



**SPEAR SOIL OPENER EFFECTS ON SOIL PHYSICAL
PROPERTIES
& IMPACT ON WHEAT PRODUCTION**

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To my wife Sarah and my daughters Jessica, Stephanie and Sophie,
for their love and encouragement.

The Parable of the Sower.

“A farmer went out to sow his seed. As he was scattering the seed, some fell along the path, and the birds came and ate it up. Some fell on rocky places, where it did not have much soil. It sprang up quickly, because the soil was shallow. But when the sun came up, the plants were scorched, and they withered because they had no root. Other seed fell among thorns, they grew up and choked the plants. Still other seed fell on good soil, where it produced a crop – a hundred, sixty or thirty times what was sown. He who has ears, let him hear.”

Matthew 13:1-9. New International Version.

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ABSTRACT

The mild Mediterranean climate of the Mid-North of South Australia is noted for cold wet conditions around the time of seeding. The red-brown earth of this region commonly has poor friability and problems with surface sealing or crusting when fine warm weather conditions follow seeding. These factors contribute to significant problems with seedling establishment if soil openers do not create a favourable seedbed environment.

Literature reviewed has demonstrated that to improve soil opener design, a greater degree of measurement of seedbed physical properties and the resulting effect on seedling establishment and growth is required. There is a paucity of published research in the area of opener effects on soil physical properties and linking these changes to plant root growth and plant top growth and grain yield. This research aimed to quantify the effects of different design parameters that spear type seed drill soil openers have on soil physical properties and the resulting effects on crop establishment and grain yield of wheat.

Field experiments were initially direct sown to spring wheat to quantify the relative benefits to crop production of spear type soil openers in comparison to other common soil opener types. Design factors that characterise the shape of a spear soil opener including width, angle of incidence to the soil, leading edge sharpness, underside area in contact with the soil, were investigated further. Seeding into dry warm and cold wet seeding field conditions and repeated using controlled environment techniques utilising soil bins and soil cores. The resulting effects on soil physical properties and plant growth were measured.

Spear type opener width and sharpness of the leading edge has a significant impact on crop establishment and growth. A lack of significant correlation between soil physical properties and plant establishment and growth in this research prevented modelling plant response data to soil physical property changes. A simple matrix of crop establishment response to different establishment conditions and soil opener design was developed.

The research concluded that wide and sharp type spear openers should be used in preference to narrow and blunt spear openers. Use of sharp spear openers may significantly increase grain yield compared with blunt or flat spear openers in dry establishment conditions on a non-compactable poorly structured soil by 8.2%. In wet establishment conditions on a compactable well structured soil by up to 20%.

Soil opener shape factors such as a flat underside and a blunt leading edge can increase penetration resistance and energy required through increased soil bulk density, leading to a reduction in total plant emergence. These changes in soil opener shape can lead to a significant reduction in plant emergence that significantly correlates with grain yield. This has significant implications for the soil opener manufacturing industry who appear to be give preference to blunt openers in an attempt to improve wear life and attachment longevity of tungsten carbide technology.

STATEMENT OF ORIGINALITY

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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

27th June 2000

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1. INTRODUCTION

1.1 Background

The quest to improve and optimise the design and use of seed drill soil openers has been going on since the invention of the seeder itself. In recent times substantial changes have occurred. There has been increased adoption of reduced tillage, no-tillage and direct drill seeding systems by farmers for reasons of soil resource protection and cost reduction. This has created a greater need for the seed drill ground engaging component to perform a number of functions on top of the principal function of placing seed accurately into the soil.

The first recorded use of animal powered seeding equipment was around 2100 B.C. by the ancient Egyptians. Metal tipped wooden seed drill plows (Figure 1.1) fitted with a woven seed funnel and bamboo seed tube were used to deliver seed to the furrow (Anderson, 1936). Of significance is that such a development was aimed at improving crop emergence in hostile environmental conditions similar to those which exist in Australia.

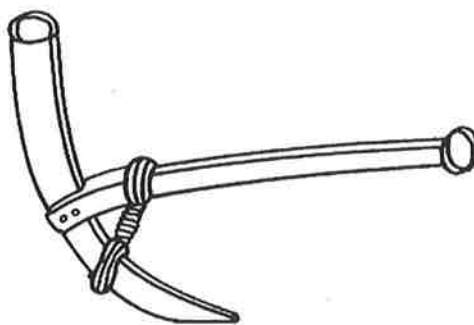


Figure 1.1 Early wooden plow, Thebes, Egypt, circa 3000 B.C. (from McKyes, 1985).

There appeared to be little attempt at that time to develop parallel technology in the more favourable rainfall conditions of Europe where hand broadcast seeding of cereal

crops persisted until the 18th century. During this period in England, Jethro Tull conceptualised, designed and constructed the first seed drill (Tull, 1733). This drill which sowed 3 rows of seed had narrow coulter hoe openers shaped to enter the soil readily, behind which were channels to funnel the seed into the ground.

The first major Australian variant on the seed drill was the development of a seeding machine by a New South Wales farmer, Raimond Ash Squire, named the 'combine'. This was a spring tine drill cultivator with a combined cultivation and seeding action achieved by replacing the seeder undercarriage with a four rank bar cultivator undercarriage. This was fitted with seed delivery tubes on the middle second and third ranks and hoe coulters or wider cultivator points (Wheelhouse, 1966). This machine was first commercially produced in 1917 by H.V. McKay and met with instant success as it reduced the need for one cultivation. Crop emergence was also improved due to improved soil tilth around the seed. This was in essence the beginning of reduced tillage seeding systems in Australia. In the 1950's there was a significant development with the first seed metering system to incorporate pneumatic distribution termed an 'air-seeder'. This was developed and commercially produced by Simplicity Air-seeders in Queensland (Norris, 1985). These seeding units enabled the use of a fully functional cultivator with an add-on seeding function.

The commercial development of the 'trash combine' and the 'air-seeder', both having improved tine break-out and tine trash clearance, have allowed widespread farmer based experimentation with stubble retention and minimum tillage systems. The growing acceptance of these agronomic practices along with the increased emphasis now being placed on optimising seedling emergence and achieving correct plant

populations, have led to more critical evaluation of the agronomic performance of seed drill soil openers and seeding equipment (Norris, 1985).

Advances in the formulation of metal alloys, and more durable methods of casting and tempering soil ground engaging components, as well as significant improvements in bonding of wear protection materials such as tungsten carbide have improved the potential wear life and increased soil cultivation and seeding cost efficiency. The geometry of the ground engaging components leading edge and the integrity of the ground engaging opener shape can now be maintained for a greater duration of its total wear life. These new materials and methods of tillage component wear protection has enabled more complex and sophisticated tillage and seed drill ground engaging components to be produced. This has in turn created new problems such as brittle cast material failing in stony soils as well as failure to retain the wear protection on the leading edge of points and shares when impacting on stones.

The success of the spear type seed drill opener in promoting better emergence, faster growth and higher grain yields in Australia and North America , has caused wide adoption by both the farming and manufacturing industries. The reasons for the success of spear type soil openers can be attributed to very accurate seed placement when combined with and integrated into seed delivery tube design. However, the effect of spear type openers on soil physical properties has not been adequately quantified, although manufacturers make many claims.

In particular, the different effects of a number of spear type seed drill opener design parameters such as width and leading edge design need further investigation. Changes

in design parameters are now possible because of the advances in metal casting technology and wear protection. These factors need to be quantified before significant further advances can be made, not only in spear type design, but also the influence of these factors on seed drill points in general.

1.2 Aims and objectives

The broad aim of the research reported in this dissertation is to quantify the effects of the main spear type seed drill soil opener design parameters on soil physical properties and the resulting effects on establishment and grain yield of wheat in loamy soils of South Australia. The five main objectives associated with this research are:

- (i) To quantify the relative importance of spear type seed drill soil opener width, on soil physical properties and consequent plant establishment and growth.
- (ii) To quantify the relative performance of a spear type seed drill soil opener and its interaction with combined seed row aligned deeper cultivation (to create improved seed bed tilth), on soil physical properties and plant establishment and growth.
- (iii) To assess the effects of modifying the spear type seed drill soil opener design on soil physical properties and consequent root development and growth of wheat in poor and well structured loams over a range of water contents.
- (iv) To investigate the effects of modifying commercial spear type soil opener designs and effects of wear on soil physical properties and the resulting effects on root development and wheat growth.
- (v) To specify the optimum design parameters for a spear type seed drill soil opener to maximise establishment, growth and grain yield of wheat on red-brown earths in South Australia.

2. LITERATURE REVIEW

2.1 Introduction

Soil tilth in the seed zone is important for optimum crop emergence and growth in sandy loam to heavy clay soils. However, achieving optimum seedling emergence and vigour is not always possible with furrow openers currently in use, as optimum tilth is usually not achieved. If seed-bed conditions are to be improved, we need better understanding of the interaction between soil openers and soil properties and the effects of soil physical changes on plant emergence and growth. The effect of different seed drill soil openers and covering devices with soil physical properties and correlation of this to plant growth is not fully understood (Ward *et al.*, 1991).

A large amount of research and development on soil openers is commercially driven and as such, little or none of the research information gathered is ever published (Fisher *pers. com.*, 1995; Robotham *pers. com.*, 1994). The only official record of a research input into seed drill soil opener design appears only when a patent is issued. For example, United States Patent 1991 US 5,025,736 and Canadian Patent Application 1991 CA 2,012,783 both of which were significant new changes in seed drill soil opener design. A considerable amount of this commercial seed drill soil opener research and development effort is carried out by both state and federal United States and Canadian governments, universities and other research organisations. Unfortunately most of this research is bound by commercial contract privacy provisions and is often barred from publication. Cost constraints and insufficient time can also often prevent companies from conducting research of publishable quality

Considering this, the review of literature covers the current state of published knowledge on the interactive influence of seed drill soil openers and soil physical properties on emergence, growth and development of cereal grain crops such as wheat. The aims of this review are to define the properties of an ideal seed-bed for crop establishment and to describe how closely different types of seed drill soil openers create these seed-bed conditions in Australia.

2.2 Properties of the seed-bed

The seed-bed is a biologically dynamic layer of soil that has a profound influence on the establishment, growth and ultimate production of grain crops. Some researchers view soil in the seed-bed as a porous non-dynamic media in which the soil supplies five of six major factors affecting plant growth. These factors are water, air, nutrients, mechanical support for plant roots and heat to enhance chemical and biological reaction. The non-soil factor is radiant energy (sunlight).

Dry periods occur regularly in most non-irrigated agricultural areas of the world, during which crops need to endure dry soil conditions. Many areas of southern Australia often have limited rainfall during the early seeding period, which imposes dry crop establishment conditions. Often crops are sown into dry soils to await the onset of rains before germination. Baker *et al.* (1996), have established that a dry, untilled, compact soil allows more successful seed germination and seedling emergence than dry, tilled, less compact soil. In contrast, particularly in mid-winter sown crops, soils may be wet at seeding or soon after seeding, creating a different series of difficulties for the establishing crop. In both cases, the type of tillage and seed placement system may be used to manipulate soil physical conditions in the seed-

bed to optimise the probability of germination, emergence and subsequent crop growth (Baker *et al.*, 1996).

To determine what effect a soil opener should have on the soil to optimise crop establishment and growth, it is necessary to determine what constitutes an ideal seed-bed. The following section looks at the various factors that can be used to characterise and identify ideal seed-bed conditions. These include the following factors:

- (i) Water content and soil water suction,
- (ii) Air-filled porosity,
- (iii) Seed-bed aggregate size distribution,
- (iv) Soil strength,
- (v) Soil temperature,
- (vi) Soil biological factors.

2.2.1 Water content and soil water suction

The soil moisture content at seed germination and seedling emergence is a critical factor in dryland farming (Reed and Dyck, 1990). However, because of textural differences between soils, it is not possible to specify the water content of an ideal seed-bed. Rather the soil property called 'soil water suction' (positive value) or 'potential' (negative value) must be used. Soil water suction is simply the energy with which water is adsorbed to soil. The lowest suction that plants generally experience is at field capacity when soil water suction varies around 10 kPa. The highest suction that plants generally experience is at permanent wilting point (1500 kPa) where most crop plants will suffer irreversible water stress (Cass *et al.*, 1996).

The optimum moisture content for tillage and seeding is a water content (θ) close to the soil plastic limit water content (θ_{pl}) (Braunack and McPhee, 1991). The plastic limit corresponds to a change from plastic to a semi-solid state of consistency (Brady, 1984). A wet (high moisture) soil would generally undergo plastic failure during cultivation or seeding with a soil opener where θ is much greater than θ_{pl} . This is in contrast to dry (low moisture) soils, where θ is much less than θ_{pl} , and may undergo brittle failure as a soil opener passes through the soil.

Collis-George and Lloyd (1979), developed a field procedure to characterise a soil seed-bed. Measurement of water content, water potential, and also air-filled porosity, soil temperature and bulk shear strength are determined to be essential elements to specify soil conditions of consequence to seed germination and plant emergence.

2.2.2 Air-filled porosity

Cass *et al.* (1996), describes air-filled porosity of soil at field capacity (% volume), which is the minimum volume of air available to plants for possible prolonged periods of time, calculated as:

$$\text{AIR-FILLED POROSITY} = \text{TOTAL POROSITY} - \text{FIELD CAPACITY WATER CONTENT.}$$

Cass *et al.* (1996), describes the total soil porosity of the soil in units of % volume of air/volume of soil is (% volume), calculated as:

$$\text{TOTAL POROSITY} = 1 - (\text{BULK DENSITY}/\text{PARTICLE DENSITY}),$$

where particle density can be taken to be 2.65 Mg m^{-3} .

Adem *et al.* (1990), determined that oxygen concentration of > 2 % and air-filled porosity of > 10 % would not restrict germination and emergence of wheat seeds. Adem *et al.* (1990), determined that a soil bulk density achieving optimum air filled porosity on red-brown earth soil at a water suction of 10 kPa was in the range 1.00-1.38 Mg m⁻³. Soil bulk density of 1.51 Mg m⁻³ at the same suction significantly reduced wheat establishment. Eavis (1972), found that mechanical impedance restricted seedling growth as bulk density and soil suction increased. The roots of field peas were shorter and thicker as soil bulk density increased and also as aeration was reduced. Seed-bed aggregate size distribution will impact on the soil air-filled porosity and should also be considered in defining ideal seed-bed conditions.

2.2.3 Seed-bed aggregate size distribution

Adequate soil tilth in the seed zone is important for optimal crop establishment (Ward *et al.*, 1990). Soil tilth is simply the condition of soil or land that has been tilled. Greater soil tilth is when tillage has achieved more fine loose soil than before it was tilled. Ideally soil should be moist and friable at seeding to ensure seed germination and establishment. Direct drilling seeding techniques improve the structural stability of soil aggregates and soil organic carbon levels compared with conventional cultivation and seeding techniques in intensive cropping systems. (Chan and Mead, 1988; Hughes and Baker, 1977). Aggregate size distribution influences the suitability of the seed-bed as a medium for the germination and emergence of seedlings and the development of roots (Braunack and Dexter, 1989b).

Soil aggregate beds of different aggregate size distributions have different physical and possibly also chemical properties (Braunack and Dexter, 1989a). Soils can have

resulting poor structural properties from high levels of exchangeable Na^+ compared to Ca^{++} . Soils of very high pH (pH > 8.4 containing free CaCO_3 ions) or very low pH (pH < 3.8 containing exchangeable Al^{+++}) have low microbiological activity, reduced root growth and are at greater risk from imposed mechanical stress when wet than soils of more neutral reaction. (Hamblin, 1987).

Finer aggregates are produced in the seed-bed when soils are tilled dry or when they are subjected to increasing numbers of tillage operations. This can result in lower seed-bed bulk density and penetrometer resistance (Braunack and McPhee, 1991).

Braunack and Dexter (1988), found that a soil crust that had less medium sized aggregates (1-4 mm) than finer or larger aggregates, increased seedling emergence time and reduced total plant emergence, but did not significantly affect grain yield. The time to seedling emergence was shorter with small (< 1 mm diameter), dry aggregates, but if the seed-bed was wet, a delay in seedling emergence was observed. Dry matter production and grain yield both decreased with increasing soil aggregate size in a drier season, but 1-2 mm aggregates optimised plant growth and grain yield in a wetter season.

Whiteley and Dexter (1984a), found that soil aggregates < 1 mm in diameter which lie between 20-100 mm from the surface of the aggregate bed is only likely to reduce wheat root elongation with a root diameter of 0.5 mm or less. In contrast to this, emerging shoots are able to displace much larger aggregates from their path.

Research by Dexter (1986a), determined that the base of a seed-bed should be composed of fine aggregates of 1-4 mm for wheat. Wheat root development is more sensitive to soil strength if the seed-bed aggregate size is large (4-6.7 mm). Large aggregates (> 20 mm) or clods reduce wheat seedling emergence in a sandy loam soil at low soil moisture, but not at high moisture levels, while root growth is reduced with increased aggregate size at low or high moisture levels (Malik *et al.*, 1985).

Initial soil water content appears to be the controlling factor in producing a suitable seed-bed tilth. Soil water content of 0.86 times the plastic limit should produce optimum tilth in a cracking clay soil (Braunack and McPhee, 1991). Tisdall and Adem (1986), found that the wetter a loam soil is at tillage, the less dust (particles < 0.5 mm diameter) and more clods (> 20 mm diameter) were formed, reducing water infiltration into the soil to almost zero when tilled at a water content of 24 % (w w⁻¹). But if tilled at very high water contents (approaching filled capacity) remoulding of aggregate structure causes smearing and compaction. (Baker *et al.*, 1996)

Research by Ojeniyi and Dexter (1979), showed that the variation in aggregate and pore sizes in a red-brown earth soil increased when the soil was tilled wet (25.2 % w w⁻¹, i.e. 1.3 times the plastic limit). When tilled at lower water contents (12.6 % w w⁻¹, i.e. 0.65 times the plastic limit), there was less variation in aggregate and pore sizes. In dry conditions, but with soil moisture content increasing with depth, dry surface soil should be retained near the surface and moist seed-bed soil at the bottom regardless of aggregate size to optimise seedling emergence (Håkansson and Von Polgár, 1984).

Seed-bed soil structure is not uniform, as smaller aggregates and pores tend to accumulate at the base of the tilled layer in a tillage pass, with larger aggregates and pores at the top of the tilled layer creating a stratified seed-bed (Ojeniyi and Dexter, 1979). At low soil moisture levels in a unstratified seed-bed of aggregates < 4 mm, seed should be placed on the bottom of the tilled layer or sown deeper if aggregates are > 4 mm to optimise seedling emergence (Håkansson and Von Polgár, 1984).

Baker *et al.* (1996), identifies the amount of soil compaction, smearing and crusting created by different openers is a most important concern when seeding into wet soils. He defines smearing as very localised compaction within the slot (perhaps only 1-2 mm thick) and slot crusting is usually a smear, which has dried hard.

The adverse effects of soil hard pans, slot-crusting and soil smearing in the soil seed-bed are not confined to root growth. Roots growing in poorly structured soil produce hormones that slow the growth of the shoot, even if the roots can transport water and nutrients to the growing plant (Passioura, 1991).

2.2.4 Soil strength

Soil strength, rather than bulk density and variation in soil suction within the range in which plants can survive mainly determine the penetration and growth of plant roots (Barley *et al.*, 1965). Soil strength depends on the cohesive and frictional properties of the material. The shear strength of soil is often measured by loading a sample in one direction (normal to the force) until it fails. The failure envelope, which develops from applying increasing loads, is described by the Mohr-Coulomb equation (Hamblin, 1987; McKyes, 1985):

$$s = c_a + \sigma_n \tan \phi$$

where, s = shear stress or strength,

c_a = the cohesive force or the attractive force of particles for each other which is often the soil to tool adhesion strength, independent of normal pressure,

σ_n = the stress normal to the shear plane,

ϕ = the angle of internal friction between the soil and tool material.

The angle of internal friction can be used to predict the soil failure patterns ahead of a soil opener as described in Figure 2.1.

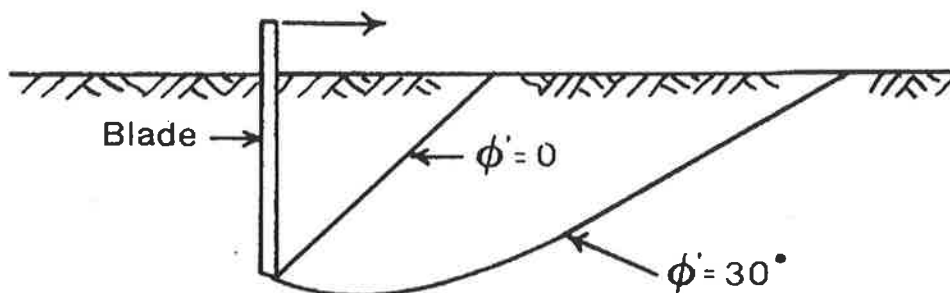


Figure 2.1 Soil failure patterns ahead of a wide cutting blade assuming internal friction angles of 0° and 30° . (from McKyes, 1985).

McKyes (1985), describes several methods of shear testing of soils. These include the laboratory based techniques using direct shear box and triaxial tests, or the rapid field based measurement techniques using an annular shear ring, shear graph, shear vane or cone and pocket penetrometers. The testing of soil shear strength in the field, rather than in the laboratory has several advantages in that it is a more rapid and less expensive process and the soil is in its natural state. Field tests however do not allow as much control of stress applications or soil water movement as can be obtained with a laboratory based triaxial test.

Baker *et al.* (1996), identifies the most important concern when drilling into already wet soil is the amount of compaction, smearing and crusting created by different openers. Smearing is described as a very localised compaction within the slot (perhaps only 1-2 mm thick) and slot-crusting is usually a smear which has dried hard.

Prebble (1970), found that wheat root penetration of a horizontal clay soil surface was decreased by soil smearing, simulated by drawing a wet spatula over the soil surface several times in a wet soil at a soil suction of 10 kPa. As the soil dried the efficiency of root penetration decreased by 50 % up to a soil suction of 100 kPa. This indicates that the process of soil drying after seeding can compound root growth difficulty when soil smear from the soil opener has occurred. Baker *et al.* (1996), determined that drilling dry or moist soils well below the plastic limit water content did not create significant smearing or compaction in the seed-bed furrow. Differences between openers reflected their ability to create a seed-bed environment that remains beneficial to establishment after the soil become wet.

Prebble (1970), interpolated that the limiting soil suction before root penetration is reduced through the seed-bed was near 1000 kPa for an un-smear soil and near 200 kPa for a smeared soil. The probable reason for the effect of smearing is that the dispersed soil caused by smearing seals pores that plant roots would have been able to access. In very wet soil, smeared surfaces may restrict drainage so a seed-bed groove may become and remain waterlogged. This will cause poor germination and seedling establishment and possibly impaired growth. Wheat seeds left under water do not develop normally.

Ehlers *et al.* (1983), found that the limiting penetration resistance for root growth is affected by tillage. In tilled soil above the plough pan, root growth was limited at a penetration resistance of 3.6 MPa. In the untilled soil and below the plough pan layer the limiting penetrometer resistance was 4.6-5.1 MPa. This difference is explained by the build-up of a continuous pore system in untilled soil, created by earthworms and the roots from preceding crops. The wheat seedling exploits these pores in developing deeper roots.

Plough pan layers are formed from shearing, deformation and compression of aggregates by soil openers and seeding impediments, particularly if the soil is worked at a high moisture content (McGarry, 1989). The benefits of tillage below the seed zone and avoiding the formation of hardpans and soil smear during the seeding operation should be most evident in wet soil conditions. Deep ripping through a compacted plough pan improved seedling vigour on a hard setting sandy loam (Mead and Chan, 1988; Finlay and Tisdall, 1990), non-hard setting sandy loam and clay soil (Elkins and Hendrick, 1983).

The extent of soil compaction during tillage, is related to the soil moisture content (Hill and Sumner, 1967), and the pressure applied to the soil (Zimmerman and Kardos, 1961). Soil water suction increased as compaction increased, accompanied by a decrease in bulk density (Taylor and Box, 1961). Severe compaction, which can occur in sandy loams, resulted in decreased soil water content at constant soil suction, particularly at high soil water contents (Hill and Sumner, 1967).

Seedling establishment problems due to seed burst in wet establishment conditions could increase as available water increases with soil water content. Wheel traffic can induce soil physical limitations to plant root growth. These limitations are usually observed as an increase in bulk density and penetrometer resistance (Voorhees, 1992). Jones (1983), found that increased clay content reduced soil bulk density, but also found that the clay plus silt content is a better index for calculating the critical bulk density for restricted root growth than clay content alone.

Differences in soil void geometry and distribution can account for the varied effect of bulk density changes on moisture content (Hill and Sumner, 1967). Soil water regimes are strongly influenced by the characteristics of the seed furrows such as bulk density distribution, tillage action of the seeding tool and surface furrow roughness (Tessier *et al.*, 1991b). The covering device or soil closer used behind the soil opener will influence these factors.

2.2.5 Soil temperature

Soil temperature affects both rate and growth distribution of plant roots in the soil (Kaspar and Bland, 1992). Lower soil temperature results in a reduced osmotic rate between the soil and plant cells. Lower air and soil temperature at the soil surface compared to the deeper soil will cause soil water and water vapour from depth to diffuse to the soil surface. Conversely a warmer air and soil temperature at the soil surface compared to the deeper soil will cause soil water and water vapour to draw to depth.

Soil temperature $< 10\text{ }^{\circ}\text{C}$ and $> 20\text{ }^{\circ}\text{C}$ at 45-85 mm depth can reduce cereal coleoptile length, reducing seedling emergence, increasing the importance of accurate depth of seed placement when seeding in soil temperatures outside of the optimum range (Radford, 1987). Adem *et al.* (1990), determined that a soil temperature of $29\text{ }^{\circ}\text{C}$ does not restrict the germination and emergence of wheat seeds. Soil temperatures in the red-brown earth soils of the Mid-North of South Australia are commonly between $10\text{-}15\text{ }^{\circ}\text{C}$ at 10 cm depth in the early winter (May) seeding period and $< 10\text{ }^{\circ}\text{C}$ at 10 cm depth in the mid winter (mid June to mid July) seeding period. This commonly results in 10-20 plus days respectively from seeding to crop emergence (Rainbow unpublished data, 1995).

Different cereal cultivars show wide variations in coleoptile length and root growth rates at different soil temperatures (Kaspar and Bland, 1992; Radford, 1987). Direct seeding furrow openers which only place seeds into a furrow do not affect seed zone soil temperature compared with deeper tillage type openers (Tessier *et al.*, 1991b).

2.2.6 Biological factors

Reduced early shoot growth may be associated with increased incidence of *Rhizoctonia spp.* in direct drilled crops (Kirkegaard *et al.*, 1994). However, growth reductions have often been observed in the absence of disease symptoms (Kirkegaard *et al.*, 1995). *Rhizoctonia spp.* have often been implicated as the cause of reduced crop shoot growth when infection is severe. Kirkegaard *et al.* (1995), determined there is no correlation of reduced plant growth at low or moderate levels of *Rhizoctonia spp.* with a possible infection of the germinating seed by fungal *Pythium spp.*, or the effects of phytohormones produced by inhibitory bacteria on the roots.

Direct drill seeding using a modified seed drill with a seed row aligned tine which cultivated 5-7 cm deeper than the seed row, as well as deep ripping to a depth of 27 cm, was effective in reducing the incidence of the fungal soil root disease *Rhizoctonia solani* in sandy soils and loam (Jarvis and Brennan, 1986; Roget and Jarvis, 1994).

2.3 Mechanics of emergence and root growth

A plant seedling can emerge by shear failure of the soil in the form of an inverted cone or by jamming small broken plates of surface soil, increasing the force required for emergence (Arndt, 1965a). When the elongating seminal roots of wheat encounter a dense layer of untilled soil with high soil strength, they can be deflected horizontally forming a mat of roots at the base of the seed-bed instead of penetrating through to the sub-soil (Dexter, 1986a). If this occurs, plants are unable to absorb sub-soil water reserves, increasing the plants sensitivity to drought. In conventional, multi-tillage seeding systems, the first tillage pass of an implement produces most of the soil break-up and some further break-up occurs with a second tillage pass, but not subsequent tillage passes (Ojeniyi and Dexter, 1979). Plant roots will grow horizontally along the top of a compacted soil layer until they find a path of low resistance such as vertical cracks in the sub-soil (Dexter, 1986b), but it is less likely that plant roots will preferentially grow towards biopores such as earthworm tunnels or channels left from the decay of root systems from the previous season (Dexter, 1986c). When a plant root meets an interface in the soil, it either may buckle and be deflected or continue to penetrate through the soil, the proportion of roots penetrating this interface can be determined by the model developed by Dexter and Hewitt (1978),

$$c = e^{-G(\theta)(P/P_{max} - P)}$$

When, c = proportion of roots penetrating an interface,

θ = angle of incidence of root with interface out of which the root is growing to wards the medium to which the root is growing into.

$G(\theta)$ is a function of θ , P is a transformed scale of soil strength and P_{max} is the limiting value of P .

Many soils, even if hard, contain macropores that provide niches for the roots to grow in, increasing the extent of growth of the root system. Because the roots are clumped within them, the rate at which the roots can extract water and nutrients from the soil between the macropores is considerably slowed (Passioura, 1991). Roots can also rupture soils by tensile failure. However, the thin radicle of wheat (0.3 mm diameter) trying to form channels in a compact loam, does not have enough bursting force to achieve this (Barley *et al.*, 1965).

Root size has a significant influence on the root's ability to penetrate strong soil layers due to the effect root diameter growth pressure can have on the mode of soil deformation during penetration (Materechera *et al.*, 1992). Whiteley *et al.*, (1982) found that root buckling stress (σ_b , kPa) was directly related to the maximum force (F_{max} , g) exerted by the root and inversely related to the square of the root diameter (d , mm). Therefore roots with larger diameters would have lowest buckling stresses;

$$\sigma_b = 4.98 F_{max} / \pi d^2.$$

Misra *et al.* (1986), demonstrated that the maximum axial root growth pressures (P_a) which roots exert are highly dependant on root diameter (d);

$$P_a = 242 d^{0.94}.$$

There is also a significant positive correlation between root diameter and a negative correlation with root elongation in stressed plants growing in very strong (penetrometer resistance of 4.2 MPa) soils (Materechera *et al.*, 1991). Root diameter is greater in undisturbed soils with higher penetration resistance compared with roots growing into loose soil (Bengough and Mullins, 1991).

Penetrometer resistance is currently the best method for estimating resistance to root growth in soil (Bengough and Mullins, 1990) and can be used to predict seed-bed strength in hardsetting soils for a wide range of packing, wetting and drying conditions (Weaich *et al.*, 1992). However, penetration resistance measured by a mechanical penetrometer is only an approximation of root penetration resistance and is well correlated with root growth, penetration resistance tends to overestimate the true resistance to root growth in the soil by a factor of between 2-8 times (Bengough and Mullins, 1990). A Penetrometer is affected by many factors including soil density, water content and soil type (Ayers and Perumpral, 1982). The contribution of soil-penetrometer friction to point resistance is a suggested explanation of the difference between penetration of a soil by a metal probe and the expected growth of a plant root (Farrell and Greacen, 1966). Also root tips tend to compress clay soil cylindrically, whereas penetrometer tips compress clay soils spherically (Cockroft *et al.*, 1969). Even though penetration resistance is only an approximation of the effect of soil strength on root growth, the research has indicated that root growth is strongly correlated to penetration resistance and is a useful measurement to characterise soil strength in the seed-bed.

Penetrometer resistance is significantly influenced by aggregate size (Misra *et al.*, 1986a) and can overestimate root growth pressure by a factor of 1.8-3.8 times, increasing with size and strength of aggregates (Misra *et al.* 1986b). Penetrometer tips with a smaller semi-angle (5° compared with 30°) would give a better approximation of root penetration resistance (Bengough and Mullins, 1991) but is not practically useful.

Research by Hussain *et al.* (1985), on a range of loam soils with variation in silt and clay content found maximum barley emergence with a surface crust strength of 75-110 kPa, while zero emergence occurred at a surface crust strength of 300 kPa. However, a crust strength < 75 kPa caused seedling emergence to decline. The failure to emerge was ascribed to the lack of root anchorage and radial support for the shoot. This is likely to be an artifact of the methodology of their research.

Collis-George and Yoganathan (1985b), found that interfacial soil strengths determined with a torsional shear box are limiting to germination at 3.0 MPa; root elongation at 2.3 MPa; coleoptile elongation at 1.7 MPa and seedling emergence at 0.8 MPa. Seed germination is not affected by soil shear strength up to 9.3 kPa. However wheat coleoptile and root elongation is significantly reduced when shear strength is as low as 2.2 kPa, resulting in reduced seedling emergence (Collis-George and Yoganathan 1985a). Research by Dexter (1986a), determined that the penetrometer strength of the underlying untilled sub-soil should not exceed 3 MPa for a wheat plant.

Wheat is more sensitive to soil mechanical impedance than other crop species such as *Lupinus angustifolius* (lupins) (Dracup *et al.*, 1992), *Pisum sativa* (field peas) (Materechera *et al.*, 1992) and *Vicia faba* (faba beans) (Materechera *et al.*, 1991). Whiteley and Dexter (1982a), determined that the root growth in a direct drilled red-brown earth for a range of plant species decreased in the order wheat > pea > canola > linseed > safflower and sunflower. Dry matter production by these crops was greatest because of better root growth and development with deep row aligned tillage using a thin chisel type soil opener, tilling to 120 mm depth while sowing seed at 30 mm from the soil surface. Production was inferior with conventional full cultivation to the same depth. Production was least with no deep tillage at all. Soil surface sealing or crust development, the extent of which is determined by the physical composition of the surface soil, can also prevent cereal seedlings penetrating through to the surface (Arndt, 1965b).

Soil mechanical resistance has a widespread influence on the growth of seedling shoots and plant roots, not only in unusually strong soils but in all soils (Barley and Greacen, 1967). The farmers main tool in optimising seed-bed conditions to optimise crop establishment and root growth is the tillage and seeding equipment used to prepare and sow the seed into the seed-bed. It is necessary to understand the mechanics of interaction of soil openers with the soil if modification of soil opener design is to be used in improving crop seed-bed conditions.

2.4 Soil opener effects in the seed-bed

The description 'soil opener' is a generic term used to describe any soil-engaging component. The function of a seed drill soil furrow opener is to place seed and

fertiliser in the soil at a regulated depth in relation to either soil moisture or the soil surface, and to manipulate soil tilth to maximise seedling establishment (Rogers and Dubetz, 1980). Any opener has a number of design parameters which describe its operational characteristics.

