]. Soil densities (the densities of the wet soil) were measured at 50-mm depth increments, and were subsequently corrected for water content to obtain the dry bulk

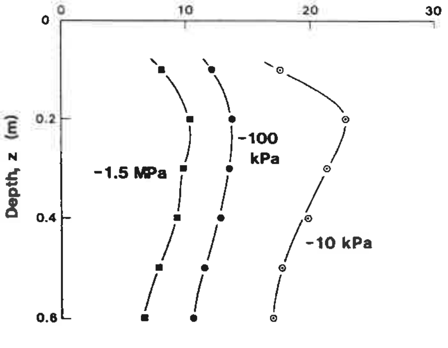

FIG. 4. Water-retention profiles at Cungena.

densities. The experimental values of gravimetric water content, volumetric water content and dry bulk density were all mutually consistent.

The pressures in the soil caused by the passage of the wheels over the surface were measured as follows. Pressure cells [17] of 30-mm diameter and 6-mm thickness were inserted at four depths at a horizontal distance of 300 mm into the undisturbed soil from the vertical pit walls. In order to insert each cell, rectangular holes of the same size were first made with a rectangular-section tube. The pressure cells were first individually calibrated with standard gas pressures in the laboratory.

When the eight pressure cells had been inserted, the pit was refilled. The pressure cells were connected to a data-logger which was designed and constructed at the University of Bayreuth. The data-logger was started just before each wheel pass over the buried pressure cells, and recorded the signals from each pressure cell at intervals of 0.1 s.

At the conclusion of the wheel passes, the pressure cells were dug out, and the recorded signals were converted to soil pressures using the individual calibration curve for each cell.

Vehicle specifications

At both Minnipa and Cungena sites, soil pressures were measured beneath tractor driving wheels and the inner wheels of seeders (with their wings-up). At Minnipa, the tractor was an "International 1486" (2 wheel-drive), fitted with dual rear wheels, and the soil pressures were measured beneath the inner driving wheels. At Cungena, the tractor was a "Phoenix 3080" (4-wheel drive) fitted with four dual wheels. Soil pressures were measured beneath the outer wheels. The seeders at both sites had a central portion (about one-third of the width) carried on an inner set of wheels, and two outer "wings" which could be lowered hydraulically to obtain the full working width of the machine (approximately 8.6 m at Minnipa and 17 m at Cungena). These wings had outer wheels to support the wings when in the down position. At Minnipa the seeder had 4 wheels (2 on the centre section and 1 on each wing). At Cungena, the seeder had 8 wheels (4 on the centre section and 2 on each wing). Soil pressures were measured with the wings up, so as to determine soil pressures under conditions of extreme loading.

The load on each wheel was measured with portable scales ("TELUB AB" weighing plate model 10T) which were checked against a commercial weigh-bridge. The contact area between each wheel and the soil was measured as follows. Talcum powder was puffed around the edge of the contact area. The vehicle was then driven off, and a sheet of clear plastic (polythene) was placed on the soil. The contact area, clearly outlined by the talcum powder, was then drawn-around with felt-tipped pen. The contact area was later measured from the plastic sheet in the laboratory.

Some details of the wheels, loads and tyre parameters are given in Table 2. The wheels were driven on the undisturbed soil over the pressure cells at a speed of approximately 0.7 m/s.

RESULTS AND DISCUSSION

Profiles of gravimetric water content, penetrometer pressure and dry bulk density in the field sites at the time of the experiments are shown in Figs 5, 6 and 7. Comparison of Fig. 5 with Figs 3 and 4 shows that the sites were at field capacity (-10 kPa) or wetter than field capacity down to 0.6 m depth. Computer modelling of soil water distribution at the Minnipa site shows that the soil profile would rarely, if ever, become as wet as this naturally [2]. The profiles of penetrometer pressure (Fig. 6) and dry bulk density (Fig. 7) both show evidence of