The most important operational parameter of seed openers is the 'opener depth'. This term refers to the depth from the original un-worked soil surface to the lower part of the opener. A distinction should be made between opener depth and seed depth as seeds are not always located at the lowest point of the opener, nor is the post seeding soil surface over the seed row at the same level as the original soil surface (Reed and Dyck, 1990).

Research by Payne (1956), and Willatt and Willis (1965), describe the process of an opener interacting with soil. As a soil opener passes through an undisturbed soil creating a furrow, soil is forced upwards and refilled from beneath with soil from the lower part of a tilled layer. This soil consists of compacted soil with density being higher at the tine side than at the tip. Sometimes soil adheres to a soil opener forming a soil body called a 'cone'. Distinct 'cone' formation can occur at low speeds and/or when soil to metal friction angle is large. Some soil in the seed furrow is pulverised by tillage action that is more pronounced at higher speeds and at greater soil heterogeneity. The loose soil pushed away by the tine partly falls back into the furrow, and partly comes to rest outside the furrow on top of the still firm soil surface. Seed 'drilling' has been the dominant technique for seed placement into soils in Europe for about a century with seed deposited by shoe openers, disc openers, or sometimes in the furrows of press wheels or packer wheels (Heege, 1993). Seeding

method research in Europe with shoe type openers and the influence of the rake angle (the angle between the soil surface in front of the opener and the opener front below the soil) was conducted. Short shoe openers with a small rake angle and long shoe openers with a large rake angle are named 'sand openers' or 'clay openers' respectively due to their suitability for use on these soils (Gebresenhet and Jönsson, 1992).

The term direct drilling or direct sowing, means in a loose sense, any method of sowing or system of crop establishment whereby seed is placed into previously untilled soil in contrast to conventional seeding which may have several tillage operations prior to seeding (Cornish and Pratley, 1987). Although attempts have been made in Australia to further define direct drilling, no-tillage or zero-tillage, they have all been used in the United Kingdom, United States and Canada to describe the same type of tillage practices. A considerable amount of research has been conducted in Australia on conventional versus direct drill seeding systems, with varied success in maintaining or improving grain yield production (Cornish and Lymbery, 1987; Felton *et al.*, 1995; Fischer *et al.*, 1988; Incerti *et al.*, 1993; Jarvis, 1987; Kirkegaard, 1995; Pratley, 1995; Radford *et al.*, 1995a; Reeves and Ellington, 1974; Schultz, 1995; Thomas *et al.*, 1995). There were wide differences in seeding machine types used in this research and consequently major differences were reported. This makes any comparative assessment of the relative importance of the various soil opener and covering devices compared with the effects of a direct drill seeding system on soil, seedling establishment, growth and grain yield, difficult to assess on a quantitative basis.

Much of this research highlighted problems with reduced early seedling growth of direct drilled crops which was rarely associated with the availability of soil water or nitrogen. High soil strength and increased severity of rhizoctonia root rot was responsible for some of these effects. Many of the soil openers used to direct sow crop in this research were highly likely to have had some problems with either inadequate seed placement, seed soil contact, soil tilth and likely problems with soil smearing. This would lead to the variable results of direct sown crops compared with conventional seeding methods. This is based on the fact that conventional 65-125 mm wide sweep type, chisel and inverted-T type, and double disk type soil openers used with finger tine harrow covering devices were used for the majority of this research. Research by Slattery and Rainbow (1995), highlighted crop establishment problems with these soil openers and covering devices. In considering the issue of variable crop yields resulting from direct drill or no-tillage seeding systems compared to conventional cultivation systems, it is necessary to review the published research available to identify the most suitable soil openers farmers should use.

2.4.1 Soil openers for no-tillage and direct drill seeding

No-tillage (direct drill seeding with minimal soil disturbance into surface residues or crop stubble (Cornish and Pratley, 1987), direct drill or other reduced tillage seeding systems with wheat and barley have been studied in Queensland from 1968 to 1982. On heavy clay soils these no-tillage and direct drill seeding systems had not always provided crop establishment and seedling vigour comparable with conventional tillage (Ward and Norris, 1982). During a study tour of reduced tillage seeding research and development in the United States of America, Ward and Norris (1976) concluded that the greater the clay content of the soil, the greater the problems associated with no-

tillage. Significant proportions of these problems appear to relate to achieving adequate seedling germination, emergence and vigour on heavy soils.

Research by Ward *et al.* (1991), found the importance of adequate soil tilth in the seed zone on heavy clay soils and the creation of optimal seed-bed conditions around the seed became more apparent when the better performing combinations of these components are compared to the commercially available systems. Ward also found that with minimum soil disturbance, using a triple-disc seeding unit, gave good seedling vigour on a light textured soil. This indicated that these soils may not need such manipulation in the seed zone to provide adequate seed soil contact. These results also suggested that creating extra seed-bed tilth described as 'the micro-seed-bed approach' might be detrimental to vigour on these soils. It is important to note that soil build-up on the triple disc seeding unit caused severe operational problems.

Seed drill soil openers operate differently when soil moisture is limiting. Wilkins *et al.* (1983), tested different seed drill soil openers, including deep cultivation, disc and hoe type openers and found that soil moisture was the most critical factor that influenced seedling emergence. Soil bulk density was influenced by openers, but did not influence seedling emergence. Deep cultivation and hoe openers lifted moist soil up into the seed-bed and laterally moved the dry surface soil, while disc openers allowed the dry soil to sift into the seed zone rather than move laterally.

Schaaf *et al.* (1980), determined that minimal soil disturbance and good penetration are important design considerations when selecting an opener for no-tillage. Narrow slot type hoe openers such as a spike or narrow chisel point opener and narrow angle

double disc openers are most suitable for no-tillage applications. The rolling and slicing action of a double disc opener fractures the soil surface along a fine line and then compresses the soil down and to either side. The large and small rake angle shoe openers, because of their sliding action through the soil, also create minimal soil disturbance. Early direct drilling research in the United Kingdom noted that the triple disc soil opener caused excessive smearing in the seed-bed where the soil was compacted and wet at the time of drilling, reducing seedling emergence (Anon, 1975).

Lindwall and Anderson (1977), found that a double and triple disc seed drill failed to penetrate untilled soil surfaces adequately when soil bulk density in the 0-50 mm layer exceeded 1.2 Mg m^{-3} , or when the quantity of surface residue exceeded 3700 kg ha^{-1} . Poor seed placement or 'hair-pinning' of surface stubble into the seed-bed reduced establishment. Soil penetration and 'hair-pinning' were not a problem with hoe openers. Lindwall *et al.* (1995), found a hoe drill provided more effective seed placement than a disc drill when soil conditions were dry at or soon after seeding in a no-tillage seeding system. 'Hair-pinning' of straw by a disc seeder in wet seeding conditions was also found to be a problem.

Baker and Mai (1982), and Baker *et al.* (1996), documented the occurrence of soil smearing with both vertically mounted double disc and triple disc soil openers. Slanting of the double disc opener in the opposite direction to the preceding triple disc coulters operating at a deeper depth. Contrasting this, slanting the double disc without a preceding coulters increased soil smearing by a double disc. Baker *et al.* (1996), determined those hoe openers with a large flat base, compact the base of the furrow. Hoe type openers that created a U-shaped furrow smeared the base and sidewall of the

furrow in wet soils. These smears were only important if the furrow remained uncovered after drilling and the smears were allowed to dry to form crusts. Baker *et al.* (1996), also concluded that inverted-T openers smeared the base of the furrow as much as most hoe openers, but caused minimal compaction. The advantage of inverted-T openers is that they leave a closed furrow. This reduces moisture loss from the furrow. Apart from the advantages of moisture conservation, this also minimises the adverse effects on root growth caused by hardening of the smeared furrow walls. inverted-T soil openers create a seed-bed environment quite different to many other no-tillage soil openers and could potentially offer many advantages to crop growth.

2.4.2 Development of the inverted-T opener

Baker (1969), developed a unique experimental procedure using soil tillage bins under controlled climatic conditions which were used to determine the effect of direct drill machinery and seeding techniques on the fate of wheat seeds and soil physical characteristics in the soil groove. In dry sandy loam soil conditions, Choudhary and Baker (1980), found that an experimental chisel soil opener (the generic 'inverted-T' opener, Plate 2.1), gave significantly higher emergence compared with a hoe soil opener. The hoe opener gave significantly better seedling emergence than a triple disc opener. In the same soil at higher moisture content, the chisel and hoe soil openers significantly improved seedling establishment in comparison with a triple disc soil opener (Choudhary and Baker, 1980; Choudhary and Baker, 1982). Choudhary and Baker (1980), determined that seedling emergence effects from a triple disc soil opener were strongly affected by changes in soil moisture and ambient conditions. Seedling emergence was at greater risk if sown by a triple disc soil opener in dry soil conditions than if the inverted-T and hoe type soil openers were used. This was due to

a triple disc opener's inability to maintain high in-groove soil moisture vapour conditions because of the nature of its soil groove formation.



Plate 2.1 'Baker type' cast inverted-T soil openers in various shapes.

Further research by Choudhary and Baker (1981a), concluded that the low emergence obtained by a triple disc soil opener was not due to smearing or compaction on this soil type. Instead, they hypothesised that poor emergence was due to the dependence of seedling emergence on the in-groove soil moisture vapour retained by the groove covering medium. This was termed 'moisture vapour potential captivity' (MVPC). Using this hypothesis Choudhary and Baker (1981b), measured in-groove soil humidity in a controlled environment in an initially dry soil (severe moisture stress conditions). A moderate negative correlation was found between the in-groove relative humidity loss rate and total germinated seedling survival. They concluded

that seed drill soil openers and covering devices should include the ability to exploit the limited supply of sub-surface soil moisture by inducing maximum moisture diffusion across the soil-seed interface. To achieve this, they stated that the seed groove should be closed to the atmosphere in a manner which protected the seed from direct radiation and maintained a high MPVC within the groove micro-environment. At the same time the soil opener should minimise surface soil disturbance to maximise the cover of surface mulch and yet physically loosen and shatter the sub-surface soil to assist in rapid root development.

To determine the physical effects of direct drilling equipment on undisturbed soils, Baker and Mai (1982a), used various techniques to describe the soil physical characteristics below or to the side of the seed grooves resulting from the passage of the drill coulters. None of the techniques used in isolation could comprehensively describe the soil physical characteristics, but collectively the data from the various assessments were in agreement with one another. Pressure sensing tubes appeared to give repeatable indication of the instantaneous soil reaction as the soil openers passed. Miniature bulk density samples (11 mm diameter) and soil penetrometer readings (a multi-probe penetrometer utilising 20 blunt-ended cylindrical steel probes 1 mm in diameter and 10 mm apart) were useful in quantifying repeatable changes in soil physical characteristics in the seed-bed.

Baker and Mai (1982b), used these measurement techniques in further research to quantify triple disc and inverted-T opener effects on soil physical properties. A triple disc soil opener clearly compacted the soil under and around the soil grooves more than a chisel opener in a silt loam soil, irrespective of the initial soil moisture content

in the range 23-29 % by weight. Compaction had little or no noticeable effect on seedling root development of either lupins or wheat when initial soil bulk densities were favourable (1.00-1.04 Mg m⁻³). Where soil bulk density was 1.32 Mg m⁻³, compaction arising from the triple disc soil opener which increased bulk density to 1.44 Mg m⁻³, had a marked effect on lupin root development and caused root distortion and deflection in some instances. This occurred regardless of wet or dry seed groove conditions after seeding. Chaudhry and Baker (1988), tested barley seedling establishment in the presence and absence of surface residue using three direct drill soil openers sowing into optimal soil conditions. After sowing, simulated rainfall was used to saturate the seed-bed. An inverted-T winged opener and hoe opener forming a U shaped soil groove gave greater seedling emergence, root and shoot weights than did a triple disc soil opener which formed a V shaped soil groove. The triple disc opener pushed part of the surface residue into the seed zone where it contacted the seed and reduced emergence. The inverted-T and hoe opener did not do this. It should be noted that these effects were consistent, regardless of soil saturation by simulated rainfall or rising water table or ambient temperature or controlled warm air temperatures.

Chaudhry *et al.* (1988), found that the absence of earthworms negated any effect of opener type or crop residue on crop emergence. This was caused by lower oxygen diffusion rates, higher soil bulk density and soil moisture content compared to soil with the presence of earthworms. By contrast, in the presence of earthworms, opener type and crop residue conditions had significant effects on seedling emergence, with hoe and inverted-T winged soil openers maximising plant growth and a triple disc and inverted-T soil openers without residues giving the poorest emergence. This research

shows that poor soil structural condition as indicated by low earthworm activity is an important limiting factor for differentiation of optimal soil opener performance. It is possible that effects of soil slaking post seeding in a poorly structured soil could have an overriding influence on soil openers exhibiting improvements in seed-bed tilth.

Baker *et al.* (1988), went on to compare several sowing techniques utilising a range of soil openers. This research concluded that when direct drilled soils containing low populations of earthworms became very wet, poor crop emergence would result as a result of low oxygen diffusion rate, higher soil bulk density and soil moisture content. In these conditions the influence of soil openers and surface residue on seedling emergence would be negligible unless substantial mechanical aeration takes place such as the results of using a power-till opener.

In wet soils with reasonable populations of earthworms, satisfactory seedling emergence could be obtained from the use of inverted-T winged soil openers in the presence or absence of surface residue, and to a lesser extent hoe soil openers when used in the presence of surface residue. Surface residue will prevent soil crust formation in drying conditions and the drying of any smeared soil in the seed-bed that may reduce establishment. A power-till opener which is a variation of a rotary hoe that aggressively tills only a narrow strip of soil in the seed bed will achieve satisfactory seedling emergence in these same soil conditions with or without surface residues. This research shows the importance of soil drying rapidly post seeding and resulting influences of smeared soil layers and soil crust development on seedling establishment.

This research confirmed earlier work, that triple disc soil openers used to seed into wet soils result in poor seedling emergence, regardless of soil condition. The interactive influence of soil openers and surface residues on seedling establishment appears to centre on their influence on soil earthworm activity, oxygen diffusion rate and bulk density in a zone close to the drilled soil grooves.

Good seedling establishment consistently obtained with an inverted-T winged soil opener in a range of optimal and sub-optimal wet and dry soil condition, in the presence or absence of surface residues, suggests that this type of soil opener may be a suitable direct drill soil opener for Australian conditions.

It should be noted that this research was conducted at seeding speeds of 5 km/h (Baker *et al.*, 1988). Seeding speeds used in Australia are commonly between 5 to 10 km/h and may often exceed this (Thomas *pers. com.*, 1995). Research by Slattery and Rainbow (1995), found that accurate seed placement could be achieved with several soil openers at speeds of up to 10 km/h. This research also found that an inverted-T type soil opener used at speeds of 8 km/h and greater, tend to shatter the soil up to the surface and the soil groove with a moisture vapour potential captivity described by Baker and Mai (1982b), is not formed. However, inverted-T soil openers gave similar or improved wheat seedling establishment and grain yield when direct sown compared with wider 200 mm soil openers on loamy sand soils over several years (Bligh, 1990). Derivations of the inverted-T opener have become popular in Australia, in particular types manufactured from cast metal alloys with tungsten carbide pieces attached to the wearing edges (Baker *et al.*, 1996) (Plate 2.1).

An experimental opener described and tested by Choudhary *et al.* (1985), was capable of operating at speeds of greater than 12 km hr⁻¹ (Ritchie *pers. com.*, 1995) while conserving the integrity of an inverted-T shape type soil groove to the soil surface. (Baker *pers. com.*, 1995). This opener, the commercially named Cross-slot[®] also had a draft power requirement of in excess of 10 kW and a vertical down force of 9800 N requiring a static seeding machine mass of 1000 kg per opener to ensure the opener effectively penetrated the soil (Ritchie *pers. com.* 1995). This results in a draft requirement of 2-3 times that of most hoe openers currently used by Australian farmers requiring an equivalent increase in tractor horsepower. There is also the possibility of greater soil compaction effects due to the large mass of the tractor and seeder. Practical considerations of cost of manufacture and operational use would preclude this type of opener from commercial use in Australian dryland farming systems.

2.4.3 Deeper seed row–aligned tillage

The research by Baker and co-authors highlight the benefits of deeper tillage in the seed-bed when directly aligned in the seed row for improved seed-bed tilth. There is also a need to keep soil opener draft and manufacture cost within the cost boundaries of Australian farmers.

Reduced growth and grain yield of cereal crops can occur when crops have been direct drilled with low cost lucerne chisel type points (Plate 2.2), providing some tillage below the seed zone, particularly in a red-earth soil when surface stubble residues are retained (Kirkegaard *et al.*, 1994). Seed placement from this point type is very poor, with some seed sown too close to the soil surface and a significant amount of seed

placed at depths of 10 cm which is the length of the soil opener tip (Slattery and Rainbow, 1995).



Plate 2.2 Narrow lucerne chisel type soil opener.

Narrow 50 mm wide hoe soil openers will bury considerable amounts (up to 55 %) of stubble residues into the seed-bed (Woodruff *et al.*, 1965a; Hanna *et al.*, 1995) and create large aggregates or clods in a loam or sandy loam seed-bed (Woodruff *et al.*, 1965b; Fenster *et al.*, 1965). Tillage with 50 mm wide soil openers will bury considerable levels of stubble residue into the seed-bed to similar levels as occurs with wider 406 mm wide sweep soil openers. Deep tillage at 76 mm depth with 50 mm wide hoe type soil openers will bury only 4 % less stubble residue compared with 152 mm tillage depth (Hanna *et al.*, 1995).

Deeper seed row-aligned tillage can lift a significant amount of moist soil from beneath the seeding depth and mix with a drier surface soil which can favour seedling emergence, provided that adequate soil firming is applied to increase seed soil contact and reduce moisture loss (Tessier *et al.*, 1991a). Modified soil openers such as hoe or disc types which are used to band fertiliser below the seed can significantly loosen soil in the seed zone, break down soil aggregates which can increase rapid drying of the soil furrow post seeding (Tessier *et al.*, 1991a; Tessier *et al.*, 1991b). Schmidt and Belford (1993), determined that seeding with a cultivation depth modified drill which cultivates 10 cm deeper than the row aligned seed row is likely to be more profitable than either conventional direct drilling or sowing after deep ripping in a sandy soil. This highlights benefits to the farming industry of combining row aligned deeper tillage with the seeder soil opener. Improved grain yield on deep sandy soils are due to increased root density and water use efficiency by a reduced soil strength from the deep soil loosening (Schmidt *et al.*, 1994). Increasing the depth of soil disturbance below a row aligned seed row can improve grain yield by 32 kg ha⁻¹ with each 1 cm increase in cultivation depth on a deep sand soil. (Schmidt and Belford, 1994).

Riethmuller (1990), found soil opener width, in the absence of deeper row aligned tillage below the seed zone had no significant effect on seedling emergence, growth or grain yield on loamy sand soils. Additional opener width can compound machine problems with seed depth control due to increased soil throw from one seed row to another (Slattery *et al.*, 1993; Slattery and Rainbow, 1995).

It is clear that deeper seed row-aligned tillage although offering some benefits for fungal root disease control and seed-bed tilth, can compound problems with seed placement, seed-soil contact and soil moisture availability to the seed. It is necessary to concentrate more on a soil opener that actually minimises these problems. The spear type soil opener offers to overcome these.

2.4.4 Spear type soil opener research

Seed drill soil opener research in North America by Schaaf *et al.* (1979), found that a range of openers including a spear type opener gave satisfactory performance under a range of moisture contents and degrees of compaction in a sandy soil. The surface remained trafficable even when wet. In a clay soil, these same openers performed satisfactorily under dry seeding conditions regardless of degree of compaction. However problems were encountered if the soil was wet and not compacted. Wet compact clay soils gave severe problems and none of the openers, including a spear type opener, performed satisfactorily. In these conditions the soil did not remain friable and the soil did not freely flow around the opener. The soil was sticky and when disturbed by the opener, large soil clods were formed.

Spear openers (Plate 2.3) have been successfully linked with other soil-engaging devices to improve seed placement. A research study in Queensland, Australia by Ward and Norris (1982), concluded that combining a smooth coulter and single rib press wheel with a spear opener optimised seedling establishment in most seeding conditions. This set-up had the greatest potential for practical application of no-tillage planting systems for heavy clay soils.

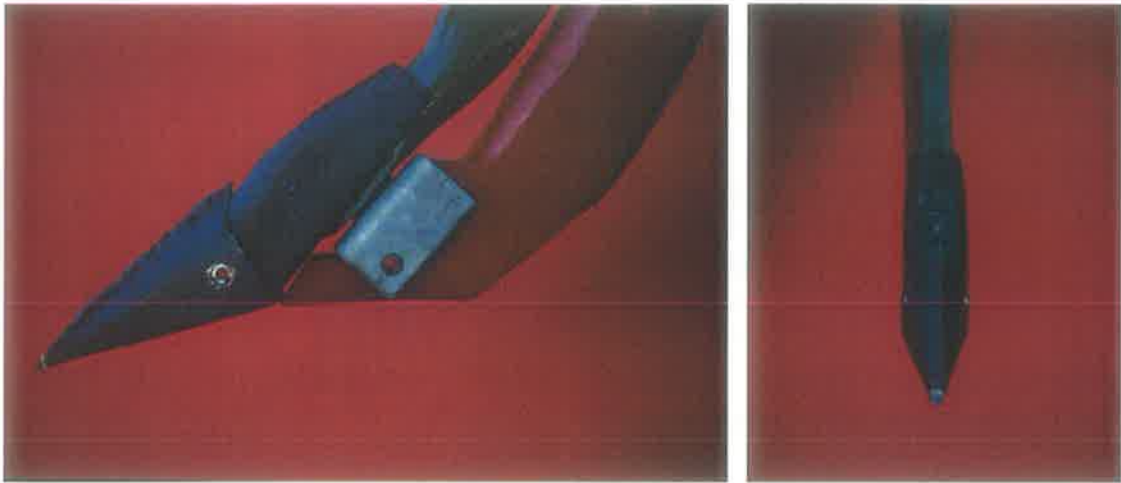


Plate 2.3 Spear type soil opener.

Deibert and French (1989, 1990, 1991), have conducted and released an extensive research evaluation for John Deere® on new concepts in seeding and fertiliser openers with several crop species under different seed-bed environments. A spear type seed drill soil opener with a press wheel covering device was tested against several other seeder points and sweep and disc seeder designs. The spear point opener used in this research has been manufactured by John Deere® for a number of years. Research results showed that it will provide optimum wheat crop establishment in a range of soil conditions and crop residues in comparison with all new John Deere® seed drill soil opener concepts, including both hoe and disc type soil openers. Unfortunately research results of this type tend not to appear in the public domain and virtually none is published in refereed journals (Baker *pers. com.*, 1995). The main factors of a spear type soil opener which appear to contribute towards its superior performance include superior seed placement from the distinct V-shaped seed groove and a sharp leading edge, reducing the potential for soil smear in the seed groove. The cutting edge of the

soil opener is a factor that should be considered in soil opener design for optimum crop establishment.

2.5 The soil opener cutting edge

There have been considerable recent changes in the design of Australian soil openers. Soil openers manufactured from pressed steel and cast alloys have increased in thickness, creating a blunter cutting edge in an attempt to improve wear life and strength when encountering soil obstacles such as rocks (Chapman *pers. com.*, 1996; Fisher *pers., com.* 1995). Introduction of tungsten carbide use for soil opener wear protection, although very effective in improving soil opener wear life, has also created the need to increase the size of a flat surface area to ensure a tungsten carbide piece remains attached to the soil opener (Fisher *pers. com.*, 1995).

The relationship of soil mechanical theory with movement of a soil opener has been studied in great detail and has been well summarised by McKyes (1985). However little research has been done on the interaction of soil with the cutting edge of a soil opener since that of Nichols *et al.* (1958). Nichols *et al.* (1958), demonstrated that a mouldboard plough share with a blunt cutting edge will compact soil, resulting in a compressed layer of soil ahead of and below the cutting edge. This soil feature is most commonly called a 'plough pan'. Nichols *et al.* (1958), also noted tearing of the soil below the base of the share by the underside of the soil opener which was referred to as adhesion cracks.

Koolen and Kuipers (1983), discussed the formation of cracks caused by compaction with a wedge-shaped soil opener in a compactable soil. They determined that in soil

of low compactability, the zone immediately under an opener tip is confined, which precludes significant soil movement in this zone. Koolen and Kuipers (1983), used the results of Nichols *et al.* (1958), to show the difference effects of sharp and a blunt cutting edges (Figure 2.2).

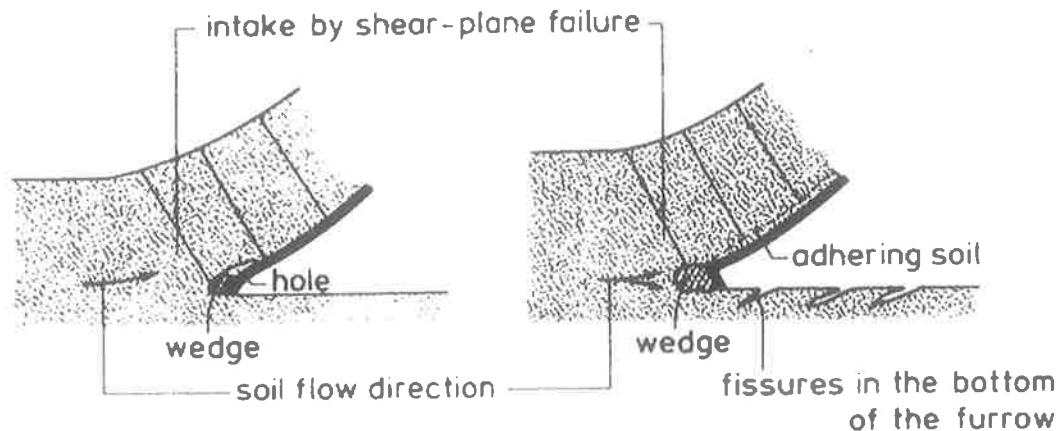


Figure 2.2 Sharp and blunt cutting edge phenomena (from Koolen and Kuipers, 1983).

Figure 2.3 shows the general shape of this zone when much compaction occurs in a compactable soil and when only deformation and not compaction occurs in a non-compactable soil.

Koolen and Kuipers (1983), stated that soil compaction by a wedge increases with increased tip angle and/or increased surface roughness. Cracks formed in compactable soil by a mechanism similar to that which produced fissures at the base of the furrow. This illustrated that soils of different water content and structure may

have different effects on a blunt cutting edge depending on whether the soils are compactable or non-compactable (Fielke, 1994).

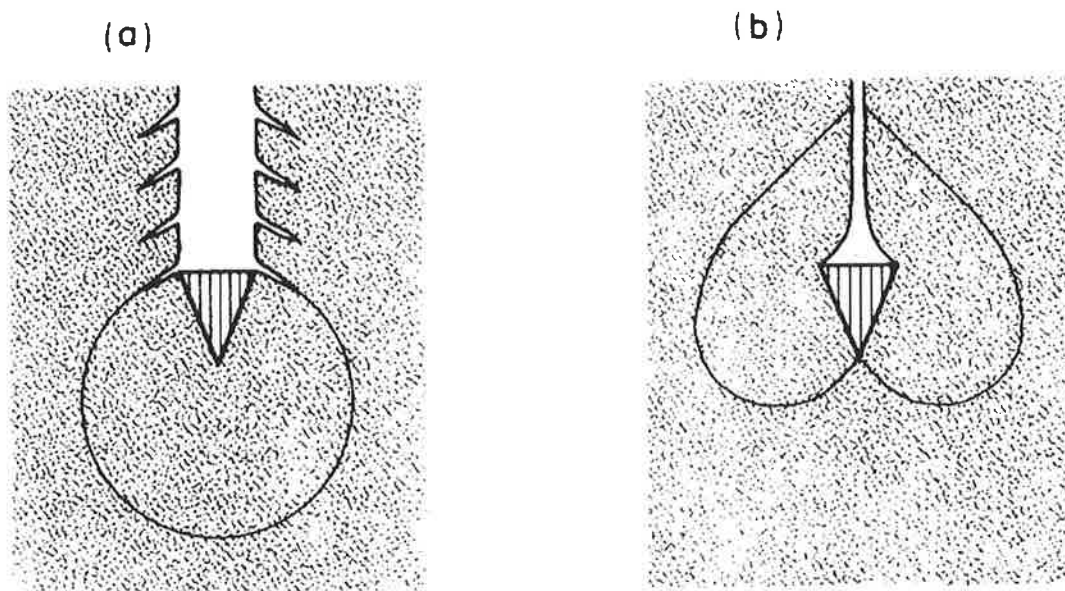


Figure 2.3 Steady state zones of a simple wedge openers influence in compactable (a) and non-compactable soil (b) (from Koolen and Kuipers, 1983).

Fielke (1994), continued research on the influence of an opener cutting edge on soil compaction. He found that the blunter the cutting edge, the greater the formation of cracks below the tillage depth. The cracks were created by soil being pushed forward by the cutting edge. However, no discrete compacted soil layer was detected in his experiments. He determined that the ideal cutting edge of a soil opener should have a zero cutting edge height to minimise forward and downward soil movement. This also allowed the top face of the soil opener to apply pressure on the soil, so reducing soil pressure at the cutting edge. An ideal soil opener should also have no underside rub and an underside clearance behind the cutting edge of greater than 10° to stop soil adhering to the underside of the soil opener. This research is at odds with the current

trend in the soil opener manufacturing industry where the cutting edge is tending to become blunter and thicker.

This research in this section has examined the process of soil failure and mechanical theory to gain greater understanding of the soil ground-engaging component. No-tillage or direct drill ground engaging components was assessed for suitability in this way, without addressing the needs for optimising plant development.

2.6 Interaction of seed drill soil openers with a covering device

Crop establishment depends on the type of soil covering device used with the seed drill opener. The use of press wheels is a good example of this. The shape of the opener and press wheel, combined with the weight of packing can have a major effect on crop emergence. Double disc openers generally produce a narrow furrow, but a narrow press wheel may not necessarily reach the bottom of the furrow. This will pack the soil above the seed, rather than around the seed which may impede emergence (Hultgreen *et al.*, 1990).

Rogers and Dubetz (1980), illustrated that moisture imbibition by wheat seeds was affected by changes in bulk density, as an increase in bulk density allowed movement of water and water vapour to the seed. They concluded that water movement to the seed increased with soil bulk density and increased moisture imbibition. The increase in imbibition was not only due to the intrinsic effect of closer soil-seed contact, but also due to changes in water transmission and soil porosity resulting from the bulk density increase. Soil bulk density increased because of a reduction in the size of voids. Smaller voids in contact with a seed are more likely to hold water than larger

voids. Larger voids tend to drain and become filled with air. Small, water-filled voids will transmit water to the seed more rapidly than air-filled voids. In addition, increased bulk density of the soil below the seed creates a firmer contact for the roots of the seedlings (Hultgreen *et al.*, 1990).

Press wheels are very effective in improving seedling establishment of a range of cereal crops compared with harrow type covering devices. This result was found on both loam and clay soils even if hardsetting (Finlay and Tisdall, 1990; Rainbow *et al.*, 1994; Slattery and Rainbow, 1995). Press wheels can therefore improve crop growth rates leading to a grain yield improvement, particularly in dry soil (Foster, 1991; Radford, 1986; Radford and Wildermuth, 1987; Rainbow *et al.*, 1992; Rainbow *et al.*, 1994; Slattery and Rainbow, 1995; Tessier *et al.*, 1991b). Press wheels have been shown to improve wheat and lupin seedling establishment on lighter loamy sand soils improvement (Bligh, 1990; Riethmuller, 1990; Riethmuller 1995). However, if soil moisture was limiting later in the growing season, press wheels did not always lead to a crop growth or grain yield (Riethmuller, 1995).

Press wheels can be used in combination with other harrow type covering devices. A significant increase in seedling emergence was observed when seeds were pressed into the base of hoe and triple disc soil grooves with press wheels before bar harrowing the surface compared with bar harrowing before packing (Choudhary and Baker, 1980).

Reduced tillage or direct drilling of crops has been shown reduce both seedling emergence and early growth on clay soils in dry soil conditions (Radford *et al.*, 1995b). In these conditions, the use of a press wheel enhanced wheat establishment,

but there was little effect of reduced tillage or use of a press wheel on a sandy clay loam soil in dry soil conditions. Kushwaha and Foster (1993), optimised crop establishment by direct drilling into dry soil even if seeding was followed by low seasonal rainfall if they used a John Deere® disc no-tillage seeder incorporating a packer or press wheel. In contrast, a hoe type soil opener with a press wheel optimised seedling emergence in years of above average rainfall. Press wheels are effective in improving wheat seedling emergence, growth and grain yield on lighter sand soils when soil moisture is not limiting (Rainbow *et al.*, 1994).

2.7 Discussion

In reviewing the literature, it is unequivocal that, for optimum crop establishment, soils should be moist at sowing. Seed should be sown into soil at a water content close to the soil plastic limit. This will avoid the process of soil smearing and soil compaction by an opener leading to problems with water infiltration or root penetration through a soil crust in the seed-bed. This will also ensure the most suitable soil strength possible for crop establishment. Although achieving these conditions is feasible in a controlled experiment, there is obvious difficulty achieving this in a commercial field situation. Soil water content varies from day to day and soil texture and structure properties vary across a paddock or field. Variation in water content, texture and structure will have a large effect on soil strength and other mechanical properties. These variations will thus effect the success of crop establishment and early growth.

A red-brown earth soil seed-bed should, ideally, consist of aggregates of 1-4 mm diameter with a bulk density of 1.00-1.38 Mg m⁻³. Bulk density is easily collected in

the field and can be used as a basis to differentiate the effect of soil openers on the seed-bed at several depths. The soil should have a water content ranging near to the plastic limit and penetration strength of less than 0.8 MPa above the seed zone and less than 1.7 MPa below the seed. Ideally further soil opener research should include testing of crop establishment response in a range of water contents at seeding, both at and well below the soil plastic limit. The using different soils of similar texture but different structural condition providing different soil strengths would provide insight into the effect of soil openers on seed-bed condition and crop establishment. The influence of soil and air temperature on crop establishment effects should be considered also as very low temperatures can have significant effect of reducing plant growth rate. Penetration resistance measured by a mechanical penetrometer only approximates root growth resistance. However, use of a mechanical penetrometer is still considered the most cost-effective way to estimate resistance to root growth in a seed-bed. A mechanical penetrometer should therefore be used to model soil opener effects of seed-bed soil strength correlated to wheat plant growth response. The use of a shear vane to measure soil strength in the seed-bed would also provide a useful rapid alternative field measurement.

Plant establishment and rate of growth can easily be measured and are a readily visible indication of seedling establishment difficulties. Often the symptoms of poor crop establishment such as soil surface crusting are also readily visible and easily identified. These measurements above the soil surface should form the foundation of any research on soil opener design. Resulting differences in growth can give an accurate indication of the ultimate performance of a soil opener.

Soil opener interaction with the soil is a more difficult to study. New experiment methods need to be used to simulate soil effects to effectively measure and correlate soil physical properties with plant establishment and growth. The mechanics of root growth have been thoroughly studied and many models developed which describe the characteristics of root growth and pressures. Research has documented the reaction by roots when a compacted layer is encountered. This research has been useful in explaining root growth responses to seeding with different soil openers. The measurement of crop root morphology and rates of elongation after being sown with different soil openers may lead to a better understanding of the efficiency and usefulness of soil openers. Primary consideration however should first be given to the measurement of plant root system biomass growth differences between soil opener types if the data is to be useful in the development of improved soil opener design.

Quantifying the effects of small changes to the design of existing seed drill soil openers is necessary to improve and optimise its design. The work of researchers studying tillage and seeding systems in this review can be divided into two main groups:

- (i) Those researchers examining the process of soil failure and mechanical theory to gain greater understanding of the soil ground engaging component. Much of the early research by both North American and Australian researchers into no-tillage or direct drill ground engaging components were assessed for suitability in this way, without addressing the needs for optimising plant development.

- (ii) Those researchers investigating the interaction between the soil and plants, resulting from different seeding machine types and tillage systems. The results in terms of grain yield effects and financial and environmentally sustainable agricultural practice are of primary interest. The 'type' of ground engaging component and seeding system used are only a means to an end.

These two streams of research are significantly interrelated. The two disciplines, one soil mechanical-tillage mechanics based and the other soil mechanical-plant physiology and crop agronomy based, are complex. This review shows that few researchers have effectively combined them both into one research program.

Research has been significantly lacking in the area of soil opener effects on soil physical properties and linking these changes to plant root growth and plant top growth and grain yield. Research conducted in New Zealand and published by Baker and co-authors is an exception as significant insight into some of the interactions of the seed drill opener, soil and plant has been achieved. The published series of research experiments conducted by Baker and co-authors were scientifically sound and followed a logical chain of development of the inverted-T soil opener culminating in the development of the Cross-slot[®] soil opener. The design of the inverted-T opener has had difficulty in Australian seeding systems due to the slower sowing speed required for it to operate correctly and create a distinct inverted-T groove. The development of the Cross-slot[®] soil opener by Baker and co-authors ensured optimum crop establishment and overcame some of these difficulties, however the cost of manufacture and operation has not made it a commercial success.

The research by Baker and co-authors highlights difficulties in the development of a new design of soil opener. There is compromise in the development of a soil opener between creating a seed-bed for optimum potential crop establishment and the engineering cost of manufacture or operating cost of the opener. Difficulties of commercial development of openers are that the opener should give optimum performance for opener wear, draft power and vertical force requirements and create optimum seed-bed conditions while at the same time placing seed and fertiliser into soils of different texture and water content, all at minimum cost.

Much of the research into no-tillage, direct drill and reduced tillage seeding systems in Australia has been confounded by the biological interaction of soil borne root diseases, in particular *Rhizoctonia spp.* In reality, these diseases are present in many of the crop producing areas of Australia. Tillage and seeding systems which effectively reduce the incidence of *Rhizoctonia spp.*, such as seed row aligned deeper tillage 5-7 cm deeper than the seed row, must be incorporated into the designs of new seed drill soil openers. There is a duty to include these principles in on-going soil opener research. The literature suggests there are also benefits in reducing seed-bed soil strength if accurate seed placement can be maintained and issues of increased soil drying are addressed. Some of this direct drill seeding research has however been severely compromised by poor seed placement and seed soil contact from some openers, in particular the lucerne chisel opener. This has negated any potential benefits from the use of a direct drill seeding system and probably significantly contributed to the variable results of direct drilling compared to conventional cultivation seeding systems found in the review by Kirkegaard and co-authors. The research by Slattery and Rainbow has further highlighted the problem of seed

placement and seed soil contact with lucerne chisel and some inverted-T openers used in much of the research reviewed by Kirkegaard and co-authors, where a press wheel covering device was usually not used.

Press wheels offer considerable benefits to crop establishment if the shape of the press wheel is properly matched to the shape of the furrow created by the opener. It would be injudicious to conduct soil opener research without the use of press wheels in the seeding process.

It is also significant that soil smearing with the use of double disc soil openers seedbed was often observed by many researchers, no further investigation took place on why it occurred, nor what is specifically required to prevent the problem. The resulting effect on crop growth and grain yield has also never been quantified. This illustrates the difficulty in quantifying soil opener effects on soil physical properties and resulting crop effects in a field situation.

The literature suggests that a spear type soil opener in combination with a press wheel would achieve optimal establishment compared with other opener types. Relatively simple design and therefore inexpensive manufacturing cost of the spear type soil opener and universal popularity in Australia and North America has demonstrated it as a tried and proven design. The lack of detailed soil physical property data correlated to plant growth response resulting from the use of this simple yet universally successful spear soil opener has raised inquiry to more fully understand the principals of why the design works so well. The question is also asked as to what

effect opener wear, blunt leading edges, width and other factors may have on a spear openers subsequent effect on resulting seed-bed conditions for the seedling.

2.8 Conclusions

Literature reviewed has demonstrated that to improve soil opener design, a greater degree of measurement of seed-bed physical properties and the resulting effect on seedling establishment and growth is required. Published research has been significantly lacking in the area of opener effects on soil physical properties and linking these changes to plant root growth and plant top growth and grain yield.

The review has highlighted the following key points:

- (i) The established methods of recording soil strength using penetrometers and shear vanes should be adequate in quantifying seed-bed conditions in further research.
- (ii) That there are optimum soil strength in a red-brown earth for wheat root and shoot growth and optimum bulk density values on the basis of their effect on air-filled porosity and soil water availability
- (iii) A clear understanding of the mode of growth of a wheat root as it encounters soil of high strength and the negative impact that this can have on further plant growth.

This review has also highlighted the need to:

- (iv) Quantify the impact of a simple soil opener design such as a spear type soil opener on soil physical properties.

- (v) Correlate the changes in soil physical properties to wheat establishment and early growth in a range of temperature and soil moisture conditions with different spear type soil openers.
- (vi) By understanding the relationship of soil opener effects on soils and resulting crop growth, soil opener design can be changed or improved on the basis of agronomic responses, rather than on the basis of soil physical changes, draft requirement or opener wear rate as is currently the case.

Published research from north America has indicated that the simple design of spear type soil openers in combination with a press wheel have achieved optimum wheat crop establishment compared with other openers, in a range of soil types and water contents. No research was found which adequately described the effects of specific changes to spear type seed drill soil opener design, or the effects of changes to spear type opener shape from wear, which correlated soil physical property changes to crop establishment and growth. The measurement of soil strength with a mechanical penetrometer or shear vane including measurement of soil density and water content, would provide a useful estimate of the resulting effects of different soil openers correlated to early wheat root growth in a seed-bed.

2.9 Rationale for further experimental research

The review of literature has indicated significant potential for further comparative research of a range of soil openers in comparison with the spear type soil opener in Australian soil conditions. Measurement of soil opener effects on soil physical properties and resulting effects on wheat plants grown in the red-brown earth soils of South-Eastern Australia, representing 18.6 % of the crop producing area of the region

(Bryson, 1996), would provide response data useful to many crop producers. The literature suggests that effectiveness of press wheels and row-aligned deeper tillage with the spear type soil opener should also be assessed. A series of experiments to quantify the relative importance of spear type seeding point design factors such as shape, width, leading edge sharpness and angle of incidence to the soil should help further scientific development and improvement of soil opener design.

3. SOIL OPENER EFFECT ON WHEAT ESTABLISHMENT

3.1 Introduction

Weather conditions in the Mid-North of South Australia are often cold and wet at the time of seeding (French *et al.*, 1968; Harding, 1995). It is during these conditions that farmers have suffered very slow wheat crop emergence and low final plant establishment.

The dominant soils on which wheat is grown in this region are the 'red-brown earths' (Stace *et al.*, 1968). These soils are noted for the tendency to slake and disperse during rainfall. This creates a disrupted layer (seal) at the surface of the soil which hardens to form a thin crust or deeper hardset layer on drying (Gusli *et al.*, 1994a and 1994b). If crops are sown before the disruptive rainfall and subsequent soil drying rate is rapid, seedlings may fail to emerge through the crust or hardset layers (Weaich *et al.*, 1996; Harding, 1995). Surface crusting and hard-setting causes significant reductions in plant emergence and restrict plant growth, particularly at tillering. The trend towards reduced tillage, narrow openers and depth modified combines and air-seeders have also resulted in variable results in seed depth control and crop establishment (Norris, 1988; Gibbs, 1991). The effects of poor soil physical properties on establishment, combined with reduced seed-bed tilth and a tendency towards poor seed placement with commercial seeding equipment, creates a scenario of potentially severe crop establishment difficulty.

The aims of the research reported here were to produce quantitative information on soil opener effects on the physical properties of surface layers of a red-brown earth

and identify factors of soil opener design that affect establishment, crop growth and grain yield of wheat.

3.2 Materials and methods

A series of experiments were established using both a simple single row seeder and a multi-row experimental seeder, with a range of soil openers, tines and covering devices over a 3 year period. Wheat *Triticum aestivum* var. Machete was sown during the growing season in a mild Mediterranean climate. Two experimental sites were sown in the Mid-North of South Australia at Hart and Yacka with a range of soil openers followed by a finger tine harrow, press wheel, or no covering device. The experiments were always located within 1 km of each other during the 3 year period. Seed treated with Batan[®] (triadimenol/cypermethrin fungicide/insecticide) (1g kg⁻¹ seed) was tested by International Seed Testing Association Guidelines (Anon, 1996b) to give a germination rate of 90% normal seedlings at 8 days in 1991 and 93 % normal seedlings at 8 days in Years 2 and 3. In 1991 seed was sown at a density of 100 grains per 5 m long plot with no fertiliser applied. In 1992 and 1993, seed was sown at a density of 207 seeds m⁻² combined with di-ammonium phosphate fertiliser (70 kg ha⁻¹ N:P:K 18:20:0). Seed in all experiments were sown with an intended average depth of 35 mm of soil cover over the seed row.

All experiments were sown as a randomised block design, containing 4 replicates. Experiments in 1991 and 1993 were sown in the mid winter period, with 1992 sown in the early winter period according to the seasonal break. Experiments were sown in one day, Hart sown 8 days later than Yacka in 1992 and 11 days later in 1993. The experiment site at Yacka had a poor structured soil in contrast to the Hart experiment

site. Experimental sites at both Hart and Yacka were relocated in neighbouring fields each year to follow crop rotations suitable for wheat production.

The single row experiment site sown in 1991 was initially cultivated up to a depth between 50-60 mm 30 days prior to seeding with 125 mm wide shares, achieving a full cut across the seed-bed. A specially constructed three point linkage tool bar which enabled both single and 3 multiple tines to be mounted was used to sow the single row experiment. Seeder depth was controlled by two adjustable depth control wheels mounted each side of the seeding tine. John Shearer[®] 580 spring and tine assemblies were set at a tine breakout force of 740 N (Robotham and Norris, 1985). All 125 mm and 200 mm wide share openers were equipped with cultivation and covering tines on the tool bar off-set at 180 mm each side of the centre row. All other openers used a single seeding tine only. Covering devices used were either a Manutec[®] 70 mm wide wedge shaped press wheel mounted on a pendulum arm set at a pressure of 5 kg cm⁻¹ press wheel in contact with the soil, or 2 row, 4 finger tine harrows set at 65° to the soil. The tine was adjusted for height to ensure the same seeding depth in each treatment. An electric 12V cone seed metering mechanism was used to distribute the single row of seed. Seed was loaded into a single cone hopper and the cone was manually tripped as the tractor and single row seeder was driven 15 m along the plot at 8 km h⁻¹. Multi-row experiments in Years 2 and 3 were direct sown with a specially designed 8 row wide, 6 rank multi-row experimental seeder at a speed of 8 km hr⁻¹. All 6 tine ranks were 500 mm apart with seed row spacings 180 mm apart for all treatments except 65 mm and 200 mm wide share treatments which were 160 mm apart (Appendix A10.1.1). Plots were 1.44 m wide by 30 m long for all treatments except 65 mm and 200 mm wide share treatments which were 1280 mm

wide by 30 m long. Seed was distributed with a Hege[®] rotating cone distribution system that had distribution accuracy for wheat of $\pm 5\%$ as stated by the manufacturer. Multi row seeding tines were all John Shearer[®] 580 series tines, except the narrow spear type soil opener (Treatment (i), Table 3.1) which had its own tine shank mounted into a John Shearer[®] 580 series tine head mount. All seeding tines were set at a tine breakout force of 740 N (Robotham and Norris, 1985). All tines had an integrated seed delivery tube that gave positive seed placement. Soil opener treatments used in experiments are illustrated in Plate 3.1. Soil openers and covering devices were all commercial unmodified types direct from the manufacturer. Opener and tine design parameters are listed in Table 3.1.

Table 3.1 Soil opener and covering device treatments.

Treatment no./ name	Soil opener – covering device
(i) Narrow spear – Press wheel	Janke [®] 36 mm wide spear type soil opener – Press wheel covering device
(ii) Wide spear – Press wheel	ARP [®] 42 mm wide RRR02 spear type soil opener - Press wheel covering device
(iii) 125 mm share – Finger tine harrow	Agpoint [®] #61A 125 mm wide share - 3 row spring tine harrows covering device
(iv) 125 mm share – Press wheel	Agpoint [®] #61A 125 mm wide share - Press wheel covering device
(v) 65 mm share – Press wheel	Agpoint [®] #61A 65 mm wide share - Press wheel covering device
(vi) 12 mm wide chisel – Press wheel	Agpoint [®] #65 12 mm wide chisel - Press wheel covering device
(vii) ‘Caldow’ type inverted-T – Finger tine harrow	Primary Sales Australia [®] Ref 92 ‘Caldow’ inverted-T opener - 3 row spring tine harrows covering device
(viii) ‘Super Seeder’ type inverted-T– Finger tine harrow	Primary Sales Australia [®] Ref 94 ‘Super Seeder’ inverted-T opener - 3 row spring tine harrows covering device
(ix) ‘Super Seeder’ type inverted-T– Press wheel	Primary Sales Australia [®] Ref 94 ‘Super Seeder’ inverted-T opener– Press wheel covering device
(x) Deeper cultivating opener plus 12 mm wide chisel opener seeding – Press wheel	Agpoint [®] #65 12 mm wide chisel aligned with the seed row, cultivating 50 mm deeper than a Agpoint [®] #65 12 mm wide chisel opener placing seed - Press wheel covering device
(xi) Deeper cultivating opener plus Narrow spear opener seeding – Press wheel	Agpoint [™] #65 12 mm wide chisel aligned with the seed row, cultivating 50 mm deeper than a Janke [®] 36 mm wide spear type soil opener placing seed - Press wheel covering device
(xii) 200 mm share – Press wheel	Agpoint [®] #61A 200 mm wide share - Press wheel covering device



Janke® 36 mm wide spear type soil opener



ARP® 42 mm wide RRR02 spear type soil opener



Agpoint® #61A 125 mm wide share



Agpoint® #61A 200 mm wide share



Agpoint® #61A 65 mm wide share



Agpoint® #61A 12 mm wide chisel



Primary Sales Australia® Ref 92 'Caldow' inverted-T opener



Primary Sales Australia® Ref 94 'Super Seeder' inverted-T opener

Plate 3.1 Soil opener types used in experiments.

The covering device used in Years 2 and 3 were 80 mm wide solid rubber banked press wheels mounted on a walking type frame assembly with a pressure of 5 kg cm^{-1} width of press wheel in contact with the soil (Appendix 10.1.2). The harrow covering device used in Years 2 and 3 was a commercial 3 row spring tine harrow, adjustable for trash residue, set at 65° to the soil.

Soils from experiment sites were analysed for nutrient status in a commercial laboratory. Soil pH and electrical conductivity (EC) was measured in a 1:5 soil:water suspension. A 1:100 soil to sodium bicarbonate solution (0.5 mol L^{-1}) suspension was shaken for 16 hours and extractable phosphorous (Extrac. P) was then determined by colorimetry as described by Colwell (1965), and extractable potassium (Extrac. K) by atomic absorption spectrophotometry. Soil nitrate nitrogen ($\text{NO}_3\text{-N}$) was determined using inductively coupled plasma spectroscopy (ICP). Soil organic carbon (OC) was measured by digestion in strong acid/dichromate solution and colour development assessed against standard sucrose. Free lime (CaCO_3 %) was determined quantitatively by manometric measurement. This method is based on pressure change with time as CO_2 is evolved in a closed system following reaction of carbonate with a solution of HCL-FeCL_2 (Martin and Reeve, 1955). Soil texture was determined by field texturing. Silt and clay were measured in a dispersed suspension of soil and water using a calibrated hydrometer. Soil slaking and dispersion were assessed using the method of Emerson (1967).

Weeds were controlled by chemical means in all experiments. Glyphosate (450 g L^{-1} ai.) broad spectrum knockdown herbicide at 2.0 L ha^{-1} in 66 L ha^{-1} water was applied 16 to 28 days prior to seeding for pre-seeding weed control at all sites. No additional

herbicides were applied in 1991. In 1992, a tankmix of 2.0 L ha⁻¹ Hoegrass® (375 g L⁻¹ a.i. diclofop-methyl), 500 ml ha⁻¹ Puma S® (69 g L⁻¹ a.i. fenoxaprop-p-ethyl, 39.1 g L⁻¹ a.i. fenchlorazole-ethyl) and a non-ionic surfactant @ 1 ml L⁻¹ water at a water rate of 66 L ha⁻¹ was used post seeding post emergence at the plant 5 leaf stage at both sites. A second tankmix application of 7 g ha⁻¹ Ally® (600 g kg⁻¹ a.i. metsulfuron methyl), 2.0 L ha⁻¹ Puma® and a non-ionic surfactant @ 1 ml L⁻¹ water at a water rate of 66 L ha⁻¹ was applied 14 days later at Hart and 26 days later at Yacka. In 1993, 2.0 L ha⁻¹ Glyphosate, 20 g ha⁻¹ and Glean® (750 g kg⁻¹ a.i. chlorsulfuron) in 66 L ha⁻¹ water was applied as a tankmix at Hart immediately post seeding. A tankmix of 2.0 L ha⁻¹ Hoegrass®, 500 ml ha⁻¹ Puma S® at Yacka, and a tankmix of 20 g ha⁻¹ Glean®, 2.0 L ha⁻¹ Hoegrass®, 500 ml ha⁻¹ Puma S® at Hart, was applied post seeding post emergence at the plant 5 leaf stage, using a non-ionic surfactant @ 1 ml L⁻¹ water at a water rate of 66 L ha⁻¹.

Plant emergence was determined in 1991 by successive counts of the total population of the single row. In 1992 and 1993, all plant emergence, plant growth, soil strength and soil moisture measurements were sampled by the transect method described by Rainbow (1993), to reduce sampling error caused by soil throw of the tines and points. All plant emergence counts were taken in a transect across the experiment site as 3 x 1 m adjacent rows to reduce effects from seed drill metering and soil cover effects. All plant growth samples were collected by the transect method, collecting 10 plants or grain heads from 3 adjacent seeder rows.

Rate of emergence from repeated plant counts from a marked position were counted every 3 days from the first day of plant emergence from the soil until 3 consecutive

days of no further plant emergence occurred. The mean emergence day (M.E.D.) was then calculated by the method described by Robinson and Sandfort (1980). Plant growth was determined by collecting 30 individual plant tops above the soil surface. Plants were collected from the single row in 1991 and 10 plants from 3 adjacent rows, in the same position as the transects taken for the plant emergence counts, in Years 2 and 3. All plant samples were dried at 70 °C for 48 hours in perforated paper bags and then weighed. Grain yield was determined by machine harvesting the entire 30 x 1.44 m or 30 x 1.28m plots, measuring the total plot grain weight. Plot edge effects although present were not considered in this study for practical considerations.

Soil matric suction was determined at seeding by the filter paper method by Fawcett and Collis-George (1967). Water content samples were collected at 0-30 mm, 30-60 mm and 60-120 mm depth intervals, immediately prior to seeding. Soil water content was determined by weighing before and after drying at 105 °C for 24 hours and expressing the weight loss as a fraction % of the dry soil mass. Soil shear strength was measured prior to seeding at 3 depths of 20 mm, 50 mm and 80 mm in the seed bed with a torsional shear box using the method by Collis-George and Lloyd (1979). Shear vane recordings were collected post seeding from 15 measurements in 3 seed rows at 2 depths. A Geonor® shear vane gauge was used by the method described by Koppi and Douglas, (1991) with a vane size of 4 vanes of 30 mm deep x 9 mm wide.

All data were analysed with Statistix® Version 3.1 Analytical Software (Anon, 1994). Plots of residual error were used to check for outlying data. Significant outlying data was entered as missing values in these cases and experiments were re-analysed.

3.3 Results

3.3.1 Field establishment conditions

The soils at both the Hart and Yacka sites were similar in nutrient status (Table 3.2). There was adequate extractable P in 1991 where no fertiliser was applied, but marginal at both sites in all subsequent years when fertiliser was applied. Extractable K was considered high and NO_3^- -N considered adequate. The Hart sites were high in organic carbon in contrast to the moderate levels at Yacka. The Hart experiments were generally moderately calcareous in contrast to the non-calcareous Yacka experiments. Soil pH varied as Yacka was slightly acid with Hart tending strongly alkaline.

Table 3.2 Soil chemical properties for the topsoils (0-120 mm depth) of the Hart and Yacka experimental sites.

Experiment	Extrac. P (mg kg ⁻¹)	Extrac. K (mg kg ⁻¹)	NO ₃ -N (mg kg ⁻¹)	OC (%)	E.C. 1:5 _w extract (dS .m ⁻¹)	CaCO ₃ (%)	PH (H ₂ O)
Hart 1991	33	720	10	1.3	0.14	<1	8.1
Hart 1992	22	650	5	1.6	0.13	5	8.6
Hart 1993	32	688	24	2.1	0.19	11	8.4
Yacka 1992	33	435	11	1.2	0.06	<1	6.7
Yacka 1993	23	518	26	1.3	0.11	2	6.8

Soils differed in mechanical characteristics as the Yacka site contained slightly less silt and more clay particles in 1992 and more sand in 1993 than the Hart site (Table 3.3). The soil shear strength at seeding was considerably higher in the Yacka 1992 experiment, possibly influenced by the higher clay content at that particular site. Emerson soil dispersion tests indicated all sites would disperse if cultivated at a water content greater than field capacity.

Table 3.3 Soil physical properties for the topsoils (0-120 mm depth) of the Hart and Yacka experimental sites.

Experiment	Particle size distribution (%)			Emerson dispersion class	Soil texture	Soil shear strength ¹ (kPa m ⁻²) recorded at seeding		
	Sand	Silt	Clay			20 mm	50 mm	80 mm
Hart 1991	61	21	18	3	Sandy loam	349	735	937
Hart 1992	66	23	11	3	Sandy loam	257	459	833
Hart 1993	65	19	16	3	Sandy loam	189	261	353
Yacka 1992	60	18	22	3	Sandy clay loam	318	679	1243
Yacka 1993	70	14	16	3	Sandy loam	112	275	356

¹ Soil shear strength recorded at water content in Table 3.4.

Soil was very wet, but trafficable in 1991 (Table 3.4), remaining wet with 86 mm of rainfall to early tillering (Table 3.5). Although the Yacka sites had lower soil water content, they had lower soil suction resulting in increased available soil water. Soil temperatures at seeding appeared relatively comparable in all experiments. Growing season rainfall in 1992 was much higher than 1993 at both sites. Although soil water content was considered ideal at seeding in Years 1992 and 1993, rainfall from seeding to tillering in 1993 was more than 2 times that of 1992 at Hart, and more than 6 times that of 1992 at Yacka. This variability between seasons is common in these regions.

Table 3.4 Matric suction, water content and temperature of the Hart and Yacka experimental sites at seeding.

Experiment	Matric suction ψ_m (MPa)			Soil water content θ_g (kg _w kg _s ⁻¹)			Soil temperature (°C at 9 am) 100 mm
	0-30 mm	30-60 mm	60-120 mm	0-30 mm	30-60 mm	60-120 mm	
Hart 1991	0.09	0.07	0.06	20.8	23.0	21.9	9.0
Hart 1992	1.98	0.36	0.22	16.8	17.8	18.1	10.2
Hart 1993	0.66	0.33	0.10	19.0	18.2	19.1	10.4
Yacka 1992	0.4	0.17	0.09	13.9	15.8	22.6	10.5
Yacka 1993	0.21	0.11	0.09	11.9	12.1	14.5	10.1

Table 3.5 Growing season rainfall (mm) at key intervals from seeding of the Hart and Yacka experimental sites.

Experiment	Rainfall (mm)		
	April - October	Seeding to emergence	Emergence to tillering (Zadok 22)
Hart 1991	NA	9.0	77.0
Hart 1992	457	10.4	34.8
Hart 1993	297	24.4	75.0
Yacka 1992	465	11.8	11.6
Yacka 1993	307	38.2	126.2

3.3.2 Single row research

Cold wet conditions at Hart post seeding in the single row experiment in 1991, demonstrates the detrimental impact high water content can have on crop establishment (Table 3.6).

There was no significant difference in emergence or mean emergence days between a spear, 125 mm wide share or 12 mm wide chisel openers using press wheels (Treatments (i), (iv) and (vi) respectively). Total plant emergence of a 200 mm wide share type opener with press wheels was significantly higher than all other openers except a 12 mm wide chisel opener both deeper cultivating and seeding followed by a press wheel (Treatments (xii) and (x) respectively). There was significant increase in individual plant growth rate with a spear opener compared to all other openers (Treatment (i)). Total plant growth within the plot resulting from use of a spear, deeper cultivating and seeding 12 mm wide chisel, and 200 mm wide share openers (Treatments (i),(x) and (xii) respectively) are not significantly different from one another but significantly higher than all other openers. Press wheels significantly

improved plant establishment when a 125 mm wide share opener (Treatments (iii) and (iv)) was used.

The inverted-T opener and the cast 'Super Seeder' inverted-T type openers (Treatments (vii) and (viii)), had significantly lower plant emergence and growth rates than all other opener types. The openers were used with no covering device according to manufacturer instructions. The principle of 'Moisture Vapour Potential Captivity' (MVPC) (Choudhary and Baker, 1981a) is supposedly an integral function of these opener types. This implies that moist water vapour should fill the inverted-T shape groove and oxygen should be readily available to the seed. In reality, the open inverted-T shaped furrow was seen to be filled with water following heavy post seeding rainfall as occurred at Hart and Yacka in 1993. Apart from the anoxic conditions this created around the seed, some degree of seed swelling and seed burst occurred in such a wet soil environment. Smearing of the sides of the seed furrow was observed, particularly with the 'Caldow Type' inverted-T opener (Treatment (vii)) due to the flat heel design. This appeared to prevent the seedling from producing lateral roots. Together, these factors have reduced emergence and retarded early plant growth.

No significant improvement in emergence nor early plant growth resulted from the deeper row aligned cultivation using a 12 mm wide chisel opener (Treatments (vi) and (x)). Although there was no significant emergence differences between with or without deeper cultivation and the spear seeding point (Treatments (i) and (xi)), there was a significant reduction in early plant growth of deeper row aligned cultivation compared to none.

Table 3.6 Opener and covering device effect on total wheat emergence, mean emergence day (M.E.D.) and shoot dry matter (D.M.) at early tillering (Zadok 22) at Hart, 1991.

Opener - covering device	Total plant emergence (%)	M.E.D. (days)	Plant D.M. (g plant ⁻¹)	Total plot D.M. (g)
(i) Narrow spear – Press wheel	41.4 b	20.5 b	1.09 a	44.7 a
(iii) 125 mm share – finger tine harrow	26.6c	17.3 b	0.62 b	16.6 c
(iv) 125 mm share – Press wheel	40.1 b	22.7 ab	0.75 b	30.4 b
(vi) 12 mm wide chisel – Press wheel	40.2 b	20.5 b	0.64 b	25.1 bc
(vii) ‘Caldow’ type inverted-T (no covering device)	9.0 d	7.3 c	0.32 c	3.3 d
(viii) ‘Super Seeder’ type inverted-T (no covering device)	19.4 cd	17.1 b	0.30 c	5.5 d
(x) Deeper cultivating opener plus 12 mm wide chisel opener seeding – Press wheel	47.5 ab	23.7 ab	0.71 b	33.9 ab
(xi) Deeper cultivating opener plus Narrow spear opener seeding – Press wheel	42.7 b	21.0 ab	0.73 b	31.5 b
(xii) 200 mm share – Press wheel	57.9 a	30.6 a	0.78 b	44.7 a
P =	0.000	0.003	0.000	0.000
L.S.D. (P<0.05)	12.1	9.7	0.18	10.9

3.3.3 Multi-row research

Significant differences in total plant emergence between opener types and covering devices were present at Hart in 1992 (Table 3.7). The spear opener combined with press wheels (Treatments (i) and (xi)) and inverted-T openers with a harrow covering device (Treatments (vii) and (viii)), gave significantly higher total plant emergence than all other opener types. Inverted-T openers gave significantly higher total plant emergence with a harrow covering device than with a press wheel (Treatments (viii) and (ix) respectively). The more accurate seed placement obtained with a narrow spear opener when combined with deep preceding row cultivation contributed to significantly higher emergence than with a 12 mm wide chisel opener (Treatments (x) and (xi) respectively). A narrow 12 mm wide chisel opener, the relatively narrow 65 mm wide share opener as well as a 125 mm wide share opener, achieved very poor establishment (Treatments (iv), (v) and (vi) respectively). Press wheels did not

significantly improve total plant emergence with a 125 mm wide share opener also (Treatments (iii) and (iv)). There was no significant difference in mean emergence days between any opener and covering device types.



Plate 3.2 Plots sown at Hart in 1992; Left plot, narrow spear opener and press wheel covering device; Right plot, 125 mm wide share opener and finger tine harrows covering device.

Differences between openers in terms of both individual plant and total plot growth at early tillering at Hart in 1992 were similar to the total plant emergence results. A spear and 65 mm wide share opener with press wheels or inverted-T openers with harrows gave significantly higher plant and plot growth (Treatments (i), (v) and (ix)). Press wheels also significantly improved plant and plot growth compared with harrows with a 125 mm wide share opener (Treatments (iii) and (iv)). Press wheels significantly improved grain yield of a 125 mm wide share opener compared with

harrows. A spear opener with press wheels (treatment (i), significantly improved grain yields compared with a narrow 12 mm wide chisel with press wheels opener (Treatment (vi)), and a 125mm wide share opener with harrows (Treatment (iii)).

Table 3.7 Opener and covering device effect on total wheat emergence, mean emergence day (M.E.D.), shoot dry matter (D.M.) at early tillering (Zadok 22) and grain yield at Hart, 1992.

Opener – covering device	Total plant emergence (%)	M.E.D. (days)	Shoot D.M. (g plant ⁻¹)	Plot D.M. (kg ha ⁻¹)	Grain yield (kg ha ⁻¹)
(i) Narrow spear – Press wheel	72.90 ab	17.09	0.36 ab	556 a	4869 ab
(iii) 125 mm share – Finger tine harrow	48.97 e	19.12	0.23 c	235 c	3980 d
(iv) 125 mm share – Press wheel	57.47 de	17.52	0.36 ab	425 ab	4586 bc
(v) 65 mm share – Press wheel	57.86 de	17.47	0.40 a	481 ab	4981 a
(vi) 12 mm wide chisel – Press wheel	63.95 bc	17.87	0.35 ab	462 ab	4325 cd
(vii) ‘Caldow’ type inverted-T – Finger tine harrow	68.87 abc	17.68	0.36 ab	518 ab	4372 c
(viii) ‘Super Seeder’ type inverted-T– Finger tine harrow	72.00 abc	18.29	0.38 ab	562 a	4545 bc
(ix) ‘Super Seeder’ type inverted-T– Press wheel	61.94 cd	17.09	0.39 ab	497 ab	4645 abc
(x) Deeper cultivating opener plus 12 mm wide chisel opener seeding – Press wheel	64.18 bcd	18.02	0.30 bc	399 b	4553 bc
(xi) Deeper cultivating opener plus Narrow spear opener seeding – Press wheel	75.81 a	19.06	0.33 ab	525 ab	4563 bc
P =	0.001	0.224	0.050	0.005	0.002
L.S.D. (P<0.05)	10.80	ns	0.09	153	386

There was no significant grain yield difference between a spear, 65 mm wide share and inverted-T openers. Although press wheels slightly reduced emergence and plant growth compared with a harrow behind inverted-T openers (Treatments (viii) and (ix)), differences were not significant and no significant grain yield resulted.

There were few significant crop emergence and plant growth differences between soil openers and covering devices at Yacka in 1992 and no significant grain yield differences were recorded (Table 3.8). This could be attributed to the very favourable

rainfall in the growing season (Table 3.5). However, press wheels significantly improved crop establishment at Yacka in 1992 with a 125 mm wide share opener (Treatments (iii) and (iv)), but did not significantly improve plant growth rates in contrast to plant growth rate improvements at Hart.

Table 3.8 Opener and covering device effect on total wheat emergence, mean emergence day (M.E.D.), shoot dry matter (D.M.) at early tillering (Zadok 22) and grain yield at Yacka, 1992.

Opener – covering device	Total plant emergence (%)	M.E.D. (days)	Shoot D.M. (g plant ⁻¹)	Plot D.M. (kg ha ⁻¹)	Grain yield (kg ha ⁻¹)
(i) Narrow spear – Press wheel	58.36 a	16.36	0.36 abc	437 abcd	4590
(iii) 125 mm share – Finger tine harrow	43.16 b	18.71	0.37 abc	335 d	4790
(iv) 125 mm share – Press wheel	56.13 a	16.27	0.37 abc	421 abcd	4765
(v) 65 mm share – Press wheel	53.08 ab	18.86	0.34 bc	370 cd	4795
(vi) 12 mm wide chisel – Press wheel	57.47 a	18.26	0.37 abc	438 abc	4840
(vii) ‘Caldow’ type inverted-T – Finger tine harrow	59.93 a	17.98	0.41 a	506 a	4456
(viii) ‘Super Seeder’ type inverted-T–Finger tine harrow	57.47 a	16.97	0.41 a	474 ab	4767
(ix) ‘Super Seeder’ type inverted-T–Press wheel	52.10 ab	15.86	0.39 ab	420 abcd	4572
(x) Deeper cultivating opener plus 12 mm wide chisel opener seeding – Press wheel	63.28 a	15.78	0.37 abc	472 abc	4726
(xi) Deeper cultivating opener plus Narrow spear opener seeding – Press wheel	57.47 a	17.98	0.32 c	378 bcd	4776
P =	0.021	0.074	0.037	0.004	0.494
L.S.D. (P<0.05)	12.09	ns	0.05	102	ns

In contrast to 1992, the 1993 Hart and Yacka experiments exhibited significant problems with surface sealing or crusting which reduced plant emergence (Tables 3.9 and 3.10). Deeper preceding row aligned tillage significantly reduced surface sealing problems with narrow openers (Treatments (i) and (xi)) in 1993 at both sites. Press wheels significantly improved crop emergence and early plant growth in 1993 at both sites also (Treatments (iii), (iv), (viii) and (ix)).