TABLE 2. VEHICLE, WHEEL, LOAD AND TYRE PARAMETERS AT THE TWO EXPERIMENTAL SITES

Site	Vehicle	Wheel	Load on wheel (kg)	Tyre Size	Tyre Ply	Inflation pressure, σ_t (kPa)	Contact area, A (m^2)
Minnipa	Tractor	Rear, inner	2940 (pair)	24.5-32	10	97	0.29
		Rear, outer		18.4-38	8	97	0.17
	Seeder	Inner wings-up	2480	12.0-24	10	280	0.13
		wings-down	1940				0.11
		Outer wings-up	0				0.00
		wings-down	540				0.077
Cungena	Tractor	Front, left pair	3700	24.5-32	10	125	0.21 (each)
		Rear, left pair	2500	24.5-32	10	125	0.21 (each)
	Seeder	Inner wings-up	3160	14.9-26	10	280	0.12
		wings-down	2050				0.09
		Outer wings-up	0				0.00
		wings-down	1110				0.09

a compacted layer between about 0.08 and 0.2 m depth at the Minnipa site. Tillage in this area is generally shallow and the soil is not normally loosened below seed-bed depth (60–80 mm).

The soils were very strong considering their high water contents. In terms of plant growth, a value of $Q_p = 1$ MPa will reduce the rate of elongation of roots to about 60% of maximum, and a value of $Q_p = 2$ MPa will reduce it to about 35% of maximum [1]. These high values of soil strength are all the more significant in view of the low levels of soil structure (such as cracks and bio-pores) at these sites which could provide pathways of low mechanical impedance for root elongation [18, 19]. Soil strength is, of course, even greater when the soil is drier. Analysis of a large number of measurements from 1986 has enabled us to develop the equations for soil penetrometer pressure in various depth layers at the two sites. The equation used is

$$Q_p = \exp(k + m\rho + nw), \text{ MPa} \tag{3}$$

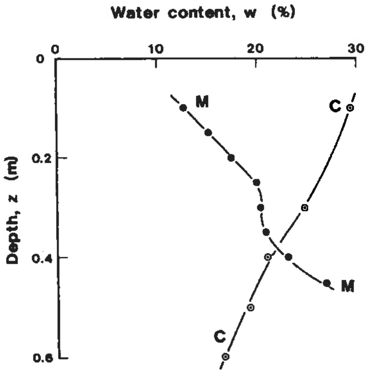

FIG. 5. Profiles of gravimetric water content, w(%), at Minnipa, M, and Cungena, C, at the time of the experiments.

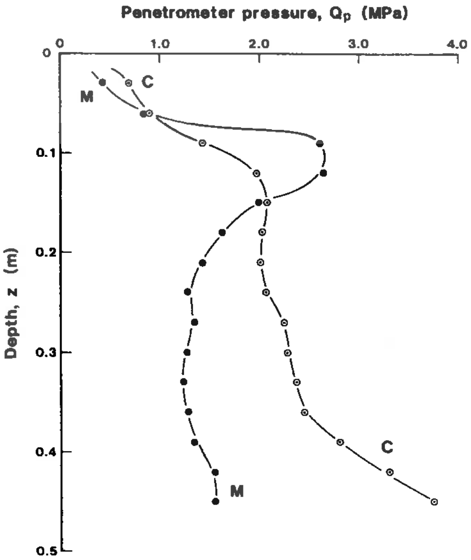

FIG. 6. Profiles of penetrometer pressure, Q_p (MPa), for the undisturbed soil at Minnipa, M, and Cungena, C, at the time of the experiments.

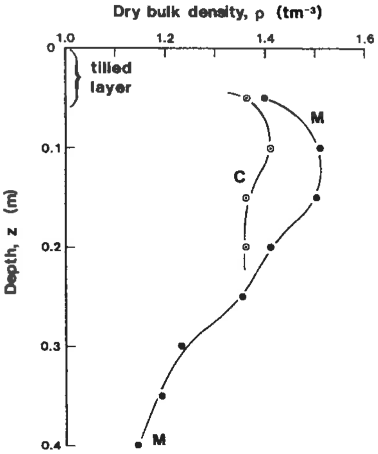

FIG. 7. Profiles of dry bulk density, ρ (t/m^3), at Minnipa, M, and Cungena, C, at the time of the experiments.

where Q_p is the pressure for penetrometer penetration into the undisturbed soil, ρ is the dry bulk density (t/m^3), and w is the gravimetric water content (%). Some values of the adjustable parameters k, m and n are given in Table 3.