Table 3.9 Opener and covering device effect on total wheat emergence, mean emergence day (M.E.D.), shoot dry matter (D.M.) at early tillering (Zadok 22) and grain yield at Hart 1993.

Opener – covering device	Total plant emergence (%)	M.E.D. (days)	Shoot D.M. (g plant ⁻¹)	Plot D.M. (kg ha ⁻¹)	Grain yield (kg ha ⁻¹)
(i) Narrow spear – Press wheel	12.97 d	16.73	0.39 a	108 de	2297 e
(ii) Wide spear – Press wheel	25.94 bc	17.38	0.37 abc	196 cde	2600 d
(iii) 125 mm share – Finger tine harrow	11.63 d	17.29	0.38 ab	89 e	1955 f
(iv) 125 mm share – Press wheel	55.68 a	16.98	0.30 ac	338 ab	3057 ab
(v) 65 mm share – Press wheel	49.80 a	16.19	0.36 abc	371 a	3225 a
(vi) 12 mm wide chisel – Press wheel	55.46 a	17.46	0.28 cd	318 ab	2747 cd
(vii) ‘Caldow’ type inverted-T – Finger tine harrow	14.98 cd	17.91	0.39 a	119 de	1367 g
(viii) ‘Super Seeder’ type inverted-T–Finger tine harrow	29.29 b	18.16	0.33 abc	202 cd	2538 d
(ix) ‘Super Seeder’ type inverted-T–Press wheel	47.18 a	17.56	0.28 cd	284 abc	3100 a
(x) Deeper cultivating opener plus 12 mm wide chisel opener seeding – Press wheel	57.69 a	18.98	0.20 d	237 bc	2858 bc
(xi) Deeper cultivating opener plus Narrow spear opener seeding – Press wheel	33.32 b	16.30	0.29 bcd	194 cd	3117 a
P =	0.000	0.080	0.005	0.000	0.000
L.S.D. (P<0.05)	12.52	ns	0.09	110	228

Individual plant growth rates were significantly lower with 12 mm wide chisel openers, inverted-T with press wheels and deeper cultivation combination openers than other opener types at Hart in 1993 (Treatments (vi), (ix), (x) and (xi)). However, emergence of openers such as a narrow spear (Treatment (i)) was too low for plant growth rates to compensate and this is reflected in significantly lower grain yields at both sites (Tables 3.9 and 3.10). Grain yields of 65 mm and 125 mm wide shares, inverted-T with press wheels and deeper cultivation openers (Treatments (iv), (v), (ix), (x) and (xi)), were significantly higher than other openers, in particular spear type openers (Treatments (i) and (ii)) in 1993 at both sites.

Highly significant grain yield differences were recorded in 1993 at Yacka (Table 3.10). As with the 1993 Hart experiment, the Yacka site exhibited significant

problems with surface sealing which restricted plant emergence. Surface sealing did not occur in 1992 at the Yacka site as weather conditions were wet during crop emergence and early growth (Table 3.5).

Table 3.10 Opener and covering device effect on total wheat emergence, mean emergence day (M.E.D.), shoot dry matter (D.M.) at early tillering (Zadok 22) and grain yield at Yacka, 1993.

Opener – covering device	Total plant emergence (%)	M.E.D. (days)	Shoot D.M. (g plant ⁻¹)	Plot D.M. (kg ha ⁻¹)	Grain yield (kg ha ⁻¹)
(i) Narrow spear – Press wheel	4.25 de	20.52	1.43 c	127 d	1095 c
(ii) Wide spear – Press wheel	8.95 cde	20.32	1.66 abc	337 cd	2175 b
(iii) 125 mm share – Finger tine harrow	12.52 cd	19.75	1.89 abc	522 bc	2314 b
(iv) 125 mm share – Press wheel	24.60 ab	17.62	1.55 bc	801 ab	2988 a
(v) 65 mm share – Press wheel	27.41 a	19.58	1.45 c	779 ab	3249 a
(vi) 12 mm wide chisel – Press wheel	22.81 ab	18.69	1.79 abc	836 ab	3470 a
(vii) ‘Caldow’ type inverted-T – Finger tine harrow	2.01 de	21.54	2.16 a	90 d	800 c
(viii) ‘Super Seeder’ type inverted-T– Finger tine harrow	8.05 cde	18.20	2.08 a	356 cd	2100 b
(ix) ‘Super Seeder’ type inverted-T– Press wheel	24.37 ab	19.69	1.83 abc	899 a	3034 a
(x) Deeper cultivating opener plus 12 mm wide chisel opener seeding – Press wheel	16.99 bc	17.88	1.83 abc	652 abc	3300 a
(xi) Deeper cultivating opener plus Narrow spear opener seeding – Press wheel	23.48 ab	19.54	2.01 ab	971 a	3108 a
P =	0.000	0.829	0.036	0.000	0.000
L.S.D. (P<0.05)	9.14	ns	0.51	350	630

Openers with low soil disturbance (Treatments (i) and (ii)), and openers that appeared to smear the seed groove such as a ‘Caldow type’ inverted-T opener (Treatment (vii)), significantly reduced crop emergence at Yacka in 1993. Deeper cultivation openers, 65 mm and 125 mm wider shares, and both 12 mm wide chisel and inverted-T with press wheels (Treatments (iv), (v), (vi), (ix), (x) and (xi)), significantly improved crop emergence, early plant growth and grain yields. These openers increase soil disturbance according to Hart shear vane results (Table 3.11).

Table 3.11 Opener and covering device effect on soil torsional shear vane resistance at Hart 1993.

Opener – covering device	Soil torsional shear vane resistance (kPa m ⁻²) Sampled 15 days post seeding	
	Sample depth (mm)	
	0-30	30-60
(i) Narrow spear – Press wheel	33.4 a	118.4 a
(ii) Wide spear – Press wheel	17.8 b	116.7 ab
(iii) 125 mm share – Finger tine harrow	8.9 c	95.8 bc
(iv) 125 mm share – Press wheel	3.1 cd	82.5 c
(vi) 12 mm wide chisel – Press wheel	0.1 d	23.7 e
(viii) ‘Super Seeder’ type inverted-T– Finger tine harrow	0.1 d	49.6 d
(ix) ‘Super Seeder’ type inverted-T– Press wheel	2.3 cd	54.1 d
(xi) Deeper cultivating opener plus Narrow spear opener seeding – Press wheel	0.1 d	2.0 f
P=	0.000	0.000
L.S.D. (P<0.05)	8.6	21.3
R ² (% total plant emergence)	0.31	0.53
R ² (D.M.plant ⁻¹)	0.33	0.38

A narrow spear opener with press wheels (Treatment (i)) had significantly higher shear vane resistance than all other openers at 0-30 mm depth. Both a narrow and wide spear opener (Treatments (i) and (ii)) had significantly higher shear vane resistance than all other openers at 30-60 mm depth (Table 3.11). Deeper cultivation (Treatment (xi)) significantly reduced soil shear strength.

There was a moderate correlation between soil shear strength at 30-60 mm depth and plant emergence. Press wheel indentations appeared to remain moist for longer periods than other treatments, keeping the seeds in contact with moist soil. The press wheel indentations also trapped rainfall, serving the same purpose.

3.4 Discussion

There are many plant establishment, growth and soil strength measurements observed in the results from these experiments, both subjective and quantified. It was observed that key soil opener design factors such as depth of cultivation in the seed row, soil opener width and the covering used in combination with a soil opener, has significant influence on the establishment and growth of a wheat crop. These factors are discussed in the following sub-sections.

3.4.1 Covering device

Results demonstrate that press wheels clearly improve crop establishment, plant growth rate and grain yield, particularly if soil crusting occurs. This supports the review of literature in Chapter 2. Press wheels used in this study in combination with all soil openers resulted in accurate depth of soil cover in both vertical and lateral dimensions. Research by Slattery and Rainbow (1995), has shown that vertical seed spread with a 125 mm combine point is ± 10 mm in sand, but the lateral spread is virtually the width of the share. It was quite likely that only 50-60 % of the seed in the seed row was effectively pressed by a 80 mm banked press wheel as only 55 mm of the press wheel comes into contact with the soil. This could account for poor crop emergence response to a press wheel at Hart in 1992. The spear type opener was better able to utilise advantages of press wheels as all seeds are pressed in the seed row due to the accurate seed placement in comparison with wider openers.

3.4.2 Deeper cultivation

Deeper cultivation with a narrow chisel opener, row aligned in front of a spear type opener accurately placing seed, gave equivalent grain yield to a wider 125 mm wide

share opener when press wheels were used in this study. Deeper row aligned cultivation combined with a poor seed placement seeding opener and seed delivery tube, such as a 12 mm wide chisel opener did not achieve accurate seed placement and consequently achieved poorer crop emergence, growth and grain yield results. The significant reduction in early plant growth from deeper cultivation if followed by a spear seeding point (Treatments (i) and (xi)) was possibly due to reduced level of seed to soil contact affecting plant growth rate. However improved crop emergence and reduced soil strength below the seed zone appeared to compensate reduced early plant growth, with improved grain yields. Row aligned preceding tillage 50 mm deeper than a seed row could be recommended in direct seeding systems based on these observations as long as seed placement is not significantly compromised.

3.4.3 Inverted-T opener

The review of the literature in Chapter 3 suggested that an inverted-T opener is a highly suitable direct drill soil opener in many soil conditions. However, data from the single row experiment in 1991 showed that inverted-T openers seem to exhibit some problems with soil smearing in the seed bed and seed burst due to poor seed-bed drainage on heavier textured soil during wet periods. Comments by farmers using these openers in the mid to upper South East of South Australia support this. However, farmer observations in the Mid-North of South Australia have indicated that inverted-T openers perform very well in loams that are dry at seeding. A cast point manufacturer had already recognised this problem and has modified the design to incorporate elevation of the opener heel up from the point similar to the 'Baker type' inverted T-boot (Anon, 1990; Fisher, 1991).

Inverted-T type openers can be used successfully for seeding wheat on red-brown earths which are dry, provided heavy rainfall does not occur immediately after seeding. Inverted-T openers gave comparable results to narrow spear and 125 mm wide share openers under these conditions. However, inverted-T-type openers should be used with caution in soils that are wet, as significant seed burst could occur.

No covering device was used with the inverted-T openers in 1991, as per manufacturer recommendations at that time. Inverted-T openers used in Years 2 and 3 experiments differed from that used in 1991, in that the leading edge of the point was lowered to reduce smearing (Anon, 1990; Fisher *pers. com.*, 1991).

Based on the research findings established by Baker (1981b), finger tine harrows should be the most suitable covering device for these openers in New Zealand cropping systems. The results of this research in Australian red-brown earths, suggest otherwise. No covering device was used with the inverted-T openers in 1991, as per manufacturer recommendations at that time. However, press wheels significantly improved inverted-T opener establishment compared with harrows and grain yield in 1993 at both sites, but not in 1992. Inverted-T opener manufacturers now recommend a covering device such as a harrow or press wheel (Fisher *pers. com.*, 1991). The use of finger tine harrow covering devices in comparison to press wheel covering devices used in conjunction with inverted-T type openers is therefore not clear cut. Press wheels achieve superior crop establishment with inverted-T openers in most seeding conditions, particularly if soil is prone to crusting. Harrows could occasionally achieve similar or slightly superior crop establishment compared with press wheels when using a 'Super Seeder' type inverted-T opener. This is likely due to the poor

seed placement of the seed delivery tubes used with these points and the inability of the press wheels to adequately press all seed to the correct depth (Slattery & Rainbow, 1992).

3.4.4 Spear opener

The research has shown that a spear opener gave significant improvement in cereal crop establishment, growth and grain yield compared with an alternative narrow 12 mm wide chisel opener as long as there is adequate seed-bed tilth or row aligned deeper cultivation is used. A spear opener achieved similar crop establishment to a 125 mm wide share opener. A spear opener was observed to be substantially easier to pull, reducing tractor draft also while achieving minimal soil surface disturbance compared to all the other soil openers. The spear point design, in particular the wide spear opener (Treatment (ii)) gave a low risk of smearing in the seed-bed, excellent seed placement and seed to soil contact, and is potentially a good alternative narrow seeding point. The accurate seed placement of spear opener integrated seed delivery tube (Slattery & Rainbow, 1993), may be a significant factor in the spear points performance.

Emergence differences between the narrow and wide spear type openers in 1993 are noteworthy. Progressively lower emergence of the narrow, wide and deeper cultivation spear openers (Treatments (i), (ii) and (xi)) respectively, translated into plant growth differences, and finally to significant yield differences. This demonstrates that productivity increases can be obtained by modifying soil opener design.

3.5 Conclusions

Based on the soil conditions of this study, the type of soil opener and covering device used on a seed drill can significantly improve cereal crop establishment and grain yield. The combination of soil opener and covering device should be selected carefully for each particular situation. Inverted-T type openers can be used successfully for the seeding of wheat on red-brown earths of low to intermediate water content at seeding, as long as heavy rainfall immediately after seeding does not occur. If a narrow chisel opener is selected, it should be recognised that a reduction in emergence, early plant growth, and possibly grain yield may be expected. A spear type soil opener had significant advantages over a narrow chisel opener in that it can achieve greater seed placement accuracy. Emergence and early plant growth was not significantly checked by the reduction in the level of soil fracturing and disturbance, of a narrow spear type opener as long as the seed-bed remained moist during establishment, resulting in improved grain yield.

Row aligned preceding tillage 50 mm deeper than a seed row is recommended in direct seeding systems as long as seed placement is not significantly compromised. Press wheels used in combination with accurate seed placement, clearly improve crop establishment, plant growth rate and grain yield, particularly if soil crusting occurs.

The cast spear type opener performed well in comparing different generic seed drill opener types and seeding machine configurations as long as adequate soil tilth or soil strength $< 20 \text{ kPa m}^{-2}$ at 0-30 mm depth occurred at seeding and plant emergence, or was created by additional deep cultivation during the seeding process. Grain yield results from direct drilled experiments on well structured red-brown earths, indicate

significant yield improvements can be achieved with spear points and press wheels in comparison with openers and covering devices such as finger tine harrows that most farmers currently use in their seeding programs. This is in addition to an opportunity for reduced soil disturbance from spear points in comparison to some other wider or larger opener types. If a spear type opener and press wheel is used in a 3 rank tine configuration, there could be significant potential for improvement in trash handling, and possibly crop establishment and grain yield. This is compared with the current farming industry standard of a full cut 6 rank seeder with 125 mm wide share openers and trash finger tine harrows as used in this research.

Research to determine how spear opener design factors influence soil physical properties is required to improve understanding of spear soil opener impact on crop establishment. Factors such as opener width, influence of the leading edge on soil smear and impact of the combination of row aligned deeper tillage should be studied further. Subjective observations were made in these experiments on effect of inverted-T soil openers on soil smear in the seed bed and also the impact of press wheels on reducing the impact on surface sealing. Crop establishment and growth results following these subjective observations suggest that soil openers can have significant influence on achieving optimal soil physical properties. Further research on quantifying these resulting soil physical factors would be helpful in an improved understanding of optimum soil opener design for crop production on a red-brown earth.

4. SPEAR SOIL OPENER IMPACT ON SOIL PHYSICAL PROPERTIES AND PLANT DEVELOPMENT IN A DRY SOIL

4.1 Introduction

The spear type soil opener has been found to give optimal cereal crop establishment in a range of soil types and seeding conditions, often leading to significant improvement in grain yield (Slattery and Rainbow, 1995). The reason for improved crop growth was most likely due to improved seed placement. However, the beneficial effects of the soil opener on soil physical properties and the subsequent effects on crop establishment have not been quantified.

A generic cast spear point is characterised by a narrow width of less than 40 mm with a spear like appearance (Figure 3.1). The leading point is directed down at a 45° angle from the top leading edge to the horizontal. The leading point is generally less than 20 mm below the rear end of the seeding point. With the sharp main wearing edge of the point running deeper, it is assumed smearing effects are reduced. Viewed from the front towards the rear of the point, the base has a distinct V-shape. This feature shapes the seed groove, giving better seed positioning and seed to soil contact.

There have been many qualitative statements made about the benefits of spear openers on crop establishment. However, their resulting effects, if they have been investigated, have not been published. There are a number of spear opener design parameters such as point shape, angle of positive entry and the interaction with deeper row aligned tillage which need further investigation. These factors need to be

quantified before significant advances can be made not only in spear type soil opener design, but also the influence of these factors on seed drill openers in general.

The aim of the research reported here was to quantify the effects of different spear type seed drill opener design parameters on indirect effects on the seedling micro-environment and soil physical properties. These responses could ultimately affect wheat crop establishment and grain yield in combination with climatic factors.

The research tested the hypothesis that wide spear type soil openers and sharp spear type soil openers provide measurable reductions in soil resistance to plant emergence and growth compared with narrow and blunt types. The research also tested the hypothesis that deep cultivation in the seed row combined with wide sharp spear type soil openers reduced soil resistance to plant emergence and growth. In contrast, sharp closing spear type soil openers combined with deep cultivation in the seed row provide measurable improvement in seed-bed firmness compared with the former.

4.2 Materials and methods

Triticum aestivum var. Janz was sown in the early winter period of a late seasonal break on the 13th and 15th of July 1994 at two experimental sites (Roseworthy and Yacka respectively) in the Mid-North of South Australia. Both sites enjoy a mild Mediterranean climate with an average growing season rainfall of 400 mm falling mainly between April and October. Seed, treated with Batan[®] (triadimenol/cypermethrin fungicide/insecticide) at 1g kg⁻¹ was germination tested by International Seed Testing Association Guidelines to give 97 % normal seedlings at 8

days. Sowing density was 185 seeds m⁻². Di-ammonium phosphate fertiliser (N:P:K 18:20:0), at a rate of 75 kg ha⁻¹ was applied at seeding.

The two experiments were sown as a randomised block design, with the site at Yacka containing 4 replicates and the site at Roseworthy containing 6 replicates. Each experiment was sown in one day, two days apart from each other. The soil at Yacka was considered poorly structured in contrast to the Roseworthy experiment site.

Experiments were sown with seeding equipment described in Chapter 3 with seed row spacings 180 mm apart (Appendix 10.1.1). Plots were 1.44 m wide by 30 m long. Seed was sown at a depth of 30 mm of soil cover over the seed row in all treatments.

Treatment openers used in experiments are shown in Plate 4.1. Spear opener and tine design parameters are listed in Table 4.1. Seeding tines were all John Shearer[®] 580 series tines, except the narrow spear type soil opener (treatment (i)) which had its own tine shank mounted into a John Shearer[®] 580 series tine head mount. All seeding tines without deep cultivation (treatments (i), (ii), (iii) and (iv)) were set at a tine breakout force of 740 N (Robotham and Norris, 1985). All deep cultivation tines (treatments (iii) and (v)) were set at a tine breakout force of 950 N. A commercial Primary Sales Australia[®] reference 91 Knife Seeder opener which was 20 mm wide, cultivating soil 50 mm below where seed was placed, was used in the deep cultivation treatments (iii) and (iv). All tines had an integrated seed delivery tube that gave positive seed placement. Treatments (ii), (iii) and (iv) used a moulded urethane seed delivery tube that fitted closely to the seeder tine. Treatments (i) and (v) had a steel seed delivery tube. All seed delivery tubes had opening orifices 20 mm wide which

extended back for 100 mm of the seed tube length. All seed tubes were cut up towards the rear at a 45° angle.

Treatment (i) was a commercial tungsten carbide tipped narrow sharp spear point soil opener manufactured by Janke®. Treatment (v) was an identical soil opener that had been ground to give the appearance of a bow of a boat. This shape had the effect of closing soil back down the slot created by the longer knife point mounted directly in front.

Treatments (ii), (iii) and (iv) all use the tungsten carbide tipped commercial ARP®-RRR02 spear point soil opener. Treatment (iv) had the leading tip completely cut off at 90° angle to the horizontal. This is successfully used in the commercial soil opener manufacturing industry as a means to improve tungsten carbide tip retention on stony soils.

Table 4.1 Seeding tine and opener design parameters.

Treatment no./ name	Opener width (mm)	Ranks of tines	Cultivation point (50mm below seed zone)	Seeding/ cultivation tine breakout force (N)
(i) Narrow sharp spear	36	3	None	740
(ii) Wide sharp spear	42	3	None	740
(iii) Deep-cult+wide sharp spear	42	6	Primary Sales Aust. Ref. 91 Knife Seeder	740/950
(iv) Wide blunt spear	42	3	None	740
(v) Deep cult+thin sharp closing spear	36	3	Primary Sales Aust. Ref. 91 Knife Seeder	950



Plate 4.1 Spear type seed drill soil openers (left to right): (i) narrow sharp spear; (ii) wide sharp spear; (iii) deep cultivation + wide sharp spear; (iv) wide blunt spear; (v) deep cultivation + thin sharp closing spear.

The covering device used was an 80 mm wide solid rubber banked type press wheel mounted on a walking type frame assembly with a pressure of 5 kg cm^{-1} across the width of press wheel in contact with the soil (Appendix 10.1.2).

Soils from both experiment sites were analysed for nutrient status in a commercial laboratory using the materials and methods described in chapter 3.

Weeds were controlled completely by chemical means. Glyphosate (450 g L^{-1} a.i.) broad spectrum knockdown herbicide at 2.0 L ha^{-1} in 110 L ha^{-1} water was used 7 days prior to seeding for pre-seeding weed control. A tankmix of 7 g ha^{-1} Eclipse[®] (714 g kg^{-1} a.i. metosulam), 350 ml ha^{-1} MCPA LVE (500 g L^{-1} a.i. MCPA low volatile ester), 150 ml ha^{-1} Lontrel[®] (300 g L^{-1} a.i. clopyralid), 1.0 L ha^{-1} Hoegrass[®] (375 g L^{-1} a.i. diclofop-methyl) and a non-ionic surfactant @ 1 ml L^{-1} water at a water rate of 110 L ha^{-1} was used post seeding post emergence at the plant 5 leaf stage at both sites. Urea (60 kg ha^{-1} N:P:K; 46:0:0) was surface applied in a liquid water mixture @ 500 L ha^{-1} 2 weeks post spraying at the plant tillering stage to supply plant nitrogen requirements.

All plant emergence, plant growth, soil strength and soil moisture measurements were sampled by the transect method described by Rainbow (1993), to reduce sampling error caused by soil throw of the tines and points. All plant emergence counts were taken in a transect across the experiment as 3 x 1 m adjacent rows to reduce effects from seed drill metering and soil cover effects. All plant growth samples were collected by the transect method, collecting 10 plants or grain heads from 3 adjacent seeder rows.

Rate of emergence was estimated from repeated daily plant counts at 3 separate centrally marked plot positions from the first day of emergence until 3 consecutive days passed with no further plant emergence. The mean emergence day (M.E.D.) was then calculated by the method described by Robinson and Sandfort (1980). Plant growth was determined by collecting 30 individual plant tops above the soil surface, 10 plants from 3 adjacent rows, in the same position as the transects taken for the plant emergence counts. All plant samples were dried at 70 °C for 48 hours in perforated paper bags and then weighed. Fertile spikes were counted from the sample of 30 plants at anthesis. Thirty grain heads were collected from each transect of anthesis plant cut and tiller count, individually thrashed and grain number and weight measured. Grain yield was determined by machine harvesting the entire 30 x 1.44 m plot and measuring the total plot grain weight.

Soil physical characteristics and moisture samples were collected from each experiment at 2 sampling intervals, at the first day of plant emergence and the 10 days post first day of emergence. Matric suction at both sites was determined at seeding by the filter paper method by Fawcett and Collis-George (1967).

Soil samples for bulk density and water content was collected immediately prior to seeding in brass tubes 72 mm diameter, 50 mm deep. After seeding, similar samples were collected in 50 mm diameter, 25 mm deep brass tubes. Tubes were driven into the soil via a metal piston in a tube guide (McIntyre, 1974). Bulk density and soil water content samples were collected at 3 depth intervals (0-50 mm, 50-100 mm and 100-150 mm) in a transect across the experiment. Soil water content was determined by weighing before and after drying wet soil in a drying oven at 105°C for 24 hours. Smaller brass tubes were utilised post seeding compared to the larger, more accurate pre-seeding brass tubes to restrict the sampling area to a smaller depth interval and seed row width.

Soil shear strength was measured at 3 depths (0–50 mm, 50-100 mm and 100-150 mm) prior to seeding with a torsional shear box (Collis-George and Lloyd, 1979) in the seed-bed.

After seeding shear strength was again measured at 15 locations in 3 seed rows close to the bulk density and moisture samples. A Geonor[®] shear vane gauge was used by the method described by Koppi and Douglas (1991), with a vane size at Yacka of 4 vanes of 32 mm deep x 7.9 mm wide, and at Roseworthy of 4 vanes 40 mm deep x 10 mm wide (Plate 4.2). A shear vane was used post seeding in preference to a torsional shear box to restrict the sampling area to the narrow seed row width.

The plastic limit soil water content was determined on disturbed soil samples by adjusting soil water content until the soil began to break apart and crumble when rolled by hand into threads 3 mm in diameter (AS 1289 C2.1, 1977). Gravimetric soil

water content was determined by weighing the samples before and after oven drying at 105 °C for 24 hours. Volumetric water content was calculated from the independent bulk density measurements.



Plate 4.2 Geonor[®] shear vane gauge used in experiments.

Soil penetrometer resistance was recorded with a mechanically driven (250 mm min^{-1}) recording penetrometer (Plate 4.3). The penetration device was a strain gauge (450 N) connected via a 4.5 mm shaft (300 mm long) to a cone 6 mm in diameter with a 30° included angle. The penetrometer, mounted on a self-leveling frame with wheels, logged force at 2 mm depth intervals. The strain-gauge was calibrated to give penetration resistance in MPa. Measurements were made to a depth of 150 mm in 3 rows, adjacent to the soil water content and bulk density sample sites in all plots.



Plate 4.3 Mechanically driven recording penetrometer used in experiments.

Penetrometer data collected was used to calculate penetration energy in MJ m^{-2} . Values were calculated by averaging data at each 2 mm depth interval from the 3 rows of each plot in the centre of the seed furrow. The value of energy was calculated from the cumulative values ranging in depth from 10-30 mm, 32-60 mm and 62-90 mm from the soil surface.

All data were analysed with Statistix[®] Version 3.1 Analytical Software (Anon, 1993). Plots of residual error were used to check for outlying data. Significant outlying data were entered as missing values in these cases and experiments were re-analysed.

4.3 Results

4.3.1 Field establishment conditions

The soils were similar in nutrient status (Table 4.2). Extractable P was marginal at both sites. Extractable K and NO₃-N were considered adequate. Yacka contained a moderate level of organic carbon and Roseworthy was considered low. Both Yacka and Roseworthy soils were calcareous. Soil pH varied as Yacka was slightly acid with Roseworthy tending moderately alkaline.

Table 4.2 Soil chemical composition at the Roseworthy and Yacka experimental sites (0-100 mm depth) in 1994.

Experimental site	Extrac. P (mg kg ⁻¹)	Extrac. K (mg kg ⁻¹)	NO ₃ -N (mg kg ⁻¹)	OC (%)	E.C. 1:5 _w extract (dS m ⁻¹)	CaCO ₃ (%)	pH (H ₂ O)
Roseworthy	25	460	7.5	0.8	0.12	3	8.2
Yacka	27	590	20	1.1	0.08	3	6.7

Soils differed in physical status as the Yacka site contained slightly more silt and clay particles and a much higher soil strength at 20 mm than the Roseworthy site (Table 4.3). Emerson soil dispersion tests indicated both sites would disperse if cultivated at a water content significantly wetter than the plastic limit.

Table 4.3 Soil physical properties at the Roseworthy and Yacka experimental sites (0-100 mm depth) in 1994.

Experimental site	Particle size distribution (%)			Emerson dispersion class	Soil texture	Bulk density (Mg m ⁻³)		Soil shear strength ¹ (kPa m ⁻²) recorded at seeding		
	Sand	Silt	Clay			0-50 mm	50-100 mm	20 mm	50 mm	80 mm
Roseworthy	73	12	15	3	Sandy Loam	1.49	1.58	349	554	1043
Yacka	60	18	22	3	Sandy clay loam	1.44	1.53	438	548	640

¹ Soil shear strength recorded at water content in Table 4.4.

Table 4.4 Matric suction, water content and temperature at seeding on the Roseworthy and Yacka experimental sites in 1994.

Experimental site	Matric suction ψ_m (MPa)			Soil water content θ ($m_w m_s^{-1}$)			Soil temperature ($^{\circ}C$ at 9 am). 100 mm
	0-30 mm	30-60 mm	60-120 mm	0-50 mm	50-100 mm	Plastic limit 0-50 mm	
Roseworthy	0.59	0.38	0.10	0.202	0.226	0.241	12.7
Yacka	7.19	1.43	0.39	0.163	0.219	0.205	10.8

Soils were dry at seeding with low water contents and high matric suction values (Table 4.4). The Yacka soil was particularly dry with matric suction values at 0-30 mm unable to sustain seed germination (i.e. $\ll 1.5$ Mpa). Seed sown at 30 mm depth of soil cover using press wheels was placed in the middle of the 30-60 mm soil band due to the furrow formation enabling seed germination to take place. Both sites were sown at water content below the soil plastic limit.

Rainfall was low at both sites post seeding, prior to crop emergence (Table 4.5). Rainfall patterns were similar at both sites from crop emergence to tillering but Roseworthy had slightly lower rainfall. Rainfall was considerably higher at Yacka than Roseworthy from crop tillering to anthesis. Rainfall during the experiment at the Roseworthy site was in the lowest decile for rainfall records over the past 100 years. Soil temperatures at seeding of these experiments were warmer than those of Chapter 3, particularly at Roseworthy.

Table 4.5 Cumulative growing season rainfall (mm) at key intervals from seeding at the Roseworthy and Yacka experimental sites in 1994.

Experimental site	Days post seeding							
	13	23	30	37	44	51	58	107
Roseworthy	0.6	29.2	34.6	37.6	38.2	38.2	43.6	70.6
Yacka	Days post seeding							
	13	26	33	40	48	54	61	117
	0.0	46.6	47.6	48.6	48.6	60.8	62.2	107.2

4.3.2 Soil penetration resistance

A narrow sharp spear (Treatment(i)) resulted in significantly higher penetration resistance energy at 10-30 mm depth than a wide sharp spear (Treatment (ii)) at both sampling intervals at Roseworthy and at emergence at Yacka (Table 4.6). The second sampling 25 days post seeding at Yacka had a significantly higher rainfall event during this period than Roseworthy (Table 4.5). There was also a significant increase in penetration resistance energy at 30-60 mm depth resulting between narrow sharp spear and a wide sharp spear (Treatments (i) and (ii)) during emergence at Yacka.

Deeper cultivation with a wide sharp spear or thin sharp closing spear (Treatments (iii) and (v)), resulted in significantly reduced penetration resistance energy at 32-60 mm and 62-90 mm depths compared with other spear openers at both sites.

The relationships between emergence, plant growth and penetration energy were fitted using Datafit™ version 2.0 data modelling software (Anon, 1993). These relationships were very variable with none showing a better correlation than $R^2 = 0.4$. Because of the poor correlation, these data are not shown here. There was no significant statistical relationship between emergence, plant growth and penetration energy.

Table 4.6 Effects of spear opener shape and deep cultivation on total penetration energy at Roseworthy and Yacka in 1994.

Roseworthy	Total penetration energy (MJ m ⁻²)					
	Sampled 13 days post seeding Sample depth (mm)			Sampled 23 days post seeding Sample depth (mm)		
	10-30	32-60	62-90	10-30	32-60	62-90
Treatment						
(i) Narrow sharp spear	13.81 a	58.08 a	56.84 a	8.28 a	33.08 a	86.48 a
(ii) Wide sharp spear	8.92 b	59.47 a	47.19 b	5.52 b	25.87 a	86.36 a
(iii) Deep-cult+wide sharp spear	6.06 b	13.68 b	7.29 c	3.09 c	5.80 b	15.88 b
(iv) Wide blunt spear	9.46 b	51.06 a	48.20 ab	7.41 a	30.82 a	72.65 a
(v) Deep cult+thin sharp closing spear	6.97 b	11.02 b	12.40 c	2.73 c	4.12 b	25.26 b
P =	0.008	0.000	0.000	0.001	0.000	0.000
L.S.D. (P<0.05)	4.08	18.61	9.40	2.74	7.91	17.54
Yacka	Total penetration energy (MJ m ⁻²)					
	Sampled 13 days post seeding Sample depth (mm)			Sampled 25 days post seeding Sample depth (mm)		
	10-30	32-60	62-90	10-30	32-60	62-90
Treatment						
(i) Narrow sharp spear	18.4 b	97.7 a	116.5 a	5.7 a	43.5 a	43.8 a
(ii) Wide sharp spear	5.5 c	62.7 c	107.0 b	5.2 ab	32.5 a	49.3 a
(iii) Deep-cult+wide sharp spear	4.8 c	11.3 d	34.6 d	1.0 bc	3.6 c	11.6 c
(iv) Wide blunt spear	32.0 a	88.6 b	107.3 b	8.2 a	36.7 a	38.1 ab
(v) Deep cult+thin sharp closing spear	7.5 c	11.4 d	54.1 c	0.2 c	1.1 c	26.1 b
P =	0.000	0.000	0.000	0.012	0.000	0.000
L.S.D. (P<0.05)	8.5	7.1	8.3	4.45	11.5	12.7

Penetrometer resistance as a function of depth in Figures 4.1, 4.2, 4.3 and 4.4, show a significant reduction in penetrometer resistance resulting from the use of deeper seed row aligned cultivation (Treatments (iii) and (v)). A narrow closing spear opener (Treatment (v)) resulted in significantly increased penetration resistance compared with a deeper cultivating wide sharp spear (Treatment (iii)) at 70-100 mm depth at Roseworthy and 60-100 mm depth at Yacka, increasing seed-bed firmness. A narrow sharp spear also resulted in significantly increased penetration resistance compared with a wide sharp closing spear at 50-60 mm depth at Yacka. This effect was also detected at Roseworthy 23 days after sowing (Figure 4.2).