Typical curves of the changes in soil vertical pressure as one of the wheels of the tractor at Cungena passed over the soil are shown in Fig. 8. It can be seen that the loading time is not very great, the soil pressure is above 50% of maximum for only about 0.4 s at the vehicle speed of 0.7 m/s. This corresponds to loading times (for pressures above 50% of maximum) of about 0.2 s and 0.1 s at the more normal operational vehicle speeds of 5 and 10 km/h, respectively.

TABLE 3. VALUES OF THE ADJUSTABLE PARAMETERS k, m AND n OF EQUATION (3) FOR DIFFERENT DEPTH LAYERS AT MINNIPA AND CUNGENA

Depth (mm)	*k*	*m*	*n*
Minnipa			
0–50	-7.3	6.0	-0.105
50–250	-6.2	6.0	-0.105
>250	-4.2	6.0	-0.105
Cungena			
0–50	-6.3	5.0	-0.061
>50	-4.8	5.0	-0.061

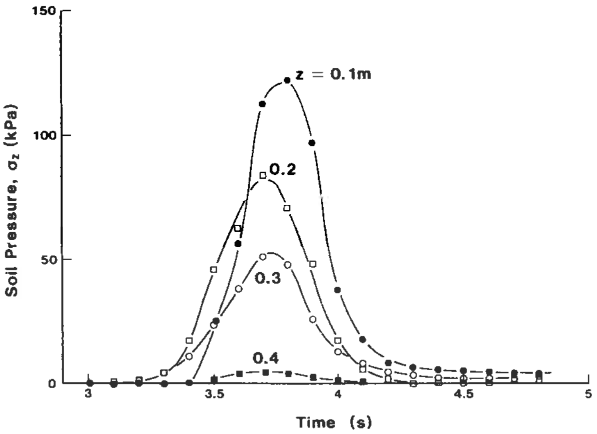

FIG. 8. Vertical pressures, σ_z (kPa), measured in the soil at depths, z (m), as a function of time (s) during a passage of a tractor wheel at Cungena.

Figure 9 shows a plot of the mean maximum peak soil pressures at various depths below the tractor wheels at Cungena. These data are well-described by the equation

$$\sigma_z/\sigma_o = \exp -(z/z_o)^{\gamma}, \tag{4}$$

where σ_o is the maximum pressure which occurs at the soil surface ($z = 0$), z_o is an (adjustable) reference depth (at which $\sigma_z/\sigma_o = 1/e$), and γ is an adjustable parameter which, in combination with z_o, describes the rapidity of attenuation of peak soil pressures with depth. Values of the parameters in equation (4) for the passes of the tractor and seeder wheels at the two sites are given in Table 4. Where pressures less than $\sigma_2 = 20$ kPa were recorded, it is possible that proper contact was not developed between the soil and the pressure cells.

Equation (1) does not provide a good description of the variation of soil pressure with depth. In particular, it predicts not enough pressure near the soil surface and too much pressure at greater depths. A similar deficiency in equation (1) was found by Blackwell and Soane [20]. This deficiency is caused partly by non-uniformity of the contact presure between a tyre and the soil [21, 22], and partly because of non-uniformity of soil properties with depths (Figs. 5–7). On strong soils, with shallow tilled layers, like those investigated

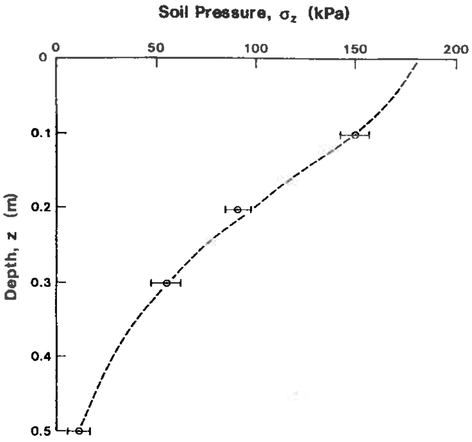

FIG. 9. Mean maximum vertical pressure, σ_z (kPa), as a function of depth, z (m), beneath a tractor wheel at Cungena.

TABLE 4. VALUES OF THE PARAMETERS σ_0, z_0 and γ OF EQUATION (4) FOR THE DIFFERENT WHEELS AT MINNIPA AND CUNGENA

Wheel	σ_0 (kPa)	z_0 (m)	γ
Minnipa			
Tractor (rear, inner)	65	0.21	1.1
Seeder (wings-up)	400	0.19	0.9
Cungena			
Tractor	180	0.27	1.6
Seeder (wings-up)	170	0.35	3.0

here, tyre tread patterns also contributes significantly to non-uniformity of contact pressure between the tyre and the soil.

It can be seen in Table 5 that the mean contact pressure, σ_m, is smaller than the tyre inflation pressure, σ_t. On hard (concrete) surfaces it is usually found that $\sigma_m > \sigma_t$ because of the carcass stiffness of the tyres. The result obtained here is due to the wheel sinkage into the shallow tilled layer. Comparison of the σ_t value with the vertical soil pressures σ_z from Fig. 9 shows that the soil pressure exceeds tyre inflation pressure at all depths down to $z = 0.2$ m for the tractor at Cungena.

For the purpose of comparison with other work, we have estimated the pressure concentration factors, ν, of equation (1). This was done by inverting equation (1) to obtain

$$\nu = \left[\frac{2 \log \left(\dfrac{\sigma_m}{\sigma_m - \sigma_z} \right)}{\log[1 + (\dfrac{R}{z})^2]} \right] \qquad (5)$$

TABLE 5. MEAN CONTACT PRESSURES, σ_m, TYRE INFLATION PRESSURES, σ_t, AND PRESSURE CONCENTRATION FACTORS, υ, CALCULATED FROM PRESSURES MEASURED AT $z = 0.3$ m AT MINNIPA AND CUNGENA

Wheel	σ_m (kPa)	σ_t (kPa)	υ (equation 5)	υ (equation 9)
Minnipa				
Tractor (average)	63	97	0.8	0.6
Seeder (inner, wings-up)	187	280	3.5	3.1
Cungena				
Tractor (average)	72	125	4.6	4.0
Seeder (inner, wings-up)	258	280	4.2	3.1

Values of σ_m were from Table 5, and values of the radius of the contact area, R, were calculated from the contact area, A, given in Table 2 using

$$R = (A/\pi)^{0.5} \tag{6}$$

The resulting values of ν were calculated using values of σ_z at $z = 0.3$ m, and are given in Table 5 for the various wheels. Values of ν calculated using σ_z at other depths differed slightly from those given in Table 5, being around $\nu = 5$ at 0.1 m depth.

The low value of ν for the tractor at Minnipa may be a consequence of the hard-pan at that site (Figs 6 and 7). A hard-pan can act like an elastic "bridge" or "beam" spreading out the load over a much wider area with a consequent reduction in ν. The larger value of ν for the seeder wheel at Minnipa would be because the greater load on the wheel (Table 2) and the greater ground contact pressure (Tables 4 and 5) were causing the soil in the hard-pan to fail plastically which would result in greater concentration of stress.

In order to improve on the predictions of equation (1) and its inverse, equation (5), we have taken some account of the non-uniformity of the pressure distribution over the area of wheel/soil contact. From Tables 4 and 5, we obtain the mean ratios

$$\frac{\sigma_o}{\sigma_m} = 1.6, \text{ and} \tag{7}$$

$$\frac{\sigma_m}{\sigma_t} = 0.7. \tag{8}$$

The pressure distribution over the area of contact can be described in two parts.

Firstly, a contact pressure $p_i = \sigma_o = 1.6\sigma_m$ acting over an inner area of radius $R/2$; and secondly, a contact pressure of $p_o = 0.8\sigma_m$ acting over the outer area or annulus of contact from $R/2$ to R. These pressures acting over these areas give the correct mean values, σ_m. The vertical pressure distribution for this combination can be written as the sum of two terms as given by equation (1):

$$\sigma_z = p_o[1 - (1 + (\frac{R}{z})^2)^{-\nu/2}] + p_e[1 - (1 + (\frac{R}{2z})^2)^{-\nu/2}], \tag{9}$$

where p_e is the extra pressure $(p_i - p_o)$ acting over the inner area. In this case $p_e = 0.8\,\sigma_m$, also. Equation (9) can also be expressed in terms of tyre inflation pressure using equation (8).