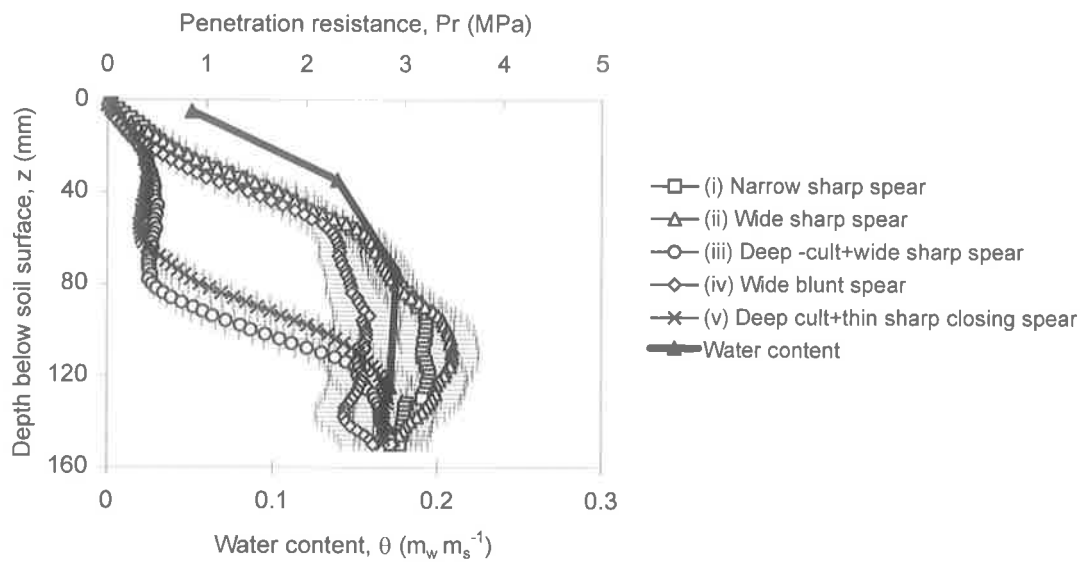


Figure 4.1 Soil opener effect on penetrometer resistance 13 days post sowing at Roseworthy and standard error of mean.

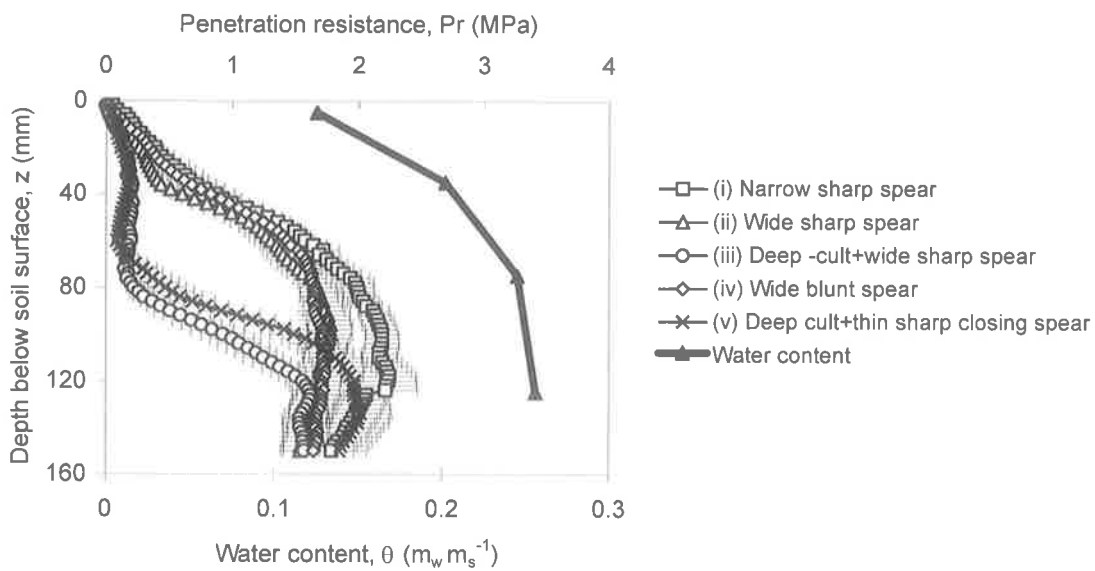


Figure 4.2 Soil opener effect on penetrometer resistance 23 days post sowing at Roseworthy and standard error of mean.

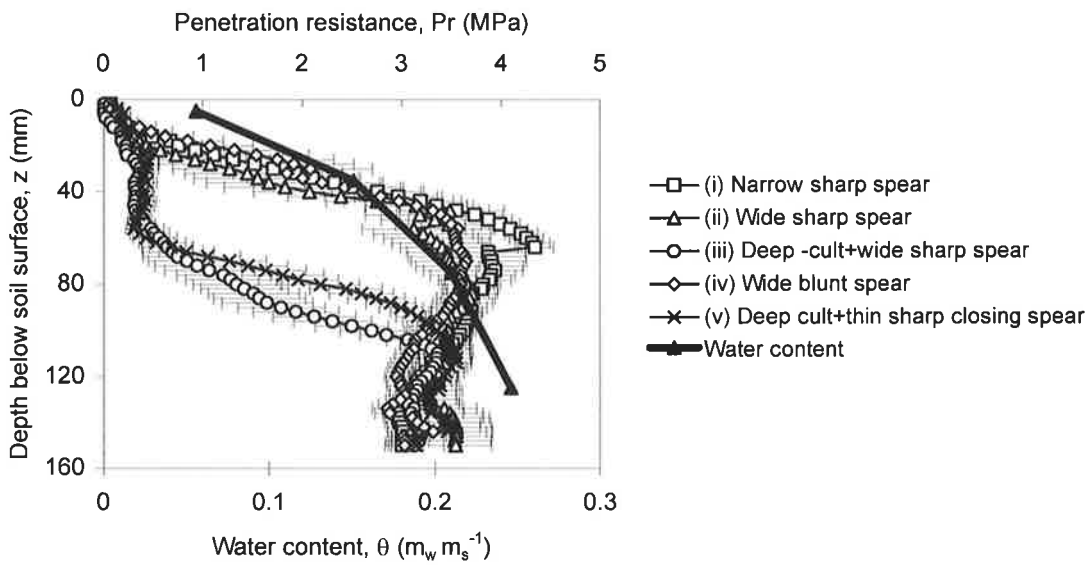


Figure 4.3 Soil opener effect on penetrometer resistance 13 days post sowing at Yacka and standard error of mean.

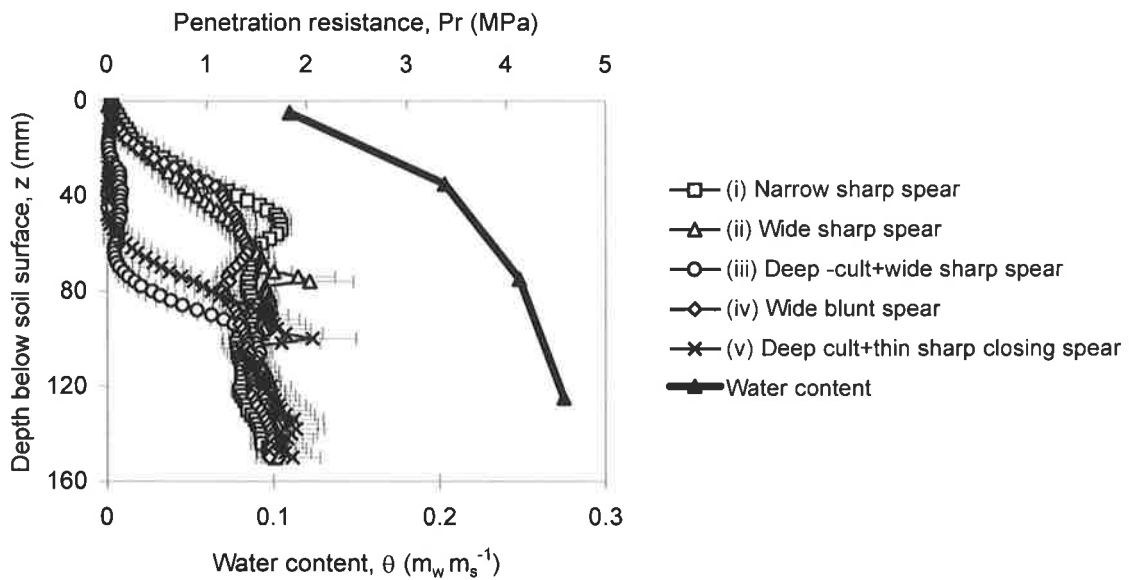


Figure 4.4 Soil opener effect on penetrometer resistance 25 days post sowing at Yacka and standard error of mean.

A wide blunt spear opener (Treatment (v)) did not result in significantly increased penetration resistance compared with sharp spear openers (Treatments (i) and (ii)). Soil water content increased, particularly at Roseworthy, during emergence because of rainfall (Figures 4.1, 4.2, 4.3 and 4.4 and Tables 4.9 and 4.10). This reduced penetration resistance values at the later measurement period. Effect of soil water content on undisturbed soil penetration resistance is shown in Appendices A10.2.1 and A10.2.2.

4.3.3 Soil shear vane resistance

Table 4.7 Effects of spear opener shape and deep cultivation on soil torsional shear vane resistance at Roseworthy and Yacka in 1994.

Roseworthy	Soil torsional shear vane resistance (kPa m ⁻²)					
	Sampled 13 days post seeding Sample depth (mm)			Sampled 23 days post seeding Sample depth (mm)		
Treatment	0-50	50-100	100-150	0-50	50-100	100-150
(i) Narrow sharp spear	52.5 a	138.4 a	95.5 a	70.0 a	107.8 a	88.9 a
(ii) Wide sharp spear	50.9 a	139.6 a	95.2 a	53.4 b	105.9 a	75.5 a
(iii) Deep-cult+wide sharp spear	19.9 b	42.7 c	31.3 b	18.6 c	97.6 a	31.1 b
(iv) Wide blunt spear	51.4 a	135.4 a	93.4 a	60.3 ab	62.0 b	83.1 a
(v) Deep cult+thin sharp closing spear	20.6 b	64.4 b	42.5 b	19.9 c	43.6 c	41.0 b
P =	0.000	0.000	0.000	0.000	0.000	0.000
L.S.D. (P<0.05)	11.2	16.5	12.4	16.5	16.8	15.6
Yacka	Soil torsional shear vane resistance (kPa m ⁻²)					
	Sampled 13 days post seeding Sample depth (mm)			Sampled 25 days post seeding Sample depth (mm)		
Treatment	0-50	50-100	100-150	0-50	50-100	100-150
(i) Narrow sharp spear	173.8 a	272.2 a	223.0 a	115.1 a	184.0 a	149.6 a
(ii) Wide sharp spear	176.1 a	268.2 a	222.2 a	110.1 a	191.0 a	150.6 a
(iii) Deep-cult+wide sharp spear	31.2 b	127.4 b	79.3 b	26.3 b	95.0 b	60.7 b
(iv) Wide blunt spear	189.2 a	275.6 a	232.4 a	117.9 a	193.0 a	155.4 a
(v) Deep cult+thin sharp closing spear	41.1 b	158.1 b	99.6 b	26.8 b	104.0 b	65.4 b
P =	0.000	0.000	0.000	0.000	0.005	0.000
L.S.D. (P<0.05)	54.2	60.4	43.5	34.3	59.7	35.8

Deeper row aligned cultivation (Treatments (iii) and (v)) generally resulted in significantly lower soil torsional shear vane resistance (Table 4.7) and bulk density (Table 4.8). A narrow sharp spear (Treatment (i)) caused significantly higher shear

vane resistance at 0-50 mm depth compared to a wide sharp spear (Treatment (ii)) post crop emergence at Roseworthy.

4.3.4 Soil bulk density

Table 4.8 Effects of spear opener shape and deep cultivation on soil bulk density at Roseworthy and Yacka in 1994.

Roseworthy	Soil bulk density (Mg m^{-3})					
	Sampled 13 days post seeding Sample depth (mm)			Sampled 23 days post seeding Sample depth (mm)		
Treatment	0-50	50-100	100-150	0-50	50-100	100-150
(i) Narrow sharp spear	1.278 a	1.493 a	1.312	1.311	1.553 a	1.626 a
(ii) Wide sharp spear	1.237 ab	1.458 a	1.415	1.286	1.560 a	1.608 a
(iii) Deep-cult+wide sharp spear	1.136 bc	1.222 b	1.280	1.195	1.361 b	1.442 b
(iv) Wide blunt spear	1.249 ab	1.394 a	1.334	1.270	1.480 a	1.613 a
(v) Deep cult+thin sharp closing spear	1.057 c	1.352 ab	1.276	1.200	1.306 b	1.483 b
P =	0.014	0.007	0.689	0.250	0.000	0.003
L.S.D. ($P < 0.05$)	0.134	0.141	ns	ns	0.085	0.106
Yacka	Soil bulk density (Mg m^{-3})					
	Sampled 13 days post seeding Sample depth (mm)			Sampled 25 days post seeding Sample depth (mm)		
Treatment	0-50	50-100	100-150	0-50	50-100	100-150
(i) Narrow sharp spear	1.517 a	1.552	1.652	1.311 ab	1.546 a	1.589
(ii) Wide sharp spear	1.433 ab	1.636	1.607	1.352 a	1.512 a	1.617
(iii) Deep-cult+wide sharp spear	1.229 c	1.519	1.622	1.231 bc	1.361 b	1.509
(iv) Wide blunt spear	1.509 a	1.640	1.609	1.331 ab	1.547 a	1.620
(v) Deep cult+thin sharp closing spear	1.306 bc	1.522	1.592	1.197 c	1.381 b	1.530
P =	0.023	0.457	0.884	0.010	0.037	0.456
L.S.D. ($P < 0.05$)	0.191	ns	ns	0.088	0.148	ns

4.3.5 Soil water content

There was no resulting significant effect of opener type on soil water content in either experiment at any depth except at 25 days post seeding at Yacka in the 100-150 mm soil depth layer (Tables 4.9 and 4.10). Soil water content on the first day of emergence was considerably lower at both sites compared with a second recording after emergence. The soil water contents at 0-50 mm were considered very dry.

Table 4.9 Effect of spear opener shape and deep cultivation on soil water content at Roseworthy 13 and 23 days after sowing in 1994.

Sampled 13 days post seeding	Soil water content θ ($m_w m_s^{-1}$)			
	Sample depth (mm)			
Treatment	0-10*	0-50	50-100	100-150
(i) Narrow sharp spear	0.053	0.136	0.186	0.159
(ii) Wide sharp spear	0.054	0.142	0.181	0.172
(iii) Deep-cult+wide sharp spear	0.051	0.129	0.159	0.163
(iv) Wide blunt spear	0.052	0.139	0.171	0.163
(v) Deep cult+thin sharp closing spear	0.046	0.148	0.177	0.197
P =	0.581	0.581	0.244	0.303
L.S.D. (P<0.05)	ns	ns	ns	ns
Sampled 23 days post seeding	Soil water content θ ($m_w m_s^{-1}$)			
	Sample depth (mm)			
Treatment	0-10*	0-50	50-100	100-150
(i) Narrow sharp spear	0.146	0.206	0.251	0.254
(ii) Wide sharp spear	0.128	0.205	0.246	0.250
(iii) Deep-cult+wide sharp spear	0.122	0.191	0.245	0.260
(iv) Wide blunt spear	0.125	0.213	0.243	0.264
(v) Deep cult+thin sharp closing spear	0.104	0.193	0.241	0.253
P =	0.482	0.283	0.971	0.911
L.S.D. (P<0.05)	ns	ns	ns	ns

* Calculated water content based on % water by mass and 0-50 mm bulk density recordings

Table 4.10 Effect of spear opener shape and deep cultivation on soil water content at Yacka 13 and 23 days after sowing in 1994.

Sampled 13 days post seeding	Soil water content θ ($m_w m_s^{-1}$)			
	Sample depth (mm)			
Treatment	0-10*	0-50	50-100	100-150
(i) Narrow sharp spear	0.063	0.160	0.215	0.249
(ii) Wide sharp spear	0.062	0.160	0.205	0.251
(iii) Deep-cult+wide sharp spear	0.047	0.118	0.200	0.244
(iv) Wide blunt spear	0.059	0.155	0.212	0.240
(v) Deep cult+thin sharp closing spear	0.051	0.160	0.219	0.244
P =	0.318	0.197	0.732	0.894
L.S.D. (P<0.05)	ns	ns	ns	ns
Sampled 25 days post seeding	Soil water content θ ($m_w m_s^{-1}$)			
	Sample depth (mm)			
Treatment	0-10*	0-50	50-100	100-150
(i) Narrow sharp spear	0.117	0.205	0.248	0.262 b
(ii) Wide sharp spear	0.123	0.221	0.243	0.292 a
(iii) Deep-cult+wide sharp spear	0.101	0.191	0.241	0.252 b
(iv) Wide blunt spear	0.109	0.203	0.248	0.271 b
(v) Deep cult+thin sharp closing spear	0.100	0.196	0.259	0.297 a
P =	0.490	0.119	0.099	0.002
L.S.D. (P<0.05)	ns	ns	ns	0.020

* Calculated water content based on % water by mass and 0-50 mm bulk density recordings

4.3.6 Rate of plant emergence and total emergence

The resulting effects of spear type seeding openers on plant emergence are shown in Table 4.11. A wide sharp spear opener (Treatment (ii)) resulted in significantly higher plant emergence than a wide blunt spear opener (Treatment (iv)). A wide sharp spear opener (Treatment (ii)) was the only treatment at Yacka that resulted with comparable rates of total emergence to Roseworthy, where there were only small differences in total emergence. Plants growing in the seed-bed prepared with a deeper cultivation + thin closing spear opener (Treatment (v)) took significantly less time to emerge than those in a deep cultivation + wide sharp spear opener seed-bed (Treatment (iii)) at Roseworthy.

Resulting effects of spear type seeding openers on plant growth are shown in Tables 4.12 and 4.13. There were few significant plant growth differences at Yacka. The one exception was at 40 days post seeding where plant biomass on seed-beds made with a wide sharp spear opener (Treatment (ii)) and a deep cultivation + wide sharp spear opener (Treatment (iii)) was significantly higher than other treatments. At Roseworthy, the reverse occurred. Narrower, blunt or closing treatments (Treatments (i), (iv) and (v)) often resulted in significantly increased plant growth rates. There were significant differences in total plot growth at tillering resulting between treatments at Yacka (Table 4.13). The significantly higher biomass resulting from a wide sharp spear opener (Treatment (ii)) and the lower biomass resulting from a wide blunt spear (Treatment (iv)) at Yacka should be noted. A narrow sharp spear (Treatment (i)) resulted in significantly lower plot growth compared to a wide sharp spear (Treatment (ii)) at both sites. Deep cultivation + a wide sharp spear (Treatment

(iii)) resulted in significantly reduced plot growth at Roseworthy compared with no deeper cultivation (Treatment (ii)), but not significantly at Yacka.

Table 4.11 Effects of spear opener shape and deep cultivation on total wheat plant emergence and mean emergence day (M.E.D.) at the Roseworthy and Yacka sites in 1994.

Treatment	Roseworthy		Yacka	
	Total plant emergence (%)	M.E.D. (days)	Total plant emergence (%)	M.E.D. (days)
(i) Narrow sharp spear	77.41 ab	14.80 b	63.17 ab	17.42 a
(ii) Wide sharp spear	78.64 ab	14.77 b	74.17 a	16.82 ab
(iii) Deep-cult+wide sharp spear	72.83 c	16.30 a	64.42 ab	16.57 b
(iv) Wide blunt spear	80.78 a	14.56 b	60.17 bc	17.45 a
(v) Deep cult+thin sharp closing spear	75.08 bc	15.02 b	49.67 c	17.11 a
P =	0.013	0.000	0.025	0.050
L.S.D. (P<0.05)	4.44	0.47	13.40	0.71

4.3.7 Rate of plant shoot growth to early tillering and anthesis

Table 4.12 Effect of spear opener shape and deep cultivation on shoot dry matter (D.M.) per plant at Roseworthy and Yacka in 1994.

Roseworthy	D.M. (g plant ⁻¹)						
Treatment	Sample day post seeding (days)/ Zadok plant growth stage						
	23 12 _z	30 13 _z	37 13.5 _z	44 13.5/21 _z	51 21 _z	58 22 _z	107 65 _z
(i) Narrow sharp spear	0.0119 b	0.0306 a	0.054	0.103 ab	0.227 a	0.361	55.4 a
(ii) Wide sharp spear	0.0134 a	0.0296 a	0.052	0.093 b	0.219 a	0.388	39.7 b
(iii) Deep-cult+wide sharp spear	0.0128 a	0.0259 b	0.047	0.078 c	0.192 b	0.356	51.7 a
(iv) Wide blunt spear	0.0126 a	0.0305 a	0.052	0.112 a	0.233 a	0.374	57.3 a
(v) Deep cult+thin sharp closing spear	0.0134 a	0.0273 b	0.053	0.092 bc	0.215 ab	0.346	49.6 a
P =	0.028	0.006	0.645	0.001	0.024	0.528	0.003
L.S.D. (P<0.05)	0.0015	0.0028	ns	0.014	0.024	ns	8.3
Yacka	D.M. (g plant ⁻¹)						
Treatment	Sample day post seeding (days)/ Zadok plant growth stage						
	26 12 _z	33 13 _z	40 13.5 _z	48 13.5 _z	54 21 _z	61 22 _z	117 65 _z
(i) Narrow sharp spear	0.0155	0.0273	0.057 ab	0.117	0.275	0.450	88.4 c
(ii) Wide sharp spear	0.0187	0.0294	0.067 a	0.123	0.335	0.522	101.9 bc
(iii) Deep-cult+wide sharp spear	0.0173	0.0285	0.068 a	0.107	0.308	0.574	133.7 a
(iv) Wide blunt spear	0.0163	0.0280	0.052 b	0.104	0.283	0.504	104.6 bc
(v) Deep cult+thin sharp closing spear	0.0173	0.0268	0.054 b	0.102	0.306	0.507	116.6 ab
P =	0.570	0.837	0.015	0.576	0.733	0.596	0.026
L.S.D. (P<0.05)	ns	ns	0.011	ns	ns	ns	25.8

A narrow sharp spear (Treatment (i)) resulted in significantly lower in plant growth at anthesis at Yacka (Table 4.12) compared with deeper cultivation type openers (Treatments (iii) and (v)). A wide sharp spear opener (Treatment(ii)) resulted in significantly lower in plant growth at anthesis compared with all other opener types at Roseworthy.

Table 4.13 Effect of spear opener shape and deep cultivation on shoot dry matter growth (D.M.) per plot at early tillering (Zadok 22) at Roseworthy and Yacka in 1994.

Treatment	Plot D.M. (kg ha ⁻¹)	
	Roseworthy Sampled 45 days post emergence	Yacka Sampled 47 days post emergence
(i) Narrow sharp spear	482 bc	524 b
(ii) Wide sharp spear	560 a	933 a
(iii) Deep-cult+wide sharp spear	473 bc	742 a
(iv) Wide blunt spear	538 ab	473 b
(v) Deep cult+thin sharp closing spear	454 c	494 b
P =	0.020	0.001
L.S.D. (P<0.05)	69	194

4.3.7 Fertile head development and grain yield

Significant difference in fertile spike development and grain yield was found at both experiment sites (Table 4.14). There were no significant differences in grains per head or grain weight at either site. Fertile spike development, grain per head and grain yield was considerably lower at Roseworthy compared to Yacka. A wide blunt spear (Treatment (ii)) resulted in significantly increasing fertile spike development and grain yield by 12.7 % (138 kg ha⁻¹) compared with a wide sharp spear (Treatment (ii)) at Roseworthy. The wide sharp spear (Treatment (ii)) resulted in significantly lower grain yield at Roseworthy than all other openers except a narrow spear opener (Treatment (i)).

At Yacka a wide sharp spear opener (Treatment (ii)) resulted in significantly increasing grain yield by 8.2 % (159 kg ha⁻¹) compared with a wide blunt spear opener (Treatment (iv)). Wheat plots resulting from the use of a wide sharp spear with deeper cultivation (Treatment (iii)) at Yacka had significantly more fertile spikes than without deeper cultivation (Treatment (ii)), but had a 5.2 % (110 kg ha⁻¹) significantly lower grain yield. Deeper cultivation with a thin sharp closing spear (Treatment (v)) resulted in significantly increasing grain yield at Yacka compared to a wide sharp spear with deeper cultivation (Treatment(iii)).

Table 4.14 Effect of spear opener shape and deep cultivation on wheat head development and grain yield at Roseworthy and Yacka in 1994.

Treatment	Roseworthy			
	Spikes per plant	Grains per head	100 grain weight (g)	Grain yield (kg ha ⁻¹)
(i) Narrow sharp spear	1.52 ab	16.65	3.52	1157 abc
(ii) Wide sharp spear	1.32 b	17.40	3.48	1085 c
(iii) Deep-cult+wide sharp spear	1.49 ab	17.43	3.43	1193 ab
(iv) Wide blunt spear	1.63 a	18.77	3.39	1223 ab
(v) Deep cult+thin sharp closing spear	1.49 ab	17.77	3.38	1232 a
P =	0.267	0.532	0.542	0.007
L.S.D. (P<0.05)	0.28	ns	ns	80
Treatment	Yacka			
	Spikes per plant	Grains per head	100 grain weight (g)	Grain yield (kg ha ⁻¹)
(i) Narrow sharp spear	1.90 b	28.98	2.52	2032 ab
(ii) Wide sharp spear	2.07 b	28.14	2.38	2100 a
(iii) Deep-cult+wide sharp spear	2.62 a	28.53	2.53	1990 b
(iv) Wide blunt spear	1.99 b	34.09	2.50	1941 b
(v) Deep cult+thin sharp closing spear	2.32 ab	30.34	2.47	2132 a
P =	0.029	0.515	0.808	0.035
L.S.D. (P<0.05)	0.45	ns	ns	124

4.4 Discussion

Plant emergence differences resulting between the wide sharp spear opener and the wide blunt spear opener (Treatments (ii) and (iv)) reflected in higher grain yield at Yacka. Significantly greater dry matter growth from the treatment per plot resulted from using a wide sharp spear compared to a wide blunt spear (Treatments (ii) and (iv)) at Yacka also.

Differences in grain yield at Roseworthy were small. Significantly lower grain yield resulting from a wide sharp spear opener and a blunt wide spear opener (Treatments (ii) and (iv)) have been attributed to very dry conditions during the latter period of the growing season. Higher plant growth rates, resulting from a wide sharp opener (Treatment (ii)), in these conditions may be to the detriment of grain yield.

Seed row aligned cultivation, deeper than the seeding depth (Treatments (iii) and (v)), significantly reduced soil resistance to plant growth. The closing spear type seeding opener (Treatment (v)) significantly increased soil firmness compared to the deep cultivation and wide sharp seeding point (Treatment (iii)) in both soil types. A narrow sharp spear also significantly increased soil penetration resistance at the 50-60 mm depth layer at Yacka. Although not statistically different, there was a slight increase in penetration resistance resulting from a wide blunt spear opener (Treatment (iv)), but not a sharp wide spear opener (Treatment (ii)) on the poorly structured soil at Yacka at the first day of plant emergence at the 30-35 mm depth (Figure 4.5). Increased replication and possibly increased sensitivity of measurement using a smaller penetrometer cone may be better able to measure this difference. This observation although not statistically significant, encourages further study.

A general summary of resulting effects of the soil openers used in these experiments based on specific soil and plant growth criteria is shown in Table 4.15.

Table 4.15 Summary of Roseworthy and Yacka results in 1994 based on defined criteria with soil data recorded 13 days post seeding.

Treatment	Soil bulk density (Mg m ⁻³)	Penetrometer Resistance (MPa)	Total penetration energy (MJ m ⁻²)			Shear Strength (KPa m ⁻²)	Total plant emerge. (%)	Shoot dry matter (Zadok 22) (Kg ha ⁻¹)
	0-50 mm depth	40-80 mm depth	Above seed	Seed depth	Below seed	0-50 mm		
Criteria:								
High	>1.5	>3	>60	>60	>60	>1000	>70	>700
Moderate						100-1000	70-50	
Low	<1.2	<1.5	<20	<20	<20	<100	50-20	<400
Very Low							<20	
Roseworthy								
(i) Narrow sharp spear	Mod	Mod	Low	Mod	Mod	Low	High	Mod
(ii) Wide sharp spear	Mod	Mod	Low	Mod	Mod	Low	High	Mod
(iii) Deep cult+wide sharp spear	Low	Low	Low	Low	Low	Low	High	Mod
(iv) Wide blunt spear	Mod	Mod	Low	Mod	Mod	Low	High	Mod
(v) Deep cult+thin sharp closing spear	V Low	Low	Low	Low	Low	Low	High	Mod
Yacka								
(i) Narrow sharp spear	High	High	Low	High	High	Mod	Mod	Mod
(ii) Wide sharp spear	Mod	High	Low	High	High	Mod	High	High
(iii) Deep cult+wide sharp spear	Mod	Low	Low	Low	Mod	Low	Mod	High
(iv) Wide blunt spear	High	High	Mod	High	High	Mod	Mod	Mod
(v) Deep cult+thin sharp closing spear	Mod	Low	Low	Low	Mod	Low	Low	Mod

Reduction in the width of a sharp spear type opener (Treatment (i) and (ii)) resulted in significant increased soil penetrometer resistance at both sites, resulting in significant reduction of plot growth. These plant growth reductions did not significantly reduce grain yield, however. Although deeper cultivation aligned with a wide sharp spear point (Treatment (iii)) resulted in significant measurable reductions in soil penetrometer resistance, plant emergence, growth or grain yield was not improved and in some cases was significantly reduced. This could possibly be because seed-soil and

root-soil contact was reduced. The drought conditions at Roseworthy in particular would only have exacerbated this problem, resulting in significantly reduced water uptake by the plant roots.

Deeper cultivation combined with a narrow sharp closing opener (Treatment (v)) significantly improved soil firmness compared with deep cultivation combined with a wide sharp spear opener (Treatment (iii)) at both sites, but this effect did not result in improvements in plant growth and significantly reduced crop emergence at Yacka. This increased soil firmness is possibly a result of the closing opener causing some degree of soil smearing.

Reduction in width of a sharp spear type opener (Treatments (i) and (ii)) and bluntness of a wide spear opener (Treatment (iv)) resulted in significant increased soil penetrometer resistance energy at Yacka in the 32-60 mm soil depth layer immediately below the seed zone. This difference did not occur at Roseworthy. The reduction in the width of a sharp spear type seeding point and bluntness of a wide spear point resulted in significant increased soil penetrometer resistance energy, resulting in reduction in plant emergence, growth and grain yield at Yacka. There was no resulting effect of reduced spear opener width or bluntness at Roseworthy, except for the increased grain yield of the blunt spear point compared with a sharp spear point. This is possibly due to soil moisture deficit of the treatment due to low growing season rainfall indicated by low dry matter at anthesis.

4.5 Conclusions

Spear type opener width and sharpness of the leading edge had a significant resulting impact on crop establishment and early growth. Based on these experiments, wide sharp type spear openers should be used in preference to narrow blunt spear openers in these relatively dry soil and rainfall conditions. Use of sharp spear openers may significantly increase grain yield compared with blunt spear openers. Seed row aligned deeper cultivation reduced penetration resistance significantly. However, crop establishment, growth and grain yield response was more greatly influenced by shape of the following opener placing seed and fertiliser.

Further research should concentrate on the effect of the spear type seeding point shape and leading edge sharpness on soil physical properties in close proximity to the seed zone. Experiments should be carried out in contrasting wet seeding conditions to determine opener effects in the light of results published in the literature and the findings of Chapter 3. Measurement of plant root growth may increase understanding of the resulting influence of soil openers on soil physical properties.



5. SPEAR SOIL OPENER EFFECTS IN WET SOILS

5.1 Introduction

Several design parameters characterise the shape of a soil opener: width, angle of incidence to the soil, leading edge sharpness, flat underside length in contact with the soil, type of cast alloy or pressed steel used in manufacture, are some of the basic parameters. The relatively recent integration of tungsten carbide into soil opener design has decreased soil opener wear. This has led to a new problem however, that of fixing a tungsten carbide tile effectively to a soil opener to prevent removal by friction or fixed obstacles such as rocks. The manufacturing industry has found that a large flat surface positioned at right angles to the soil surface is very effective in improving tungsten carbide retention. This creates an extremely blunt cutting edge in complete contrast to a zero cutting edge height recommended by Fielke (1994). Without a tungsten carbide tip, spear soil openers used in strong soils with a high sand content, wear to a sharp leading edge but erodes from the underside of the soil opener (Rainbow and Stevens, 1995). This creates a flat base that increases the contact area of the furrow base as wear continues.

Research results presented in Chapter 4 suggest that a wider spear opener was preferable to a narrow spear opener and a sharp cutting edge was preferable to a blunt cutting edge. Seed placing soil opener shape was a more critical factor than deeper row aligned tillage in maximising crop establishment and growth.

The aim of the research reported here was to quantify the effects of different spear opener designs on soil physical properties when used in wet soil, in contrast to the dry

soil conditions described in Chapter 4. The effects of these soil physical properties on wheat crop establishment, plant root and shoot development and grain yield were measured.

The research tested the hypothesis that wide and sharp spear type soil openers provide measurable reductions in soil resistance to plant emergence and root and shoot growth compared with blunt and flat underside types.

5.2 Materials and methods

Triticum aestivum var. Janz was sown in the middle winter period on the 20th and 29th of July 1995 at two experimental sites (Yacka and Roseworthy respectively) in the Mid-North of South Australia. Both sites enjoy a mild Mediterranean climate with an average growing season rainfall of 400 mm falling mainly between April and October. Seed, treated with Vincit C[®] (flutriafol/cypermethrin fungicide/insecticide) at 1g kg⁻¹, was germination tested by International Seed Testing Association Guidelines to give 97 % normal seedlings at 8 days. Sowing density was 212 seeds m⁻². Di-ammonium phosphate fertiliser (N:P:K 18:20:0), at a rate of 75 kg ha⁻¹ was applied at seeding.

The two experiments were sown as a randomised block design, with the site at Yacka containing 6 replicates and the site at Roseworthy containing 5 replicates. Roseworthy originally contained 6 replicates, however, problems with tractor wheel-slip during the seeding operation required that Replicate 6 at the extreme end of the experiment be abandoned. Each experiment was sown in one day, nine days apart. The Yacka site soil was considered to be poorly structured in contrast to the Roseworthy soil.

Experiments were sown with seeding equipment described in Chapter 3 with seed row spacings 180 mm apart (Appendix 10.1.1 and Plate 5.1). Plots were 1.44 m wide by 30 m long. Seed was sown at a depth of 25 mm of soil cover over the seed row in all treatments.



Plate 5.1 Sowing equipment seeding at the Yacka experimental site 1995.

All treatments used a moulded urethane seed delivery tube that closely fitted to the seeder tine (Appendix 10.1.2). All the seed delivery tubes had an opening orifice of 20 mm width which was extended back for 100 mm of the seed tube length. All the seed tubes were cut up towards the rear at a 45° angle.

Treatments (i),(ii), (iii) and (iv) all used the tungsten carbide tipped commercial ARP-RRR02 spear point soil opener. Treatment (ii), (iii) and (iv) had modified leading tips (Figure 5.1). Treatment (ii) had the leading tip completely cut off at 90° angle to the horizontal. Treatment (iii) was ground flat on the underside, horizontal to the normal soil surface producing a flat underside leading edge. Treatment (iv) is a combination of the cuts of Treatments (ii) and (iii), producing both a blunt and flat underside leading edge.

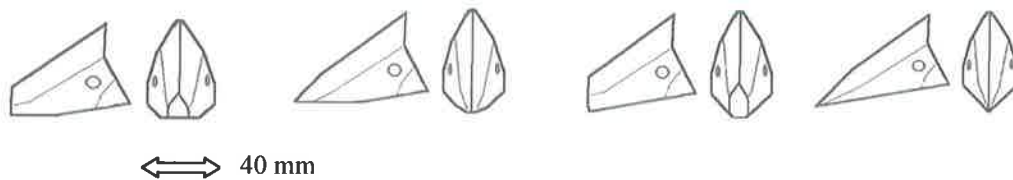


Figure 5.1 Spear soil opener treatments used in 1995 experiments. Left to right: (i) blunt flat spear, (ii) flat spear, (iii) blunt spear, (iv) sharp spear.



Plate 5.2 Spear soil opener treatments used in 1995 experiments. Left to right; (i) blunt flat spear, (ii) flat spear, (iii) blunt spear, (iv) sharp spear.

Soils from both experiment sites were analysed for nutrient status in a commercial laboratory using the materials and methods described in chapter 3.

Weeds were controlled completely by chemical means at both sites. Glyphosate (450 g L⁻¹ ai.) broad spectrum knockdown herbicide at 2.0 L ha⁻¹ was applied 30 days prior to seeding at the seasonal break. A second application of 2.0 L ha⁻¹ Glyphosate (450 g

L⁻¹ ai.) and Goal CT[®] (240 g L⁻¹ a.i. oxyfluorfen) at 75 ml ha⁻¹ in 110 L ha⁻¹ water was used 4 days prior to seeding for pre-seeding weed control. Post emergent weeds at Roseworthy were controlled at the 5 leaf wheat growth stage using a tank-mix of 7 g ha⁻¹ Eclipse[®] (714 g kg⁻¹ a.i. metosulam), 350 ml ha⁻¹ MCPA LVE (500 g L⁻¹ a.i. MCPA low volatile ester), 150 ml ha⁻¹ Lontrel[®] (300g L⁻¹ a.i. clopyralid), 1.5 L ha⁻¹ Hoegrass[®] (375 g L⁻¹ a.i. diclofop-methyl) and a non-ionic surfactant @ 1 ml L⁻¹ water at a water rate of 110 L ha⁻¹. Weeds were controlled at Yacka with a tank-mix of 35 g ha⁻¹ Logran[®] (714 g kg⁻¹ a.i. triasulfuron) selective herbicide and 2.0 L ha⁻¹ Glyphosate (450 g L⁻¹ ai.) at 36 days prior to seeding at the seasonal break. A second application of a tank-mix of 2.0 L ha⁻¹ Gyphosate and 75 ml ha⁻¹ Goal[®] were applied 15 days prior to seeding. Post emergence weeds at Yacka were controlled with at tankmix of 2.0 L ha⁻¹ Hoegrass[®], 500 ml ha⁻¹ Puma S[®] (69 g L⁻¹ a.i. fenoxaprop-p-ethyl, 39.1 g L⁻¹ a.i. fenchlorazole-ethyl) and a non-ionic surfactant @ 1 ml L⁻¹ water at a water rate of 110 L ha⁻¹ applied at the plant 5 leaf stage. Urea (60 kg ha⁻¹ applied at Roseworthy and 53 kg ha⁻¹ at Yacka, N:P:K; 46:0:0) was surface applied in a liquid water mixture @ 500 L ha⁻¹ 2 weeks post spraying at the plant tillering stage to supply plant nitrogen requirements.

All plant emergence, plant growth, soil strength and soil moisture measurements were sampled by the methods described in chapter 4. Plant root growth samples were collected using containers manufactured from 2 mm galvanised metal plate 200 mm wide x 400 mm length x 200 mm deep using some of the principles described by Srivastava *et al.* (1982). The sampling locations were laid out in a transect across the plots of both experiments. The galvanised container boxes were placed over the length of the same sown row corresponding to a specific tine on the seeder drill to

reduce seed metering and soil throw variation. Using the multi-row experimental seeder static weight of 1.6 tonnes, a large plate welded to a foot mounted centrally on the seeder (Plate 5.3) was used to gently press the galvanised containers into the soil. Plants within the cores were hand sprayed with Glyphosate (6.75 g L^{-1} a.i.) to prevent further plant growth. The containers with soil were then carefully lifted by hand and transported in a nearby trailer for extraction of the soil body. Soil layers were progressively removed by elevating the soil a known height above the galvanised container and slicing off each layer with a Teflon[®] coated saw. The depth of the first layer of soil was to just above sowing depth, approximately 0-50 mm and also 50-100 mm depths. Each layer was bagged and oven dried at $50 \text{ }^{\circ}\text{C}$ for 72 hours and stored for later root extraction using the method of Hignett (1976).



Plate 5.3 Soil core collection at the Roseworthy experiment for root mass determination.

Root separation from the soil was achieved using a set of 3 cylindrical root washers (Cahoon and Morton, 1961). Each sample was split in 3 and washed for 20 to 30 minutes until roots stopped floating to the surface. Soil in the root washer was

checked for trapped roots before disposal. Plant roots forced to the top of the whirlpool were caught in a 350 µm wire sieve. The soil was then transferred to a plastic cylinder to extract macro organic matter using the method described by Barley (1955). Wet root samples were oven dried in aluminium trays at 70 °C for 48 hours then stored in an airtight container. Wheat roots were sorted from the other organic matter by hand and weighed. Separating plant roots from fragments of organic matter and soil proved to be very difficult. This affected the accuracy of the data. It became clear that the technique used was flawed and a different method needed to be developed but the experiment was too far advanced to do this at this point.

All data was analysed with Statistix[®] Version 4.1 Analytical Software (Anon, 1994). Plots of residual error were used to check for outlying data. Significant outlying data was entered as missing values in these cases and experiments were re-analysed.

5.3 Results

5.3.1 Field establishment conditions

The soil nutrient status at the Yacka site was considerably higher than the Roseworthy site (Table 5.1). Extractable P at Roseworthy was low but adequate at Yacka. Extractable K and NO₃-N was considered adequate at both sites. Roseworthy and Yacka contained a moderate level of organic carbon (O.C.). Both Yacka and Roseworthy soils were calcareous and low in salinity. Soil pH varied as Yacka was slightly alkaline and Roseworthy tending moderately alkaline. The sites differed in physical status as the Yacka site contained slightly more silt and clay particles and a higher soil strength at 20 mm than the Roseworthy site (Table 5.2). Of note are high soil water contents and very low soil suction at seeding at both sites (Table 5.3).

Roseworthy was sown at soil water content greater than the plastic limit and Yacka was sown at water content slightly below the soil plastic limit. Soil temperatures at seeding were considered cold at seeding. Emerson soil dispersion tests indicated soils would disperse if cultivated at a water content greater than field capacity. Rainfall patterns during the experiments were similar at both sites (Table 5.4).

There was soil cone development on the leading edge of the blunt and blunt flat spear openers (Treatments (i) and (iii)) as described in the literature by Payne (1956), and Willatt and Willis (1965). This appears as a small cone of soil building up on the blunt tip of the soil opener which forms the primary contact with new soil, rather than the metal edge of the soil opener.

Table 5.1 Soil chemical composition at the Roseworthy and Yacka experimental sites (0-100 mm depth) in 1995.

Experimental site	Extrac. P (mg kg ⁻¹)	Extrac. K (mg kg ⁻¹)	NO ₃ -N (mg kg ⁻¹)	OC (%)	E.C. 1:5 _w extract (dS m ⁻¹)	CaCO ₃ (%)	pH (H ₂ O)
Roseworthy	24	410	13	1.0	0.13	4	8.3
Yacka	44	600	20	1.1	0.12	3	7.5

Table 5.2 Soil physical properties at the Roseworthy and Yacka experimental sites (0-100 mm depth) in 1995.

Experimental site	Particle size distribution (%)			Emerson dispersion class	Soil class	Bulk density (Mg m ⁻³)		Soil shear strength ¹ (kPa m ⁻²) recorded at seeding		
	Sand	Silt	Clay			0-50 mm	50-100 mm	20 mm	50 mm	80 mm
Roseworthy	66	17	17	3	Sandy loam	1.45	1.52	579	876	1099
Yacka	62	18	20	3	Sandy clay loam	1.49	1.63	630	827	913

¹ Soil shear strength recorded at water content in Table 5.3.

Table 5.3 Matric suction, water content and temperature at seeding at the Roseworthy and Yacka experimental sites in 1995.

Experimental site	Matric suction ψ_m (MPa)			Soil water content θ ($m_w m_s^{-1}$)			Soil temperature. (°C at 9 am 100 mm)
	0-30 mm	30-60 mm	60-120 mm	0-50 mm	50-100 mm	Plastic limit 0-50 mm	
Roseworthy	0.020	0.05	0.05	0.285	0.271	0.250	9.3
Yacka	0.10	0.15	0.06	0.275	0.289	0.300	10.5

Table 5.4 Cumulative growing season rainfall (mm) at key intervals from seeding at the Roseworthy and Yacka experimental sites in 1995.

Experimental site	Days post seeding								
	13	26	31	33	40	48	55	61	90
Roseworthy	15.1	15.5	19.7	20.7	32.9	39.5	39.5	44.7	94.3
Yacka	Days post seeding								
	15	28	34	41	48	50	55	62	98
Yacka	28.2	28.8	28.8	33.2	41.8	41.8	41.8	46.8	106.8

5.3.2 Soil penetrometer resistance

Penetrometer resistance as a function of depth (Figures 5.2, 5.3, 5.4 and 5.5) highlight the effects of changes in water content on penetration resistance. There were no significant resulting differences in penetration resistance between openers 13 days post seeding at Roseworthy and 15 days post seeding at Yacka (Figures 5.2 and 5.4). Soil water contents at this time were high. However, a blunt flat spear and flat spear (Treatments (i) and (ii)) created a seed-bed resulting in significantly higher penetration energy at 10-30 mm than resulting from a blunt spear (Treatment (iii)) at Roseworthy 13 days post seeding at crop emergence (Table 5.5).

The seed-bed resulting from a flat spear opener (Treatment (ii)) had significantly higher penetration resistance at 30-40 mm depth compared with the resulting effects of all other openers 31 days post seeding at Roseworthy (Figure 5.3). A blunt flat spear opener (Treatment (i)) resulted in significantly lower penetration resistance than all other openers at 60-90 mm depth at Roseworthy also 31 days post seeding. A flat spear opener (Treatment (ii)) resulted in a significantly higher requirement in penetration energy compared to the resulting effects of a blunt spear opener (Treatment (iii)) 31 days post seeding at Roseworthy. Resulting penetration energy differences between the soils treated with different openers were not significant at Roseworthy at deeper soil depths.

Treatments sown with a sharp spear (Treatment (iv)) at Yacka resulted in significantly lower penetration resistance 28 days post sowing compared with all other openers at 5-40 mm depth (Figure 5.4). Soil treated with this sharp spear opener (Treatment (iv)) also resulted in significantly less penetration energy at 10-30 mm compared to the resulting effects of all other openers 28 days post seeding at Yacka (Table 5.5). Soil treated with a blunt flat spear opener (Treatment (i)) resulted in significantly higher penetration energy at 10-30 mm compared with the resulting effects of all other openers at Yacka 15 days post seeding at crop emergence (Table 5.5). Resulting soil penetration energy was significantly lower for a blunt spear (Treatment (iii)) compared to the resulting effects of a blunt flat spear and sharp spear opener (Treatments (i) and (iv)) at 32-60 mm soil depth at Yacka 15 days post seeding.

Table 5.5 Effects of spear opener shape on total penetration energy.

Roseworthy		Total penetration energy (MJ m ⁻²)					
		Sampled 13 days post seeding Sample depth (mm)			Sampled 31 days post seeding Sample depth (mm)		
Treatment		10-30	32-60	62-90	10-30	32-60	62-90
(i) Blunt flat spear		16.2 a	44.1	61.7	37.7 ab	76.0	93.5
(ii) Flat spear		14.5 a	49.2	65.0	48.6 a	90.5	91.8
(iii) Blunt spear		10.8 b	49.6	58.7	27.1 b	71.4	91.9
(iv) Sharp spear		14.2 ab	44.9	60.8	38.1 ab	82.3	81.8
P =		0.050	0.922	0.737	0.047	0.549	0.368
L.S.D. (P<0.05)		3.6	ns	ns	14.2	ns	ns
Yacka		Total penetration energy (MJ m ⁻²)					
		Sampled 15 days post seeding Sample depth (mm)			Sampled 28 days post seeding Sample depth (mm)		
Treatment		10-30	32-60	62-90	10-30	32-60	62-90
(i) Blunt flat spear		13.0 a	35.8 ab	42.3	37.5 a	73.3	65.7
(ii) Flat spear		9.6 b	32.4 bc	37.2	43.1 a	72.9	57.6
(iii) Blunt spear		8.6 b	29.9 c	38.7	33.8 a	65.8	61.8
(iv) Sharp spear		9.5 b	38.3 a	42.0	14.9 b	62.3	65.8
P =		0.037	0.008	0.353	0.000	0.309	0.223
L.S.D. (P<0.05)		3.0	4.5	ns	10.6	ns	ns

Effect of soil water content on undisturbed soil penetration resistance is shown in Appendices A10.2.1 and A10.2.2.

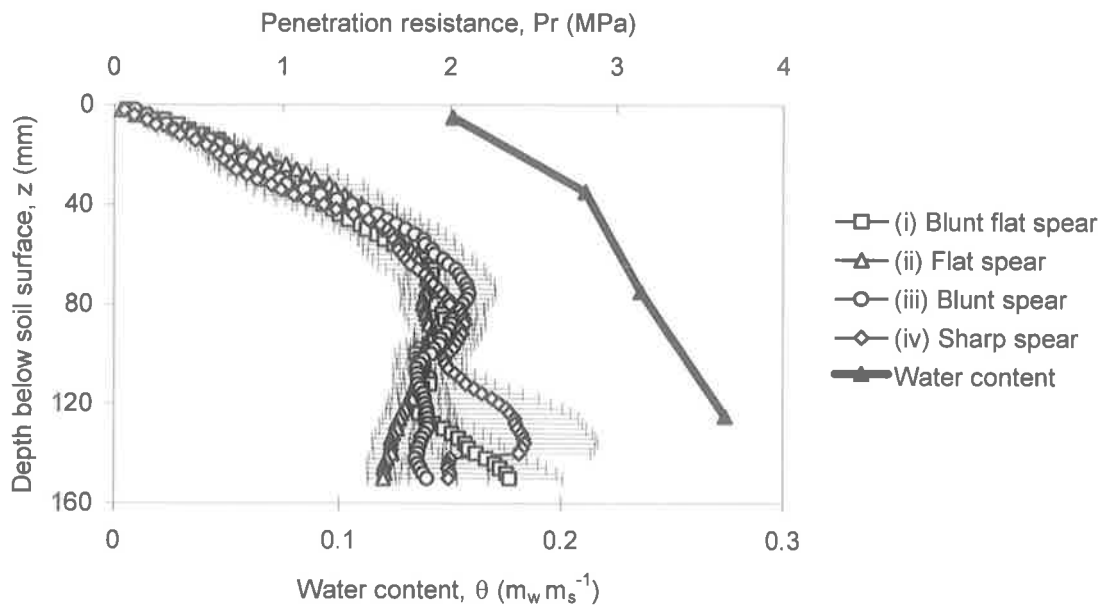


Figure 5.2 Spear opener effect on penetrometer resistance 13 days post sowing at Roseworthy and standard error of mean.

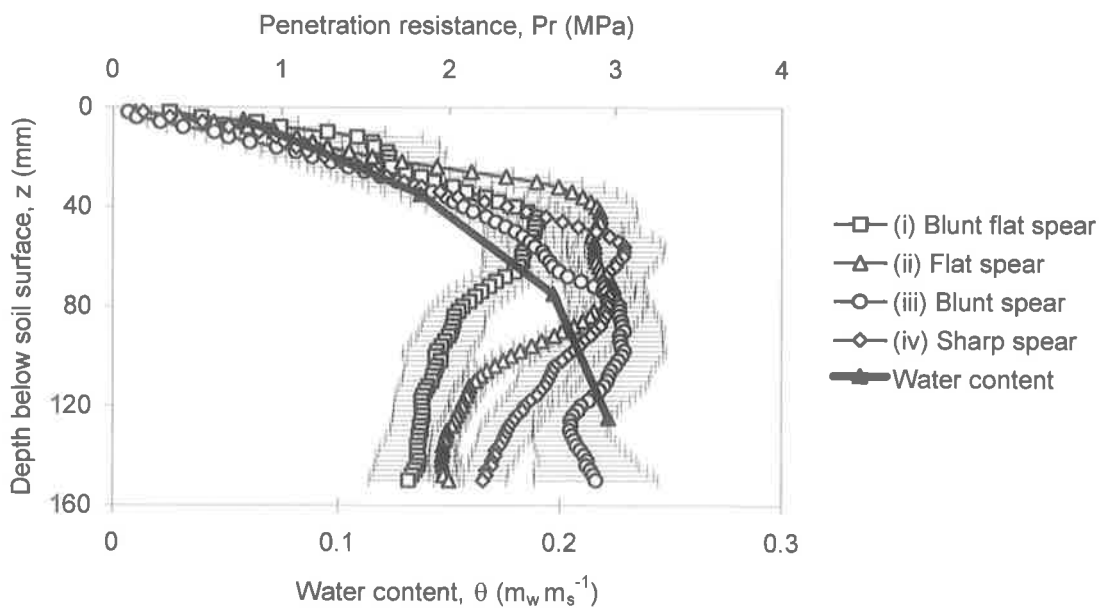


Figure 5.3 Spear opener effect on penetrometer resistance 31 days post sowing at Roseworthy and standard error of mean.

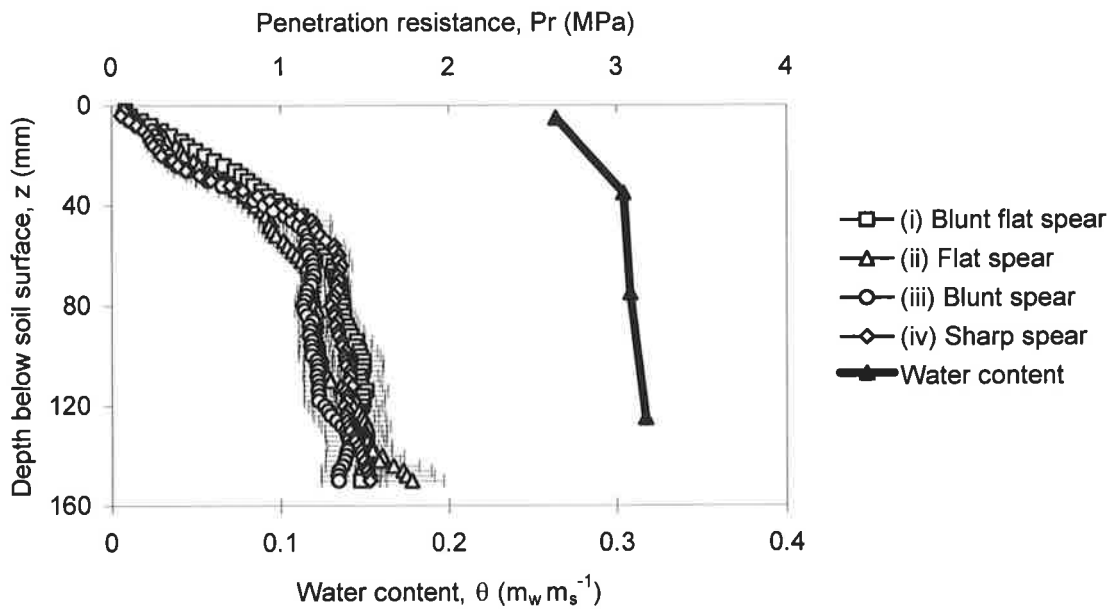


Figure 5.4 Spear opener effect on penetrometer resistance 15 days post sowing at Yacka and standard error of mean.

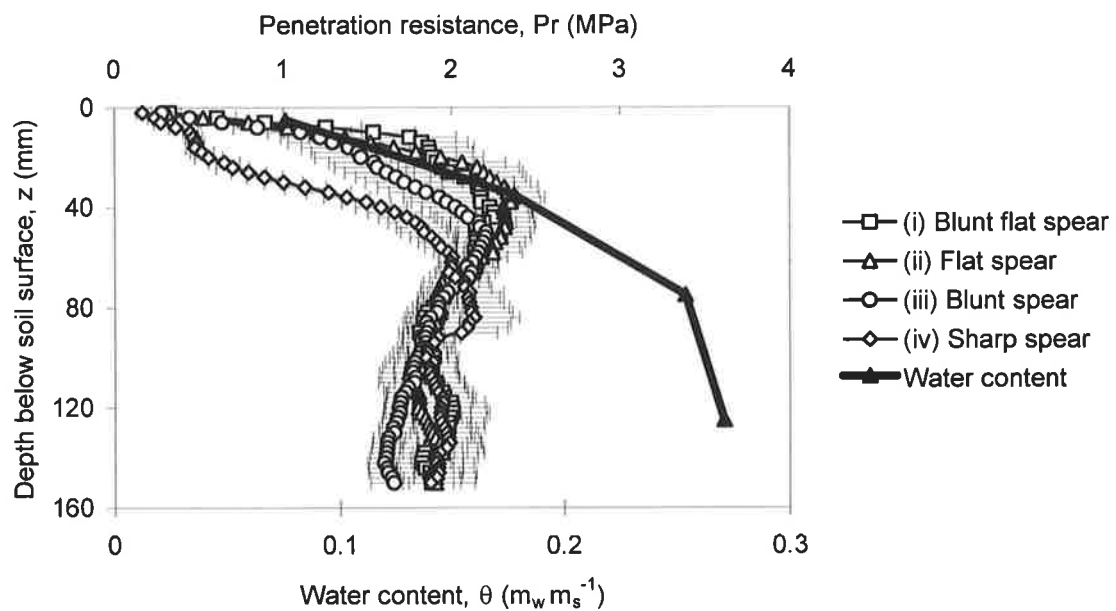


Figure 5.5 Spear opener effect on penetrometer resistance 28 days post sowing at Yacka and standard error of mean.

5.3.3 Soil shear vane resistance

A blunt flat spear (Treatment (i)) resulted in significantly increased soil torsional shear vane resistance at crop emergence at Yacka compared with resulting effects of a flat or blunt spear (Treatments (ii) and (iii)) (Table 5.6). A sharp spear resulted in significantly less shear vane resistance compared with all other opener types at 0-50 mm soil depth 28 days post seeding at Yacka. There were no significant torsional shear vane differences at Yacka at 50-100 mm soil depth and also Roseworthy at either depth.

Table 5.6 Effects of spear point shape on soil torsional shear vane resistance at Roseworthy and Yacka in 1995.

Roseworthy		Soil torsional shear vane resistance (kPa m ⁻²)			
		Sampled 13 days post seeding Sample depth (mm)		Sampled 31 days post seeding Sample depth (mm)	
Treatment		0-50	50-100	0-50	50-100
(i) Blunt flat spear		56.6	137.2	128.3	219.5
(ii) Flat spear		54.5	137.0	146.6	221.4
(iii) Blunt spear		58.3	143.5	136.0	236.9
(iv) Sharp spear		55.1	139.8	133.2	228.7
	P =	0.914	0.743	0.500	0.139
	L.S.D. (P<0.05)	ns	ns	ns	ns
Yacka		Soil torsional shear vane resistance (kPa m ⁻²)			
		Sampled 15 days post seeding Sample depth (mm)		Sampled 28 days post seeding Sample depth (mm)	
Treatment		0-50	50-100	0-50	50-100
(i) Blunt flat spear		87.9 a	117.0	130.7 a	184.8
(ii) Flat spear		72.4 b	114.3	130.4 a	185.0
(iii) Blunt spear		76.5 b	112.7	123.3 a	191.4
(iv) Sharp spear		79.2 ab	118.5	95.8 b	189.2
	P =	0.014	0.670	0.006	0.869
	L.S.D. (P<0.05)	11.0	ns	20.1	ns

5.3.4 Soil bulk density

At crop emergence soil treated with the flat spear opener (Treatment (ii)) was found to have significantly higher soil bulk density at Roseworthy in the 0-50 mm soil depth

interval compared with all other opener types (Table 5.7). Soil seeded with a sharp spear (Treatment (iv)) had significantly lower bulk density than soil seeded with a flat or blunt spear (Treatments (ii) and (iii)) at Roseworthy in 100-150 mm soil depth 31 days post seeding. A sharp spear (Treatment (iv)) at Yacka also significantly reduced soil bulk density compared with a flat or blunt flat spear opener (Treatments (i) and (ii)) at both 0-50 mm and 50-100 mm soil depths.

Table 5.7 Effects of spear opener shape on soil bulk density at Roseworthy and Yacka in 1995.

Roseworthy		Soil bulk density (Mg m ⁻³)					
		Sampled 13 days post seeding Sample depth (mm)			Sampled 31 days post seeding Sample depth (mm)		
Treatment		0-50	50-100	100-150	0-50	50-100	100-150
(i) Blunt flat spear		1.314 b	1.517	1.589	1.373	1.513	1.577 ab
(ii) Flat spear		1.423 a	1.498	1.577	1.426	1.612	1.616 a
(iii) Blunt spear		1.332 b	1.541	1.587	1.300	1.581	1.614 a
(iv) Sharp spear		1.320 b	1.526	1.567	1.372	1.581	1.549 b
P =		0.007	0.940	0.885	0.734	0.475	0.036
L.S.D. (P<0.05)		0.059	ns	ns	ns	ns	0.050
Yacka		Soil bulk density (Mg m ⁻³)					
		Sampled 15 days post seeding Sample depth (mm)			Sampled 28 days post seeding Sample depth (mm)		
Treatment		0-50	50-100	100-150	0-50	50-100	100-150
(i) Blunt flat spear		1.526	1.588	1.595	1.461 ab	1.606 a	1.602
(ii) Flat spear		1.530	1.606	1.598	1.464 a	1.616 a	1.580
(iii) Blunt spear		1.438	1.599	1.593	1.330 bc	1.569 ab	1.570
(iv) Sharp spear		1.466	1.588	1.581	1.296 c	1.525 b	1.579
P =		0.232	0.895	0.965	0.028	0.039	0.393
L.S.D. (P<0.05)		ns	ns	ns	0.132	0.066	ns

5.3.5 Soil water content

There was no significant resulting effects of opener type on soil water content at either site, except at Yacka 28 days post seeding where soil sown with a blunt spear (Treatment (iii)) resulted in being significantly drier than soil sown with a sharp spear opener (Treatment (iv)), at 50-100 mm (Tables 5.8 and 5.9). A flat spear opener (Treatment (ii)) resulted in significantly higher soil water content compared with both

blunt and sharp spear openers (Treatments (iii) and (iv)) at Yacka also 28 days post seeding at 0-10 mm.

Table 5.8 Effects of spear opener shape on soil water content at Roseworthy 13 and 31 days after sowing in 1995.

Sampled 13 days post seeding	Soil water content θ ($m_w m_s^{-1}$)			
	Sample depth (mm)			
Treatment	0-10*	0-50	50-100	100-150
(i) Blunt flat spear	0.147	0.207	0.236	0.267
(ii) Flat spear	0.150	0.207	0.236	0.269
(iii) Blunt spear	0.152	0.218	0.240	0.275
(iv) Sharp spear	0.153	0.212	0.230	0.286
P =	0.973	0.684	0.891	0.522
L.S.D. (P<0.05)	ns	ns	ns	ns
Sampled 31 days post seeding	Soil water content θ ($m_w m_s^{-1}$)			
Treatment	Sample depth (mm)			
	0-10*	0-50	50-100	100-150
(i) Blunt flat spear	0.061	0.135	0.197	0.228
(ii) Flat spear	0.057	0.146	0.196	0.220
(iii) Blunt spear	0.058	0.135	0.197	0.215
(iv) Sharp spear	0.055	0.132	0.197	0.226
P =	0.544	0.877	0.999	0.851
L.S.D. (P<0.05)	ns	ns	ns	ns

* Calculated water content based on % water by mass and 0-50mm bulk density recordings

Table 5.9 Effects of spear opener shape on soil water content at Yacka 15 and 28 days after sowing in 1995.

Sampled 15 days post seeding	Soil water content θ ($m_w m_s^{-1}$)			
	sample depth (mm)			
Treatment	0-10*	0-50	50-100	100-150
(i) Blunt flat spear	0.272	0.308	0.317	0.307
(ii) Flat spear	0.279	0.307	0.301	0.310
(iii) Blunt spear	0.254	0.293	0.308	0.324
(iv) Sharp spear	0.252	0.307	0.304	0.326
P =	0.133	0.504	0.496	0.397
L.S.D. (P<0.05)	ns	ns	ns	ns
Sampled 28 days post seeding	soil water content θ ($m_w m_s^{-1}$)			
Treatment	sample depth (mm)			
	0-10*	0-50	50-100	100-150
(i) Blunt flat spear	0.077 ab	0.180	0.251 ab	0.276
(ii) Flat spear	0.092 a	0.181	0.257 ab	0.267
(iii) Blunt spear	0.065 b	0.185	0.244 b	0.267
(iv) Sharp spear	0.070 b	0.166	0.264 a	0.276
P =	0.023	0.822	0.061	0.692
L.S.D. (P<0.05)	0.017	ns	0.015	ns

* Calculated water content based on % water by mass and 0-50mm bulk density recordings

Soil water content was considerably higher at Yacka at both sampling intervals in contrast to Roseworthy. Yacka rainfall from seeding to emergence was 87 % higher than Roseworthy.

5.3.6 Rate of plant emergence and total emergence

Plant emergence was much lower at Roseworthy in contrast to the Yacka site (Table 5.10). A sharp spear opener (Treatment (iv)) resulted in significantly higher emergence compared to all other openers at both sites except a blunt spear opener (Treatment (iii)) at Roseworthy which was lower in plant emergence, but not significantly. All other openers (Treatments (i), (ii) and (iii)) did not result in significant differences in plant emergence at either site. A blunt and sharp spear opener (Treatments (iii) and (iv)) resulted in significantly greater mean emergence days than other openers at both sites.

Table 5.10 Effects of spear opener shape on total wheat plant emergence and mean emergence day (M.E.D.).

Treatment	Roseworthy		Yacka	
	% Total plant emergence	M.E.D. (days)	% Total plant emergence	M.E.D. (days)
(i) Blunt flat spear	42.02 b	13.56 b	86.73 b	12.51 b
(ii) Flat spear	39.11 b	13.66 b	87.26 b	12.70 b
(iii) Blunt spear	48.43 ab	14.34 a	87.79 b	13.22 a
(iv) Sharp spear	62.51 a	14.19 a	91.43 a	13.39 a
P =	0.047	0.011	0.022	0.000
L.S.D. (P<0.05)	16.98	0.49	4.27	0.32

5.3.7 Plant root growth

The difficulty in separating plant roots from fragments of organic matter and soil reduced the reliability of the root growth data collected. There is no reason to suspect

that the soil opener treatments had a differential influence on the latent condition of the organic matter and plant roots collected from the plot.

With this proviso, the sharp spear opener resulted in significantly lower plant root growth compared to the blunt flat and flat spear opener (Treatments (i) and (ii)) at 0-50 mm and 50-100 mm (Table 5.11) at Roseworthy. There were no significant root growth differences at Yacka (Table 5.11).

Table 5.11 Spear opener shape effect on plant root growth 10 days post emergence.

Treatment	Root dry matter (mg plant ⁻¹).					
	Roseworthy			Yacka		
	Depth below seed (mm)			Depth below seed (mm)		
	0-50	50-100	Total 0-100	0-50	50-100	Total 0-100
(i) Blunt flat spear	10.90 ab	3.62 a	14.52 ab	9.88	2.58	12.46
(ii) Flat spear	12.85 a	4.01 a	16.16 a	9.19	3.04	12.23
(iii) Blunt spear	6.11 bc	2.33 ab	8.44 bc	8.55	2.31	10.85
(iv) Sharp spear	4.29 c	1.56 b	5.85 c	7.78	2.46	10.24
P =	0.016	0.049	0.014	0.670	0.680	0.720
L.S.D. (P<0.05)	5.41	1.88	6.42	ns	ns	ns

5.3.8 Plant shoot growth to early tillering and anthesis

A sharp spear opener (Treatment (iv)) resulted in significantly higher plant growth despite resulting in the lowest root dry matter than all other openers 40 days post seeding at the Roseworthy site (Table 5.12). However, by 48 days this advantage had disappeared except that the blunt flat spear opener (Treatment (i)) had still resulted in significantly less growth (Table 5.12). At 55 days post seeding (tillering) all differences had disappeared. A sharp spear opener (Treatment (iv)) produced significantly higher plot growth at tillering (Zadok 22) than a blunt flat spear

(Treatment (i)) at Roseworthy (Table 5.13). A flat spear opener (Treatment (ii)) resulted in significantly higher plant growth at anthesis (Zadok 65) at Roseworthy compared to all other openers (Table 5.12).

The Yacka experiment, in contrast to Roseworthy, showed small differences in the growth of wheat. The only difference was higher dry matter at the early growth stage in the plots sown with a blunt spear opener.

Plants taken from a sharp spear opener plot (Treatment (iv)) at Yacka were significantly lower in early shoot growth per plant of 28 days post seeding compared plants from a blunt flat spear plot (Treatment (i)). Also at tillering (Zadok 21 and 22) plants from a sharp spear opener plot at Yacka (Treatment (iv)) were significantly lower in individual plant growth and total plot growth compared to plants of blunt flat and flat spear opener plots (Treatments (i) and (ii)) (Tables 5.12 and Table 5.13). There were no significant plant growth differences at anthesis (Zadok 65) at Yacka (Table 5.12). Plate 5.4 shows the effect on plot growth of a blunt flat spear opener (Treatment (i)) compared to a sharp spear opener (Treatment(iv)). Plate 5.5 shows the effect a blunt flat spear opener (Treatment (i)) has on soil smear in the seed groove.