Equation (9) gives greatly improved estimates of the maximum soil pressures at small depth ($0<z<2R$). At greater depths, soil pressure becomes increasingly independent of the pressure distribution at the surface and becomes dependent only on the total load and the concentration factor, ν. Equation (9) cannot be solved for ν as in equation (5). However, values of ν can be obtained iteratively from equation (9). The values of ν obtained are less sensitive to z than with equations (1) or (5). The values are also somewhat smaller as can be seen in Table 5.

The mean of the values of ν obtained from equation (9) for the seeder at Minnipa and for the tractor and seeder at Cungena is $\nu = 3.6$. This value was obtained under the very wet conditions as described. As the soils dry and become stronger, as described by equation (3), the soils may be expected to become increasingly elastic and ν would be expected to become closer to 3. Values of ν greater than 4 or 4.5 seem unlikely in these soils.

Figure 10 shows the ratio of penetrometer pressures after, Q_a, and before, Q_b, wheel passes at Minnipa and Cungena. At Cungena, the soil strength as measured by the penetrometer, has been increased significantly at depths down to $z = 0.1$ m by the wheel pass, with little change below that depth. At Minnipa, on the other hand, soil strength was reduced significantly by the wheel pass between depths of $z = 0.05$ m and $z = 0.25$ m.

This weakening of soil by compaction is largely caused by the breakage of cementing bonds between the soil particles during plastic failure. Another mechanism which can contribute to this effect is the reduction of effective water stresses as very wet soil is compacted. Such strength decreases have been described previously and are the basis of the soil property known as "sensitivity" in civil engineering [23, 24]. When such disturbed soil is left without further disturbance, soil particles can rearrange into configurations of lower energy and cementing bonds can re-form and become stronger with time. These mechanisms give rise to the "age-hardening" of soil after disturbance [25, 26, 27]. This age-hardening can take from weeks to years depending on the soils type and the conditions.

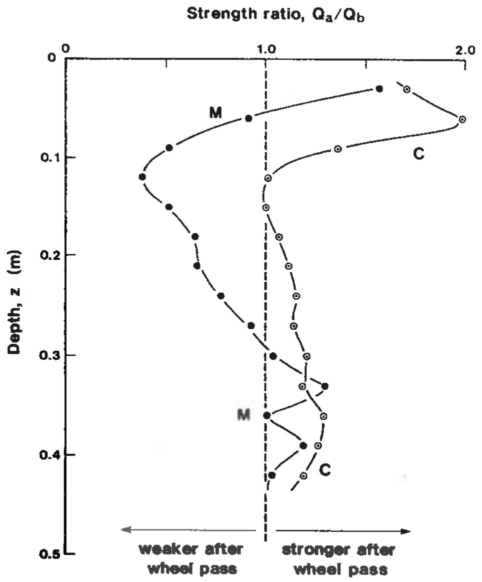

FIG. 10. Strength ratio, Q_a/Q_b, comparing the penetrometer resistance, Q_a, after a wheel pass with the penetrometer resistance, Q_b, before a wheel pass at Minnipa, M, and Cungena, C.

It seems likely, therefore, that the strength, Q_p, of the Minnipa soil will increase steadily with time until $Q_p > Q_b$ as a result of the extra compaction which it has received.

CONCLUSIONS

(1) The soils on the sites at Minnipa and Cungena were already fairly strong and compact, but under the wet conditions of the experiment the wheels of agricultural vehicles were still able to cause plastic failure.

(2) Significant pressures are transmitted in these soils beneath the wheels of agricultural vehicles down to depths of at least 0.3 m. The variation of maximum vertical pressure with depth was well-described by a new, empirical equation (equation 4) and by equation (9) which accounted in a rather simple way for the non-uniformity of the pressure distribution over the area of soil/wheel contact.

(3) Pressure concentration factors fell into the range of values obtained by other workers. The smallest value obtained for the tractor at Minnipa was attributed to a hard-pan below the depth of tillage distributing the load over a greater area.

(4) Penetrometer strength of soil can be less after the passage of wheels than in the undisturbed soil. This is mainly due to soil sensitivity caused by the breakage of bonds between soil particles. Age-hardening after the passage of the wheels would be expected to cause a steady increase in soil strength to a new equilibrium value greater than that before passage of the wheels.

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