Relationships between emergence, plant growth and penetration energy were fitted using Datafit™ version 2.0 data modelling software (Anon, 1993). None of these correlations showed significant correlation (i.e. $R^2 < 0.36$). These data are therefore not presented here.

Table 5.12 Effects of spear opener shape on shoot dry matter (D.M.) per plant at Roseworthy and Yacka in 1995.

Roseworthy		D.M. (g plant ⁻¹)						
Treatment		Sample day post seeding (days)/ Zadok plant growth stage						
		26 12 _z	33 13 _z	40 14.5	48 16 _z	55 21 _z	61 22 _z	90 65 _z
(i) Blunt flat spear		0.0171	0.0343	0.070 b	0.149 b	0.255	0.378	65.4 b
(ii) Flat spear		0.0193	0.0372	0.071 b	0.188 a	0.250	0.367	91.8 a
(iii) Blunt spear		0.0198	0.0391	0.071 b	0.173 ab	0.237	0.440	75.5 b
(iv) Sharp spear		0.0219	0.0437	0.086 a	0.184 a	0.248	0.359	73.3 b
P =		0.293	0.300	0.034	0.034	0.950	0.283	0.019
L.S.D. (P<0.05)		ns	ns	0.012	0.026	ns	ns	15.3
Yacka		D.M. (g plant ⁻¹)						
Treatment		Sample day post seeding (days)/ Zadok plant growth stage						
		28 12.5	34 13.5	41 15 _z	48 16 _z	55 21 _z	62 22 _z	98 65 _z
(i) Blunt flat spear		0.0272 a	0.0803	0.150	0.249	0.376 a	0.578 a	85.3
(ii) Flat spear		0.0244 b	0.0782	0.147	0.255	0.329 b	0.553 a	83.2
(iii) Blunt spear		0.0238 b	0.0801	0.134	0.246	0.321 bc	0.468 b	84.6
(iv) Sharp spear		0.0238 b	0.0799	0.145	0.260	0.296 c	0.467 b	85.2
P =		0.004	0.966	0.364	0.916	0.000	0.025	0.992
L.S.D. (P<0.05)		0.0018	ns	ns	ns	0.031	0.084	ns

Table 5.13 Effects of spear opener shape on shoot dry matter (D.M.) growth per plot at early tillering (Zadok 21) at Roseworthy and Yacka in 1995.

Treatment	Plot D.M. (kg ha ⁻¹)	
	Roseworthy	Yacka
	Sampled 55 days post emergence	Sampled 55 days post emergence
(i) Blunt flat spear	308 b	1062 a
(ii) Flat spear	426 a	1074 a
(iii) Blunt spear	373 ab	899 b
(iv) Sharp spear	451 a	908 b
P =	0.043	0.031
L.S.D. (P<0.05)	99	145



Plate 5.4 Plots at the Roseworthy experiment site. Left, blunt flat spear opener (Treatment (i)); Right, sharp spear opener (Treatment(iv)).



Plate 5.5 Seed bed groove smear of a blunt flat soil opener (Treatment (i)) at the Roseworthy experimental site.

5.3.9 Fertile head development and grain yield

Resulting spear soil opener effects on grain yield factors are shown in Table 5.14. There were no significant differences in fertile spikes per plant, grains per head or 100 grain weight at either the Roseworthy or Yacka site.

A sharp spear resulted in significantly increased grain yield compared to all other opener types at Roseworthy by 8.5% (193 kg ha⁻¹), 12% (260 kg ha⁻¹) and 20% (404 kg ha⁻¹) for a blunt, blunt flat and flat spear opener respectively (Treatments (iii), (i), and (ii)).

Table 5.14 Effects of spear opener shape on wheat head development and grain yield at Roseworthy and Yacka in 1995.

Treatment	Roseworthy			
	Spikes per plant	Grains per head	100 Grain weight (g)	Grain yield (kg ha ⁻¹)
(i) Blunt flat spear	1.91	28.64	3.22	2196 bc
(ii) Flat spear	2.17	27.93	3.32	2052 c
(iii) Blunt spear	1.86	27.39	3.17	2263 b
(iv) Sharp spear	1.88	27.65	3.30	2456 a
P =	0.210	0.790	0.205	0.003
L.S.D. (P<0.05)	ns	ns	ns	177
Treatment	Yacka			
	Spikes per plant	Grains per head	100 Grain weight (g)	Grain yield (kg ha ⁻¹)
(i) Blunt flat spear	2.01	30.67	2.77	3979
(ii) Flat spear	1.91	30.51	2.75	3856
(iii) Blunt spear	1.87	33.07	2.86	3926
(iv) Sharp spear	1.81	31.87	2.93	3898
P =	0.700	0.237	0.242	0.679
L.S.D. (P<0.05)	ns	ns	ns	ns

Linear regression analysis of opener effects on plant emergence and grain yield at Roseworthy resulted in a significant correlation of $R^2 = 0.65$. This compares with soil opener effects on total individual plant and plot dry matter at tillering having no

correlation with grain yield of $R^2 = 0.08$ and $R^2 = 0.11$ respectively. There were no significant grain yield differences at Yacka and no correlation with plant emergence.

5.4 Triaxial compression tests

Triaxial compression tests were performed on un-worked soil of the Roseworthy and Yacka 1994 sites with dry soil. The tests were conducted by the methods described in Appendix A10.3 and results detailed in Appendix A10.3.1 and A10.3.2.

Table 5.15 Triaxial compression test results of soil cores of Roseworthy and Yacka experiment sites 1994.

Cell pressure $\sigma_2 = \sigma_3$ (kPa)	Roseworthy			Yacka		
	Water content θ ($m_w m_s^{-1}$)	Deviator stress $\sigma_1 = \sigma_3$ (kPa)	Strain at max deviator stress (%)	Water content θ ($m_w m_s^{-1}$)	Deviator stress $\sigma_1 = \sigma_3$ (kPa)	Strain at max deviator stress (%)
Dry soil						
100	0.21	180	11.2	0.18	227	8.0
200		339	13.5		492	11.2
400		550	16.2		658	14.1
Moist soil						
100	0.37	89	6.3	0.29	121	6.1
200		150	12.3		222	14.1
400		253	12.4		287	13.2
Wet soil						
100	0.49	48	9.3	0.43	60	4.8
200		76	15.3		44	13.4
400		88	18.6		65	7.8

Triaxial compression results (Table 5.15) show that the deviator stress $\sigma_1 = \sigma_3$ of the Roseworthy soil is much lower than Yacka when soil is dry with a relatively similar % deviator stress. In wet soil, however, the Yacka soil has a much lower deviator stress $\sigma_1 = \sigma_3$ than the Roseworthy soil with a correspondingly lower maximum % deviator stress. This data was used to calculate the soil cohesion (C) and angle of internal friction (ϕ) using Mohr's circles. (Table 5.16). This data indicates an increased angle of internal

friction of wet Roseworthy soil with a lower cohesion compared to the wet Yacka soil. This would indicate that the wet Roseworthy soil must compress more than the wet Yacka soil before soil failure will occur. This may explain the tendency of the Roseworthy soil to smear when wet. This is also supported by the higher angle of internal friction and lower cohesion of the wet Roseworthy soil compared to the wet Yacka soil. Contrasting this the dry Yacka soil had a higher angle of internal friction and cohesion compared to a dry Roseworthy soil. This may explain the tendency of the Yacka soil to smear when dry.

Table 5.16 Cohesion (C) and angle of internal friction (ϕ) from triaxial compression tests of undrained soils of Roseworthy and Yacka 1994 sites from determination by Mohr's circles.

	Roseworthy			Yacka		
	Water content θ ($m_w m_s^{-1}$)	C (kPa)	ϕ	Water content θ ($m_w m_s^{-1}$)	C (kPa)	ϕ
Dry soil	0.21	32	20°	0.18	36	23°
Moist soil	0.37	16	13°	0.29	24	13°
Wet soil	0.49	12	4.5°	0.43	22	3.5°

5.5 Discussion

Research results of different shaped spear soil openers would suggest that a critical factor in maximising grain yield is achieving optimum establishment. This is strongly supported by significant correlation of plant emergence to grain yield. Total plant numbers had a significant impact on total crop biomass as indicated in the Roseworthy results at tillering. Fertile spike and grain head development factors were not significantly correlated with increased grain yield at Roseworthy.

Resulting grain yield differences demonstrated between sharp spear (Treatment (i)) and the other blunt and flat openers, suggests that improved opener design through

optimum crop establishment can have significant productivity and economic benefits for the farming industry.

A general summary of resulting effects of the soil openers used in these experiments based on specific soil and plant growth criteria is shown in Table 5.17.

Table 5.17 Summary of Roseworthy and Yacka results in 1995 based on defined criteria with soil data recorded 31 and 28 days post seeding respectively.

Treatment	Soil bulk density (Mg m ⁻³)	Penetrometer resistance (MPa)	Total penetration energy (MJ m ⁻²)			Shear strength (KPa m ⁻²)	Total plant emerge (%)	Shoot dry matter (Zadok 22) (Kg ha ⁻¹)
			Above seed	Seed depth	Below seed			
	0-50 mm depth	40-80 mm depth				0-50 mm		
Criteria:								
High	>1.5	>3	>60	>60	>60	>1000	>70	>700
Moderate						100-1000	70-50	
Low	<1.2	<1.5	<20	<20	<20	<100	50-20	<400
Very Low							<20	
Roseworthy								
(i) Blunt flat spear	Mod	Mod	Mod	High	High	ns	Low	Low
(ii) Flat spear	Mod	Mod	Mod	High	High	ns	Low	Mod
(iii) Blunt spear	Mod	Mod	Mod	High	High	ns	Low	Low
(iv) Sharp spear	Mod	Mod	Mod	High	High	ns	Mod	Mod
Yacka								
(i) Blunt flat spear	High	Mod	Low	High	High	Mod	High	High
(ii) Flat spear	High	Mod	Low	High	Mod	Mod	High	High
(iii) Blunt spear	Mod	Mod	Low	Mod	High	Mod	High	High
(iv) Sharp spear	Mod	Mod	Low	Mod	High	Low	High	High

Most of the penetration resistance differences found were in the 10-40 mm soil depth layer which suggests that a soil opener has greatest impact on changes in soil physical properties in a relatively shallow layer of soil. The soil structure in this soil layer is clearly significantly altered as shown by soil strength and water retention. Torsional shear vane resistance appears to give a similar gross result as using a series of penetration resistance values with depth and calculating penetration energy, but contributes little to understanding where small changes in soil strength occur.

Although soil water content had a significant impact on soil strength measurements, there was virtually no impact of soil opener type on soil water content in the furrow. However, none of the data collected in Chapters 4 and 5 reveal the changes soil openers have made to soil physical properties laterally across the seed furrow. Clearly soil water retention has a significant impact on furrow soil strength. The amount of tillage surrounding the furrow and aggregate size can impact on soil water content in the furrow floor where seed is placed. Therefore measurement of soil strength, water content and bulk density in areas immediately surrounding the seed furrow may improve understanding of observations.

In trying to measure a greater proportion of plant roots growing at different layers in the soil, the principle of extracting large cores of soil with multiple plants was considered a good methodology. However, the bulk of soil processed in measurement of plant root growth clearly created additional difficulty in separation of fresh roots from the massive amount of residual organic matter in the soil. If plant samples had been separated and soil washed off the intact roots, rather than dividing soil samples by cutting, drying and then washing, plants could easily have been separated from organic matter using staining techniques to improve selection precision. Clearly, improved accuracy could be achieved through sampling of an entire intact root system.

The results of research outlined in this chapter have demonstrated that a wide sharp soil opener can reduce soil resistance to plant emergence compared with blunt and flat underside types. There was a significant correlation of higher total plant establishment with higher grain yield at the Roseworthy site. There was, however,

poor correlation between soil physical properties associated with different soil openers and plant establishment.

5.6 Conclusions

Soil opener shape factors such as a flat underside and a blunt leading edge can increase penetration resistance and energy required through increased soil bulk density, leading to a reduction in total plant emergence. These changes in soil opener shape can lead to a significant reduction in plant emergence which at Roseworthy significantly correlated with reduced grain yield. The resulting effects of soil physical properties on plant root growth is unclear and requires an improved sample collection method to enable collection of entire plant root systems.

Further research should concentrate on resulting soil physical property effects of soil opener shape on plant establishment in contrasting wet and dry soils. Collecting data to represent data across the soil profile may give greater understanding to soil opener effects on soil physical properties not only below, but across the seed furrow.

6. SPEAR SOIL OPENER EFFECTS UNDER SIMULATED WET AND DRY ESTABLISHMENT CONDITIONS

6.1 Introduction

Research in Chapter 4 showed that spear type opener width and sharpness of the leading edge has a significant resulting impact on crop establishment and growth in dry soil establishment conditions. Research in Chapter 5 showed soil opener shape factors such as a flat underside and blunt leading edge can result in increased penetration resistance and energy required as a result of these soil openers increasing soil bulk density. The resulting effect of these changes to soil physical properties can lead to a reduction in crop emergence from wet seeding conditions.

Research reported in Chapter 5, highlighted the logistical difficulties of field collection and measurement of complete plant root samples. Furthermore, measurement of soil penetration resistance with a 6 mm cone on a linear plan aligned along the seed row represents only a two dimensional view of the impact of a soil opener. This cannot adequately represent the effects of a soil opener passing through soil and placing seed in a three dimensional plane.

The aim of the research reported here was to quantify the effects of spear type soil opener design on soil physical properties under more controlled conditions than hitherto reported. Control was improved by using two techniques, a soil bin method and a soil core method. These methods allowed more measurements of both physical and biological properties at greater accuracy than the field experiments reported on previously.

The research tests the hypothesis that wide and sharp spear type soil openers provide measurable reductions in soil resistance to plant establishment compared with blunt and flat underside types in conditions of contrasting soil wetness, from wet to dry.

6.2 Materials and methods

A series of 4 experiments were sown using two different techniques. Both were developed to enable greater ability to collect complete undisturbed plant root samples and enable greater physical control during the recording of soil penetration resistance. Experiments sown using a soil bin technique include Stanley Flat, wet establishment conditions (Experiment 6a) and Stanley Flat, dry establishment conditions (Experiment 6b). Difficulty in loading the soil bins at the experiment site at Yacka used in Chapters 4 and 5 precluded the planned utilisation of this technique there. The soil core collection equipment developed for root sampling in Chapter 5 was utilised at Yacka. Experiments sown using a soil core technique include Yacka, wet establishment conditions (Experiment 6c) and Yacka, dry establishment conditions (Experiment 6d).

6.2.1 Soil bin technique

A set of 20 soil bins was constructed from galvanised plate. Four half-size soil bins were also constructed for use during seeding. These soil bins were a further development of the method used by Baker (1969). The soil bins were designed to attach to a tractor drawn three-point linkage extraction unit. An extraction unit (Plate 6.1 and Appendix A10.3.1) was constructed from high carbon hardened steel grader blade, welded with specialist welding equipment to form a one-piece U-shaped ripper blade. The bottom blade was slightly inclined by 2° to ensure the extraction unit

operated with its own down-force. At the rear of the U-blade, a water injection pipe was welded to the rear edge with a series of 16, 3mm diameter holes drilled facing to the rear as part of the water lubrication system of the extraction unit. A power take-off roller gear pump was attached to the tractor to provide water pressure to the injection pipe from a 200 L water tank attached to the top of the extraction unit at a flow rate of 0.4 L s^{-1} . This water tank also provided additional ballast to improve penetration of the extraction unit. A set of two depth control wheels mounted on the outside wing of the extraction unit ensured bins were filled to the correct depth.

Soil bins were extracted from the Stanley Flat site in preference to Roseworthy for transport and logistical considerations. The Stanley Flat soil site was selected as the soil texture and structure was similar to Roseworthy.

The insides of the soil bins were coated with Shell™ mould release oil, to prevent soil adhering to the metal during the collection process. Mould release oil was selected in preference to other products tested. These included spray-on Teflon™ coating and spray-on lithium grease. A stainless steel plate lining the base as used by Baker (1969) was tested unsuccessfully due to the increased depth and weight of soil. The bins constructed for Baker's research were constructed from mild steel plate that rapidly corroded requiring a stainless steel liner. The galvanised plate used in these experiments maintained a polished low friction finish, performing similar to the stainless steel. Soil bins were loaded with soil using a tractor and three point linkage extraction unit. The soil bins were manually hooked onto the rear of the extraction unit. The tractor proceeded at the slowest possible speed, with the bin manually held up from the rear. The tractor operator lowered the extraction unit into the soil while a

second operator released the rear of the soil bin. During this procedure, water was pumped from the holding tank into base of the bin to lubricate the soil-metal interface.

The tractor proceeded along its path at the correct sampling depth until soil had been collected over the entire length of the bin (Plate 6.1). The tractor was then halted and the bin was raised to the surface by the extraction unit. Bins were then levelled to a depth of 15 cm from the top of the bin edge with a bladed levelling tool to ensure all bins achieved the same soil depth. Metal plates were then attached to each end of the bin to prevent soil loss. Bins were then loaded with a front-end loader and transported by trailer to a storage and greenhouse facility where further work on the experiment was carried out.

Soil bins for Experiment 6a, were prepared for seeding by wetting the soil bins up until above saturation with a measured quantity of water applied with a hand watering can and allowing them to air-dry without exposure to sunlight, down to a soil water content of $0.24 \text{ m}_w \text{ m}_s^{-1}$. Soil bins for Experiment 6b were prepared for seeding by wetting the soil bins up until above saturation and allowing them to air-dry with exposure to sunlight, then repeating this process for a second time without exposure to sunlight down to a water content of $0.20 \text{ m}_w \text{ m}_s^{-1}$. A second wetting and drying process was carried out as the exposure to sunlight intended to achieve more rapid drying of the soil contained in the bin, caused significant surface cracking of the topsoil layer. The method of drying soil bins without exposure to sunlight, although slower, achieved a more satisfactory result.

Following collection, wetting and drying the soil in the bins had lower soil bulk density than initial field conditions with a greater degree of variation (Table 6.1). Penetration resistance was also significantly lower in soil bins post seeding than in the field (Figure 6.1).



Plate 6.1 Loading a soil bin at Stanley Flat.

Table 6.1 Soil bin collection effects on soil bulk density at Stanley Flat 1996.

Sample depth (mm)	Pre-bin collection soil bulk density (Mg m^{-3})		Post-bin collection soil bulk density (Mg m^{-3})	
	Mean	(Stand. dev. σ^{n-1})	Mean	(Stand. dev. σ^{n-1})
0-50 mm	1.386	0.075	1.160	0.131
50-100 mm	1.493	0.036	1.232	0.106
100-150 mm	1.559	0.013	1.166	0.133

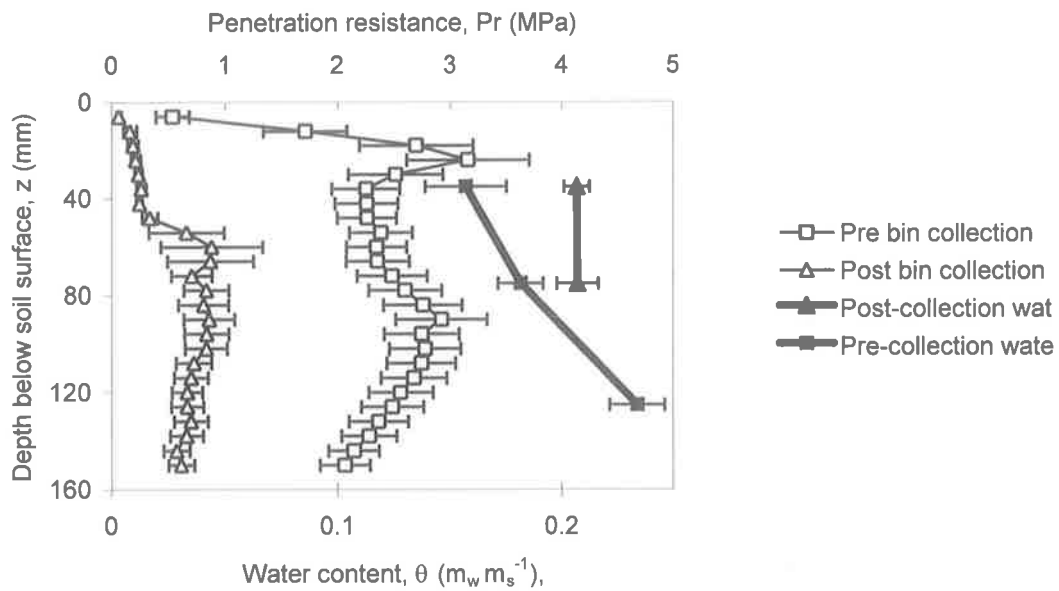


Figure 6.1 Soil bin collection effect on penetrometer resistance.

The soil bins were bolted together on a large concrete shed floor with the end plates removed in a single line of 5 bins representing 5 replicates of a single treatment. A half size bin was bolted to each end to enable the seeding unit to ramp up and down at each end to ensure the seeding unit operated correctly. Loose soil was placed in the gap between each soil bin to ensure even transition of the seeder. The seeding unit consisted of a three-point linkage single tine seeder with the spear soil opener and seed delivery tube attached. A John Shearer™ 580 series tine was set at a tine breakout force of 740 N (Robotham and Norris, 1985). All treatments used a moulded urethane seed delivery tube as described in Chapter 5. The covering device used was a 80 mm wide banked press-wheel (Appendix A10.1.2) mounted on a pendulum arm set at a pressure of 5 kg cm⁻¹ press-wheel width in contact with the soil. The tine was adjusted for height to ensure the same seeding depth in each treatment.

Treatments (i),(ii), (iii) and (iv) all used the tungsten carbide tipped commercial ARP-RRR02 spear point soil opener used in experiments described in Chapter 5 (Figure 5.1 and Plate 6.2). Treatment (i), (ii) and (iii) had modified leading tips. Treatment (ii) was ground flat on the underside, horizontal to the normal soil surface producing a flat underside leading edge. Treatment (iii) had its leading tip completely cut off at 90° angle to the horizontal. Treatment (i) is a combination of treatments (ii) and (iii), producing both a blunt and flat underside leading edge. Treatment (iv) remained as a sharp spear opener.



Plate 6.2 Spear soil opener treatments used in the 1996 soil bin and core experiments. Left to right; (ii) flat spear, (i) blunt flat spear, (iii) blunt spear, (iv) sharp spear.

Triticum aestivum var. Janz was sown at a depth of approximately 25 mm of soil cover over the seed row. Germination of seed treated with Raxil C™ (triadimenol/cypermethrin fungicide/insecticide) at 1g kg⁻¹ was tested by International Seed Testing Association Guidelines, giving 98 % normal seedlings at 8 days. Seed was sown at a density of 40 seeds per meter of row, which in commercial seeding systems is equivalent to 222 grains m⁻². Di-ammonium phosphate fertiliser (N:P:K; of 18:20:0) was applied at a rate of 1.35 g m⁻¹ row, equivalent to 75 kg ha⁻¹ at seeding.

Seed and fertiliser were loaded into a single cone hopper. The cone was manually tripped as the tractor and single row seeder was driven at 5 km h⁻¹ for 15 m, cross straddling the row of soil bins. A pair of self-guiding ski-bars that ran down each side of the bins ensured central seeding in the soil bin (Plate 6.3). Sown soil bins were then moved into a green house using a front-end loader.



Plate 6.3. Seeding soil bin experiment

Green house facilities were constructed with enlarged doors and height to allow transport of the soil bins by tractor. Soil bins were mounted on steel tables above the floor for improved drainage (Plate 6.4). Soil collection trays were mounted at each end of the soil bin to collect soil falling from the open ends. A micro irrigation system with a distribution accuracy of $\pm 5\%$ was constructed and suspended overhead

with non-drip valves to simulate heavy rainfall at an intensity of 0.8 mm min^{-1} . The sprinklers were operated by a timer-controlled solenoid to apply an equal amount of water each hour depending on daily water pressure variation.

Weed control was achieved by hand spraying a broad-spectrum knockdown Glyphosate ($6.75 \text{ g.L}^{-1} \text{ a.i.}$) 10 days prior to seeding. Secondary weed control was achieved by hand weeding. Folimat™ ($1.3 \text{ g.L}^{-1} \text{ a.i. omethoate}$) was hand applied to all plants to prevent mite damage.



Plate 6.4. Green house facility, arrangement of soil bins and irrigation system.

6.2.2 Soil core technique

Soil for Experiments 6c and 6d from Yacka were prepared for seeding on the 23rd September 1996 and 3rd November 1996 respectively by applying artificial rainfall via

high volume spray nozzles attached to a commercial field crop-spraying unit. Rainwater was sprayed onto 60 m² of soil surface at 25 mm per hour for 1 hour and 4 hours. This gave totals of 25 and 100 mm respectively, raising the soil water contents to 8.4 % and 16.6 % to a depth of 50 mm. The plots were left to drain for 24 hours and were then sown using the identical multi-row experimental seeder described in Chapter 5 (Plate 5.1). The same openers were used as in the soil bin experiments. The covering device used was an 80 mm wide banked press-wheels mounted on a walking type frame assembly (Appendix A10.1.2) set at a pressure of 5 kg cm⁻¹ press-wheel width in contact with the soil. *Triticum aestivum* var. Janz was sown at a rate equivalent to 286 grains m⁻² to a depth of approximately 30 mm of soil cover over the seed row at a speed of 8 km h⁻¹. Germination of this seed, treated with Raxil CTM (triadimenol/cypermethrin fungicide/insecticide) at 1g kg⁻¹ was tested by International Seed Testing Association Guidelines and gave 97 % normal seedlings at 8 days. Diammonium phosphate fertiliser (N:P:K 18:20:0) equivalent to 75 kg ha⁻¹ was applied with the seed.

Frames manufactured from 2 mm galvanised metal plate 200 mm wide x 400 mm length x 200 mm deep were then laid out over the length of the seeding row to reduce seed metering and soil throw variation. Using the multi-row experimental seeder static weight of 1.6 tonnes, a large plate welded to a foot mounted centrally on the seeder as described in Chapter 5 was used to gently press the soil cores into the soil. The cores were then manually removed and transported to the green house facility used in Experiment 6a and 6b.

Weed control in the soil used in the soil core technique at Yacka was achieved by spraying with a broad-spectrum knockdown Glyphosate ($450 \text{ g L}^{-1} \text{ a.i.}$) application at 3.0 L.ha^{-1} in 110 L.ha^{-1} water, 10 days prior to seeding. Secondary weed control was achieved by hand weeding within the soil cores. Folimat™ (1.3 g L^{-1} omethoate) was applied to all plants to prevent mite damage to emerging plants in the soil cores.

6.2.3 Measurements

Soils from both experiment sites were analysed for nutrient status in a commercial laboratory using the materials and methods described in chapter 3. Plant emergence was determined by the methods described in Chapter 4. Plant root samples were collected by gently washing soil out of the soil bin away from the plant roots until a total of 10 whole root systems were exposed. The complete plant and root system was oven dried at $70 \text{ }^{\circ}\text{C}$ for 48 hours in aluminium foil trays then weighed. The plant root systems were dissected from the shoot, removing the grain, and weighed.

Soil physical properties were measured and soil moisture samples were collected in each experiment on the day of seeding and at the plant 2 leaf stage immediately before collection of plant samples by the methods described in Chapter 4. Soil bulk density and water content in Stanley Flat Experiments 6a and 6b were determined at post seeding by the use of 50 mm diameter (ϕ) x 25 mm deep brass bulk density rings. Soil bulk density and water content in Yacka Experiments 6c and 6d were determined at core collection by the use of 72 mm ϕ x 50 mm deep brass soil rings. Soil bulk density and water content samples were collected post seeding at 2 depths of 0-50 mm and 50-100 mm directly in the seed furrow in all experiments. In the soil bin Experiments 6a and 6b, samples were also collected at the same depths 40 mm each

side of the seed row. One set of samples was collected from each soil bin or core at each measurement.

Soil water content was determined by weighing soil before and after drying in an oven at 105 °C for 24 hours. Soil shear strength was recorded prior to seeding at 30 mm depth in the seed bed with a torsional shear box using the method by Collis-George and Lloyd (1979). Average shear strength was calculated from 3 shear vane measurements in the seed row adjacent to the soil bulk density samples taken at 2 depths. A Geonor™ shear vane tester was used with the method described by Koppi and Douglas (1991). A vane size of 4 vanes, 50 mm deep x 12.2 mm wide was used in Experiments 6a and 6c. A vane size of 4 vanes, 40 mm deep x 10 mm wide was used in Experiment 6b and a vane size of 4 vanes, 32 mm deep x 7.9 mm wide was used in Experiment 6d.

Soil penetrometer resistance was measured with a mechanically driven (100 mm min⁻¹) recording penetrometer with a strain gauge (100 N) connected to a 2 mm diameter cone via a 1.5 mm shaft. Force in the cone was logged at 2 mm depth intervals. The penetrometer was mounted on a self-levelling frame that was clamped to the soil bin, or with an adaptor plate clamped to a soil core (Plate 6.5). The frame was indexed to move horizontally across the seed furrow in a series of 12 mm intervals, ensuring common reference points in each soil bin. This set up gave 3 dimensional data sets similar to those described by Tessier *et. al.* (1990) who used a multiple cone penetrometer. The Stanley Flat wet and dry Experiments 6a and 6b penetrometer recordings were taken to a depth of 140 mm, 13 times in 12 mm indexed transects across the seed furrow. Uniform starting depth was achieved by lowering the cone

down until it reached a soil reference marker that was 12 mm above undisturbed soil within the bin.



Plate 6.5 Soil penetrometer with 2 mm cone mounted on an indexed frame.

In the case of the Yacka wet soil Experiment 6c, penetrometer recordings were taken to a depth of 140 mm, 11 times in 12 mm indexed transects across the seed furrow. Data was corrected for starting depth using a soil reference marker 12 mm above undisturbed soil. Due to the high initial penetration resistance, Yacka dry soil Experiment 6d strength was measured using the 6 mm cone penetrometer and method described in Chapter 4.2. In this Experiment 6d, penetrometer recordings were taken to a depth of 140 mm, 3 times along the same seed row within the core. In all experiments, the strain gauge was calibrated to give penetration resistance in MPa.

Penetrometer data collected was used to calculate penetration energy in MJ m⁻². Values were calculated by averaging data at each 2 mm depth interval from the 9 values at 12 mm intervals ranging within ± 48 mm each side of the seed furrow in the bin or core centre. The value of energy was calculated from the cumulative values ranging in depth 30 mm below the seed zone.

All soil and plant growth data was analysed with Statistix™ for Windows Version 2.0 Analytical Software (Anon, 1996). Plots of residual error were used to check for outlying data. Significant outlying data was entered as missing values in these cases and experiments were re-analysed.

To enable clearer indication of the shift in penetration resistance values, images for each soil opener were mapped with Microsoft® Excel 97 and then imported for image analysis. Analysis was performed with the digital image analysis UTHSCSA Image Tool™ software (Anon, 1999). Sub images ± 48 mm each side of the image centre and 30 mm below the seed zone were cut from the full colour images. The sub image was then converted to a grey scale image. Using the Image Tool™ density threshold tool that is based on NIH Image for Macintosh (National Institutes of Health, USA). Sub images were then selected for each penetration resistance range. The area values were then used to calculate the relative percentage of the soil area for each penetration resistance range.

6.3 Results

6.3.1 Soil bin and core establishment conditions

Soil used from both Stanley Flat and Yacka had adequate to high levels of extractable P (Table 6.2). Extractable K and NO₃-N was considered adequate at both sites. Soils

from both sites contained moderate levels of organic carbon (OC). Both sites were calcareous and low in salinity.

Table 6.2 Soil chemical composition at the Stanley Flat and Yacka experimental sites (0-100 mm depth) in 1996.

Experimental site	Extrac. P (mg kg ⁻¹)	Extrac. K (mg kg ⁻¹)	NO ₃ -N (mg kg ⁻¹)	OC (%)	E.C. 1 _s :5 _w extract (dS m ⁻¹)	CaCO ₃ (%)	pH (H ₂ O)
Stanley Flat Wet establishment 6a Dry establishment 6b	47	564	18	1.3	0.10	3	6.9
Yacka Wet establishment 6c Dry establishment 6d	38	445	16	0.91	0.09	3	7

Table 6.3 Soil physical properties at the Stanley Flat and Yacka experimental sites (0-100 mm depth) in 1996.

Experimental site	Particle size distribution (%)			Emerson Dispersion Class	Soil texture class
	Sand	Silt	Clay		
Stanley Flat Wet establishment 6a Dry establishment 6b	59	20	21	3	Sandy clay loam
Yacka Wet establishment 6c Dry establishment 6d	62	18	20	3	Sandy clay loam

Soil texture was determined to be a sandy clay loam at both sites and soils were dispersive if cultivated at a water content greater than field capacity (Table 6.3). Soil water content was similar in both Stanley Flat and Yacka wet establishment Experiments 6a and 6b (Table 6.4). Soil water content was considerably lower at 0-50 mm in Yacka dry establishment Experiment 6d compared with Stanley Flat Experiment 6b, but higher than Stanley Flat experiment 6b at 50-100 mm depth.

Soil bulk density (Table 6.4) collected pre-seeding was significantly lower in Stanley Flat experiments compared to Yacka experiments due to disturbance using the soil bin collection process. This resulted in a Stanley Flat soil that was considered to be

wetter at both depths of the wet establishment Experiment 6a and at 0-50 mm in dry establishment Experiment 6b, compared with the Yacka Experiments 6c and 6d. Soil shear strength was considerably higher at Yacka than Stanley flat experiments as a result of this (Table 6.4).

Soils were sown at a water content near to the plastic limit in the wet establishment experiments at both sites, but much lower than the soil plastic limit water content in the dry establishment experiments (Table 6.4).

Table 6.4 Soil water content, bulk density and shear strength pre-seeding at Stanley Flat and Yacka experiment sites in 1996.

Experiment	Soil water content θ ($m_w m_s^{-1}$) (Stand. dev. σ^{n-1})			Soil bulk density ($Mg m^{-3}$) (Stand. dev. σ^{n-1})		Soil shear strength Soil shear box ($kPa m^{-2}$)
	Sample depth (mm)			Sample depth (mm)		(Stand. dev. σ^{n-1})
	0-50	50-100	Plastic limit 0-50 mm	0-50	50-100	30 mm depth
Stanley Flat						
Wet establishment 6a	0.242 (0.033)	0.229 (0.022)		1.160 (0.131)	1.232 (0.106)	335.7 (57.7)
Dry establishment 6b	0.206 (0.026)	0.207 (0.042)	0.272			364.4 (86.6)
Yacka						
Wet establishment 6c	0.240 (0.024)	0.269 (0.024)		1.445 (0.055)	1.480 (0.049)	1111.7 (218.8)
Dry establishment 6d	0.122 (0.022)	0.246 (0.026)	0.291			1102.5 (158.2)

Simulated rainfall post seeding in wet establishment Experiments 6a and 6c, was controlled to 4 rainfall events every second day over a 12 hour period, totalling 37.6 and 36.4 mm respectively (Table 6.5). Simulated rainfall post seeding in dry establishment Experiments 6b and 6d was controlled to one rainfall event over a 12 hour period totalling 8.4 mm and 10.6 mm respectively.

Table 6.5 Simulated rainfall post seeding in soil bins and cores in 1996.

Experiment	days post seeding							Total rainfall
	1	2	3	4	5	6	7	
	Simulated rainfall (mm)							
Stanley Flat								
Wet establishment 6a	10	0	8.4	0	8.6	0	10.6	37.6
Dry establishment 6b	0	8.4	0	0	0	0	0	8.4
Yacka								
Wet establishment 6c	8.6	0	9.2	0	9.6	0	9.0	36.4
Dry establishment 6d	0	10.6	0	0	0	0	0	10.6

Mean air and soil temperature was relatively cool in the wet establishment Experiments 6a and 6c and warmer in Experiments 6b and 6d (Table 6.6). However minimum overnight temperatures were very low and maximum peak daily temperatures were very high in all experiments, particularly Experiment 6d, which created some concern. Unfortunately climate control cooling was not available at the time of these experiments. Although it was considered that this would not significantly affect the findings of this research, results should be considered in light of this.

Table 6.6 Average greenhouse temperature variation during the emergence experiments in soil bins and cores in 1996.

Experiment	Daily temperature °C							
	Air 1.5 m		Soil surface		50 mm soil depth		100 mm soil depth	
	Mean	Min /max	Mean	Min /max	Mean	Min /max	Mean	Min /max
Stanley Flat								
Wet establishment 6a	15.0	6.0 /38.9	16.8	7.5 /34.9	17.7	7.8 /34.9	17.4	7.7 /33.9
Dry establishment 6b	18.6	6.5 /40.6	19.6	7.3 /36.8	20.4	9.2 /32.2	20.0	8.6 /32.6
Yacka								
Wet establishment 6c	13.1	3.3 /34.9	14.5	4.5 /32.2	16.1	6.7 /33.5	15.3	7.5 /29.7
Dry establishment 6d	22.3	5.6 /47.3	24.4	7.8 /56.2	24.4	10.2 /44.4	25.9	11.1 /48.8

6.3.2 Soil penetrometer resistance

Results of soil penetration resistance for Experiments 6a to 6d are shown in Figures 6.2 to 6.6. Yacka dry establishment penetration resistance results (experiment 6d) are presented with a depth dimension only as high penetration resistance values required the use of a 6 mm cone, rather than a 2 mm cone due to the deflection of the narrow 1 mm penetrometer shaft. The relative area histogram of penetration resistance of each spear opener for Experiments 6a to 6d are shown in Figures 6.7 to 6.10. Penetration energy created by the openers for various depth intervals are shown in Table 6.11. Seed was located at 72 mm depth in the soil bins and 30 mm depth in soil cores.

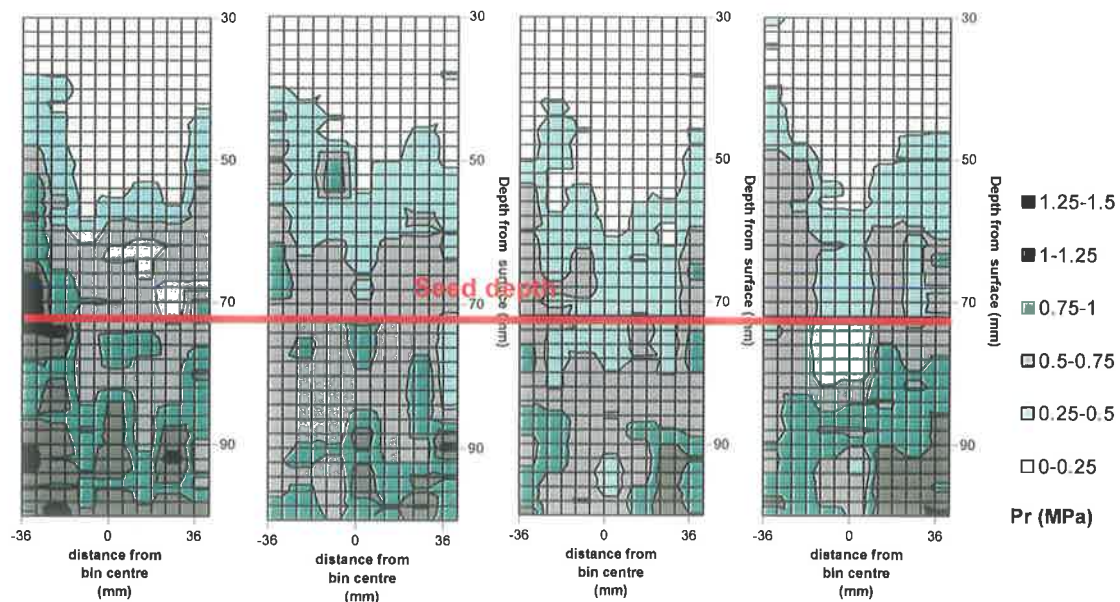


Figure 6.2 Spear opener (left to right; (i) blunt flat spear, (ii) flat spear, (iii) blunt spear, (iv) sharp spear) effect on penetrometer resistance in Stanley Flat soil bins in wet establishment conditions (Experiment 6a).

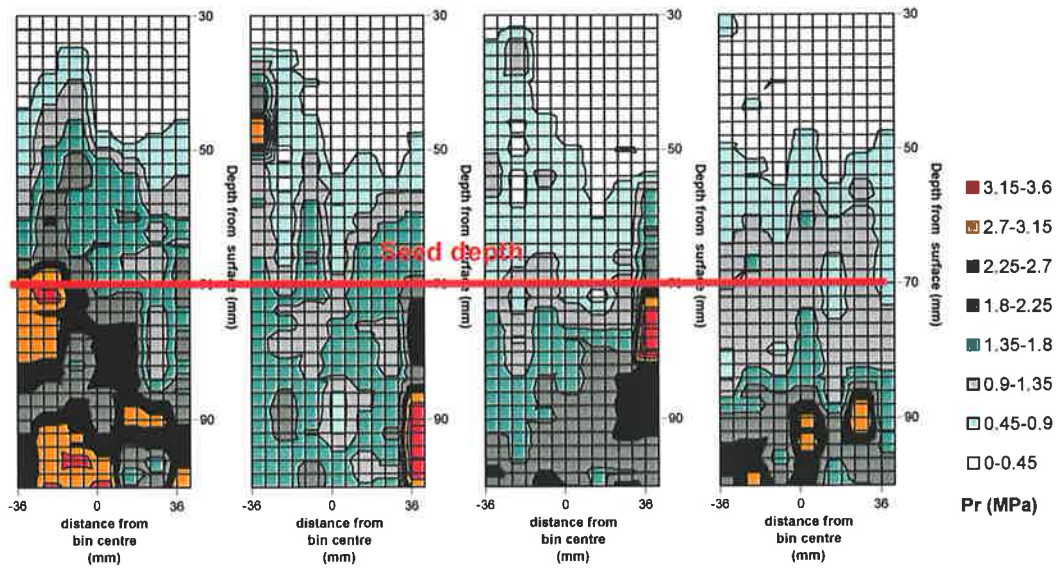


Figure 6.3 Spear opener (left to right; (i) blunt flat spear, (ii) flat spear, (iii) blunt spear, (iv) sharp spear) effect on penetrometer resistance in Stanley Flat soil bins in dry establishment conditions (Experiment 6b).

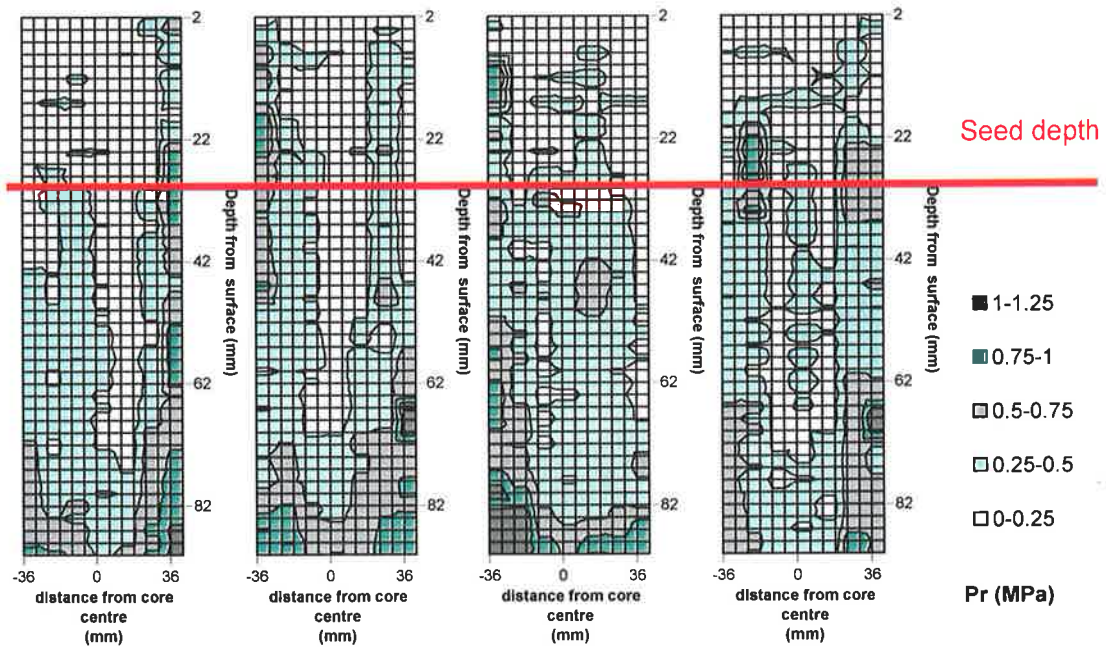


Figure 6.4 Spear opener (left to right; (i) blunt flat spear, (ii) flat spear, (iii) blunt spear, (iv) sharp spear) effect on penetrometer resistance (Pr) in Yacka soil cores in wet establishment conditions (Experiment 6c).

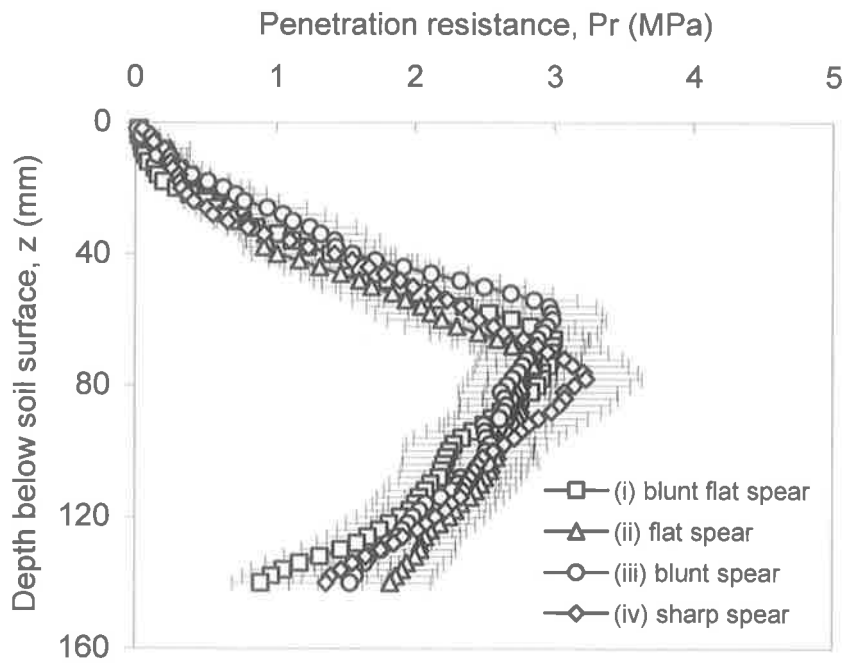


Figure 6.5 Spear opener effect on penetrometer resistance (Pr) in Yacka soil cores in dry establishment conditions (Experiment 6d) and standard error of mean.

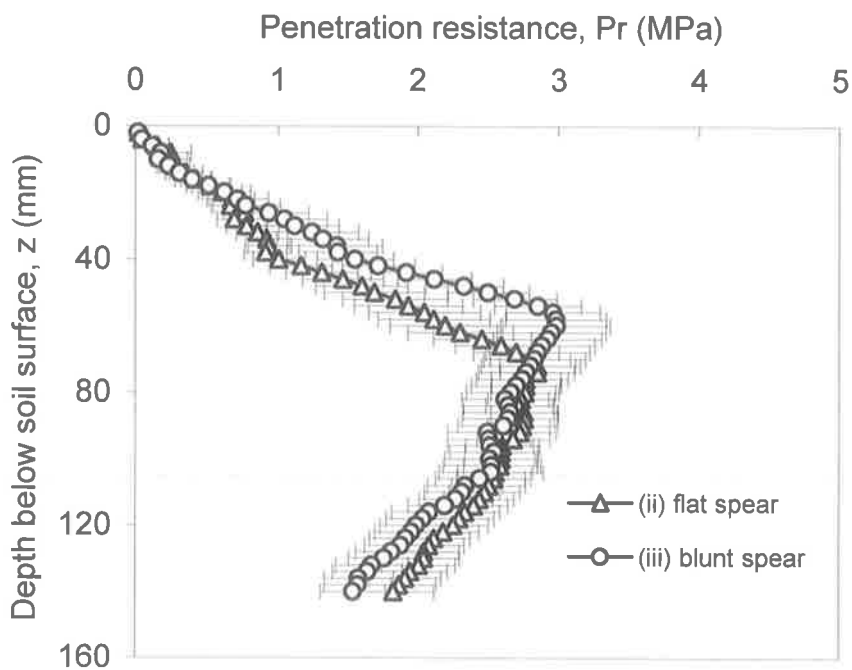


Figure 6.6 Flat and blunt spear opener effect on penetrometer resistance (Pr) in Yacka soil cores in dry establishment conditions (Experiment 6d) and standard error of mean.

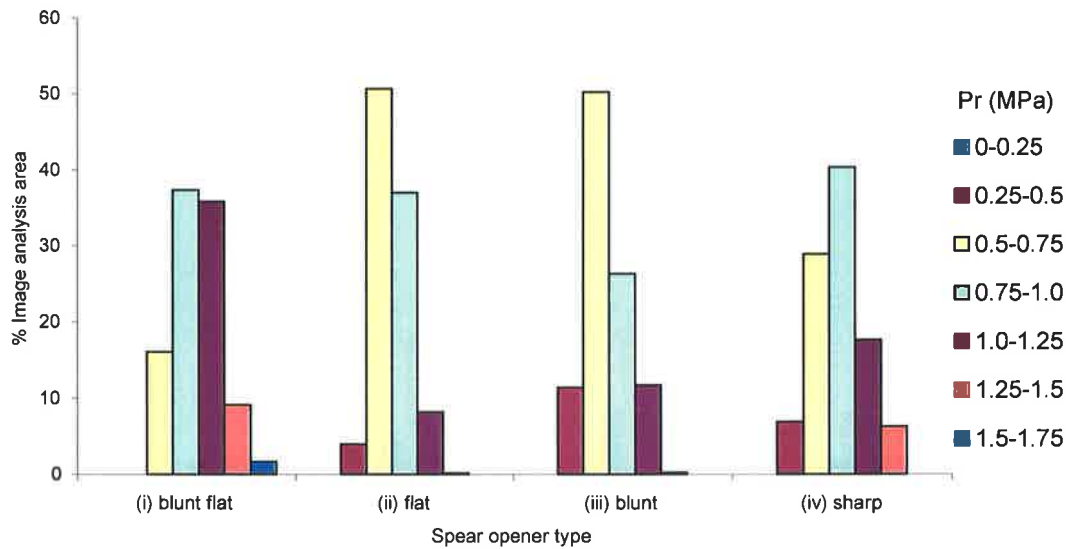


Figure 6.7 Spear opener effect on mean percentage (%) area penetration resistance (Pr) range in Stanley Flat soil bins in wet establishment conditions (Experiment 6a) calculated using image analysis on soil images $2.88 \times 10^{-3} \text{ m}^2$ ranging 0-30 mm below the seed zone.

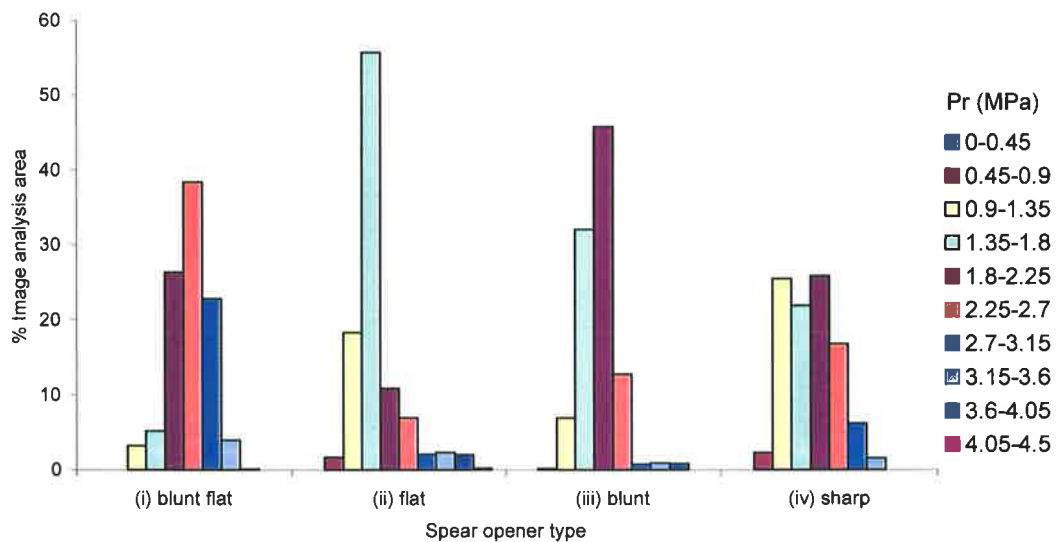


Figure 6.8 Spear opener effect on mean percentage (%) area penetration resistance (Pr) range in Stanley Flat soil bins in dry establishment conditions (Experiment 6b) calculated using image analysis on soil images $2.88 \times 10^{-3} \text{ m}^2$ ranging 0-30 mm below the seed zone.

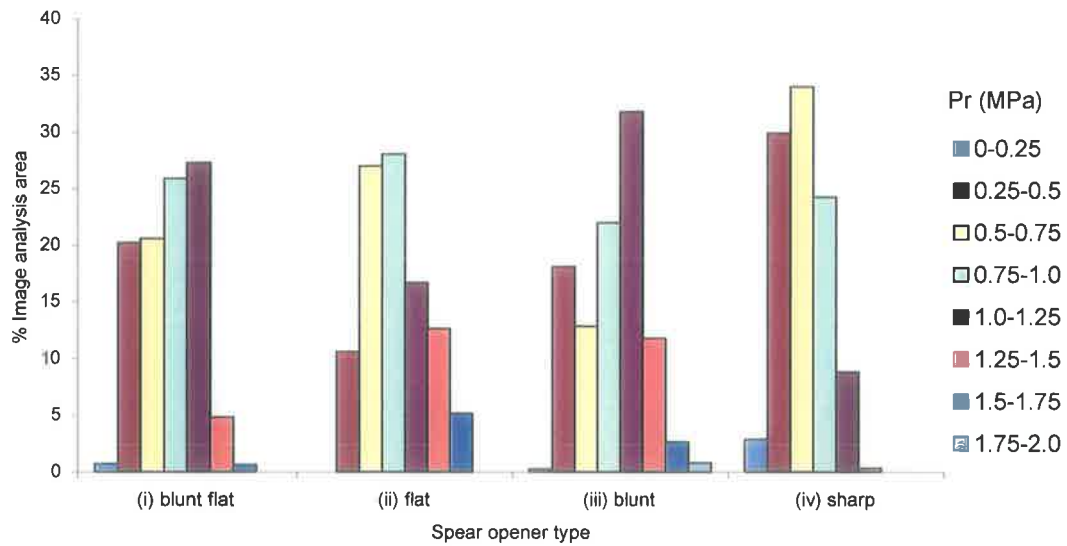


Figure 6.9 Spear opener effect on mean percentage (%) area penetration resistance (Pr) range in Yacka soil cores in wet establishment conditions (Experiment 6c) calculated using image analysis on soil images $2.88 \times 10^{-3} \text{ m}^2$ ranging 0-30 mm below the seed zone.

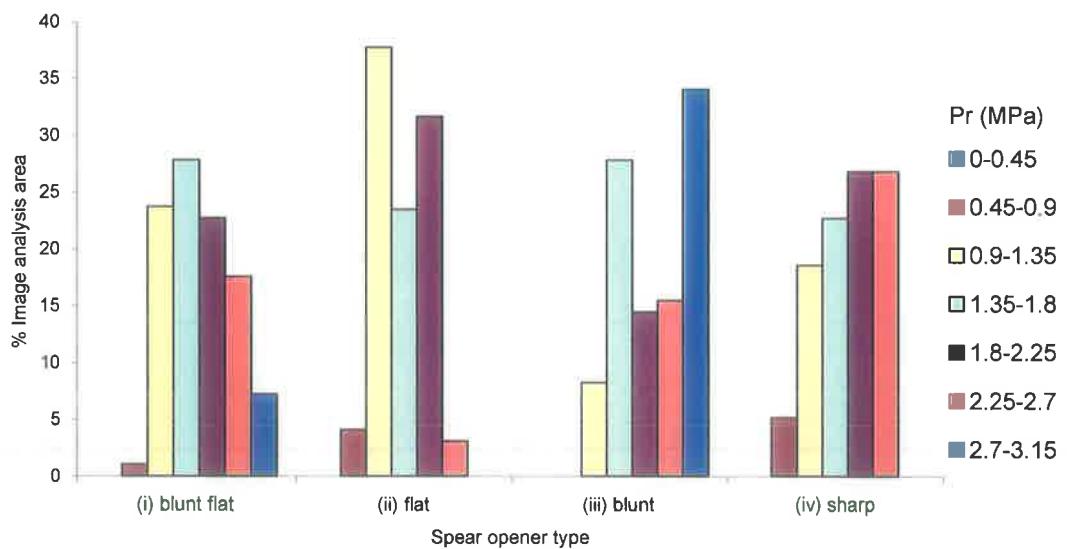


Figure 6.10 Spear opener effect on mean percentage (%) area penetration resistance (Pr) range in Yacka soil cores in dry establishment conditions (Experiment 6d) calculated using image analysis on soil images $1.8 \times 10^{-4} \text{ m}^2$ ranging 0-30 mm below the seed zone.

Mean penetrometer resistance values in an area of $2.88 \times 10^{-3} \text{ m}^2$ 0-30 mm below the seed zone beginning at 72 mm soil depth showed very small standard errors (Appendix A10.5.1). Taking this into account in interpreting data, it was assumed that gross soil penetration resistance changes within each penetration resistance range were real and significant.

A small zone of increased compaction in a 0.75-1.0 MPa range was apparent below 72 mm in seedbeds created with blunt flat and flat spear openers (Treatments (i) and (ii)) of Stanley Flat wet establishment Experiment 6a (Figure 6.2). There was also significantly lower penetration resistance resulting from a sharp spear opener (Treatment(iv)) 10 mm below all other openers. Stanley Flat dry establishment conditions (Experiment 6b) results in Figure 6.4 demonstrated significantly higher resulting penetration resistance in the same soil zone from a blunt flat and blunt opener (Treatments (i) and (ii)) compared to a flat and sharp opener (Treatments (ii) and (iv)). However a discrete compacted zone immediately below the seed zone was not evident in soils seeded under dry conditions. These results are supported by the histograms of soil penetration resistance range total area from image analysis (Figures 6.7 and 6.8). There was a shift to higher penetration resistance in the seedbed created with a blunt and flat spear opener (Treatments (ii) and (iii)). This was also true for the blunt flat spear opener (Treatment (i)) compared to a sharp spear opener in the Stanley Flat wet establishment Experiment 6a (Figure 6.7). Under dry establishment conditions (Experiment 6b, Figure 6.9), there was a shift to higher penetration resistance in a seedbeds created with blunt flat and blunt spear openers (Treatments (i) and (ii)) compared to flat and sharp spear openers (Treatments (ii) and (iv)).

These results are supported by the penetration energy results in Table 6.7. These data show significantly higher penetration energy at 32-62 mm depth from the soil surface in seedbeds created by a blunt flat opener (Treatment (i)) compared to all other openers in the Stanley Flat wet establishment Experiment 6a. The same results were found in the Stanley Flat dry establishment Experiment 6b. However, a sharp spear opener (Treatment (iv)) did not result in significantly different penetration energy at 32-62 mm depth compared to a blunt flat opener (Treatment (i)) in the same experiment.

The sharp spear (Treatment (iv)) opener resulted in significantly lower penetration resistance than all other openers in wet establishment conditions at Yacka (Experiment 6c) (Figure 6.4). This is supported by the histogram of penetration resistance (Figure 6.9) showing that blunt, blunt flat and flat spear openers (Treatments (i), (ii) and (iii)) resulted in a higher penetration resistance than a sharp spear opener (Treatment (iv)).

The blunt spear opener (Treatment (iii)) resulted in significantly higher penetration resistance at 40-60 mm soil depth compared to a flat spear opener (Treatment (ii)) in dry establishment conditions at Yacka (Experiment 6d). Other openers did not result in significant differences (Figures 6.5 and 6.6). This is supported by the histogram of penetration resistance in Figure 6.10.

Results shown in Table 6.7 indicated that the blunt flat and blunt openers (Treatments (i) and (iii)) caused seedbeds to have significantly higher penetration energy than flat and sharp openers (Treatments (ii) and (iii)) at 32-62 mm in wet establishment

conditions at Yacka (Experiment 6c). A blunt opener (Treatment (iii)) resulted in significantly higher penetration energy than all other openers at the same depth in dry establishment conditions at the same site (Experiment 6d). Effect of soil water content on undisturbed soil penetration resistance is shown in Appendices A10.3.2 and A10.3.3.

Table 6.7 Effects of spear opener shape on total penetration energy on Stanley Flat and Yacka soils of experiments in 1996.

Stanley Flat		Total penetration energy (MJ m ⁻²)					
		Wet establishment conditions Depth below surface(mm)			Dry establishment conditions Depth below surface (mm)		
Treatment		10-30	32-62	64-94	10-30	32-62	64-94
(i) Blunt flat spear		17.9	34.3 a	40.2	36.9	63.2 a	63.7
(ii) Flat spear		15.5	19.2 b	36.6	35.0	50.4 b	67.4
(iii) Blunt spear		11.2	23.3 b	37.5	27.3	44.9 c	55.3
(iv) Sharp spear		13.1	22.0 b	37.9	25.7	56.3 ab	66.8
P =		0.319	0.004	0.986	0.363	0.013	0.837
L.S.D. (P<0.05)		ns	6.6	ns	ns	9.6	ns
Yacka		Total penetration energy (MJ m ⁻²)					
		Wet establishment conditions Depth below surface (mm)			Dry establishment conditions Depth below surface (mm)		
Treatment		10-30	32-62	64-94	10-30	32-62	64-94
(i) Blunt flat spear		14.4	29.8 a	52.6 ab	8.5	42.6 b	92.2
(ii) Flat spear		12.8	23.0 b	59.9 a	11.3	36.1 b	87.5
(iii) Blunt spear		13.9	30.1 a	58.5 a	9.9	70.0 a	86.9
(iv) Sharp spear		12.3	21.2 b	43.9 b	10.0	34.5 b	97.7
P =		0.898	0.001	0.029	0.771	0.015	0.954
L.S.D. (P<0.05)		ns	4.3	11.0	ns	21.4	ns

6.3.3 Soil shear vane resistance

No significant resulting differences in shear strength were observed between openers in either of the Stanley Flat experiments (Table 6.9). At Yacka, the seedbed created by the sharp spear opener (Treatment (iv)) resulted in significantly lower shear strength than a blunt flat and blunt opener (Treatments (i) and (iii)) at 0-50 mm soil depth. This difference was not significant in dry establishment conditions. Soil shear vane resistance at Yacka in dry establishment conditions was particularly high. No

significant differences in shear strength were observed between openers in either of the Stanley Flat experiments (Table 6.9).

Table 6.9 Effects of spear opener shape on soil torsional shear vane resistance on Stanley Flat and Yacka soils of experiments in 1996.

Stanley Flat	Soil torsional shear vane resistance (kPa m ⁻²)			
	Wet establishment conditions Sample depth (mm)		Dry establishment conditions Sample depth (mm)	
	0-50	50-100	0-50	50-100
Treatment				
(i) Blunt flat spear	18.2	22.3	30.4	38.4
(ii) Flat spear	18.6	20.5	34.0	45.7
(iii) Blunt spear	18.1	20.6	33.3	50.8
(iv) Sharp spear	17.7	24.9	25.3	39.7
P =	0.986	0.561	0.748	0.710
L.S.D. (P<0.05)	ns	ns	ns	ns
Yacka	Soil torsional shear vane resistance (kPa m ⁻²)			
	Wet establishment conditions Sample depth (mm)		Dry establishment conditions Sample depth (mm)	
	0-50	50-100	0-50	50-100
Treatment				
(i) Blunt flat spear	17.3 a	49.7	89.3	160.9
(ii) Flat spear	13.7 ab	51.4	40.0	140.7
(iii) Blunt spear	17.3 a	52.2	80.8	184.7
(iv) Sharp spear	11.8 b	43.7	42.0	173.3
P =	0.050	0.099	0.167	0.571
L.S.D. (P<0.05)	4.6	7.3	ns	ns

6.3.4 Soil bulk density

Resulting effects of soil openers on soil bulk density were not significantly different in the seed furrow at the bin centre in the Stanley Flat wet establishment conditions (Experiment 6a, Table 6.10). However, a sharp spear opener (Treatment (iv)) resulted in significantly lower soil bulk density at 0-50 mm depth \pm 40 mm each side of the furrow centre than all other openers, but higher bulk density in the furrow centre at 50-100 mm soil depth. In contrast to this in Stanley Flat dry establishment conditions (Experiment 6b), there were no significant resulting opener effects except that a sharp and blunt spear opener (Treatments (iii) and (iv)) resulted in significantly higher bulk density at 50-100 mm soil depth \pm 40 mm each side of the furrow centre.

In wet establishment conditions at Yacka (Experiment 6c), a sharp spear opener (Treatment (iv)) resulted in significantly lower soil bulk density in the furrow centre at 50-100 mm soil depth than all other openers (Table 6.11). There were no resulting opener differences in dry establishment conditions at Yacka.

Table 6.10 Effects of spear opener shape on soil bulk density of Stanley Flat soil of experiments in 1996.

Wet establishment conditions	Soil bulk density (Mg m ⁻³) Sampled 13 days post seeding			
	Sample depth 0-50 mm		Sample depth 50-100 mm	
	Bin centre	± 40 mm from centre	Bin centre	± 40 mm from centre
Treatment				
(i) Blunt flat spear	1.287	1.316 a	1.252 bc	1.285
(ii) Flat spear	1.266	1.285 a	1.305 ab	1.279
(iii) Blunt spear	1.255	1.269 a	1.225 c	1.237
(iv) Sharp spear	1.245	1.199 b	1.331 a	1.215
P =	0.913	0.022	0.020	0.227
L.S.D. (P<0.05)	ns	0.070	0.068	ns
Dry establishment conditions	Soil bulk density (Mg m ⁻³) Sampled 13 days post seeding			
	Sample depth 0-50 mm		Sample depth 50-100 mm	
	Bin centre	± 40 mm from centre	Bin centre	± 40 mm from centre
Treatment				
(i) Blunt flat spear	1.154	1.166	1.154	1.172 b
(ii) Flat spear	1.135	1.150	1.135	1.166 b
(iii) Blunt spear	1.121	1.183	1.121	1.240 a
(iv) Sharp spear	1.155	1.196	1.155	1.246 a
P =	0.738	0.295	0.738	0.025
L.S.D. (P<0.05)	ns	ns	ns	0.062

Table 6.11 Effects of spear opener shape on soil bulk density of Yacka soil of experiments in 1996.

	Soil bulk density (Mg m ⁻³)			
	Wet establishment conditions Sampled 10 days post seeding		Dry establishment conditions Sampled 11 days post seeding	
	Sample depth (mm)		Sample depth (mm)	
Treatment	0-50	50-100	0-50	50-100
(i) Blunt flat spear	1.163	1.437 a	1.203	1.348
(ii) Flat spear	1.209	1.425 a	1.208	1.405
(iii) Blunt spear	1.226	1.418 a	1.269	1.364
(iv) Sharp spear	1.157	1.312 b	1.213	1.406
P =	0.567	0.030	0.763	0.755
L.S.D. (P<0.05)	ns	0.088	ns	ns

6.3.5 Soil water content

Soil water content resulting from a blunt flat and blunt spear opener (Treatments (i) and (iii)) in the Stanley Flat wet establishment Experiment 6a was significantly higher in the furrow centre at 0-50 mm depth compared with a flat and sharp spear opener (Treatments (ii) and (iv)) (Table 6.12). A blunt opener (Treatment (iii)) also resulted in significantly higher water content than all other openers ± 40 mm from the furrow centre at both 0-50 mm and 50-100 mm soil depths in the same experiment. Contrasting this a flat spear opener (Treatment (ii)) gave significantly higher soil water content than all other openers ± 40 mm from the furrow centre at 0-50 mm depth. There were no other significant soil opener effects on soil water content in the Stanley Flat Experiments 6a and 6b.

Table 6.12 Effects of spear opener shape on soil water content of Stanley Flat soil of experiments in 1996.

Wet establishment conditions	Soil water content θ ($m_w m_s^{-1}$) Sampled 13 days post seeding			
	Sample depth 0-50 mm		Sample depth 50-100 mm	
Treatment	Bin centre	± 40 mm from centre	Bin centre	± 40 mm from centre
(i) Blunt flat spear	0.290 a	0.245 b	0.257	0.253 b
(ii) Flat spear	0.250 b	0.238 b	0.260	0.245 b
(iii) Blunt spear	0.290 a	0.283 a	0.279	0.282 a
(iv) Sharp spear	0.254 b	0.253 b	0.278	0.249 b
P =	0.006	0.034	0.294	0.000
L.S.D. (P<0.05)	0.026	0.030	ns	0.013
Dry establishment conditions	Soil water content θ ($m_w m_s^{-1}$) Sampled 13 days post seeding			
	Sample depth 0-50 mm		Sample depth 50-100 mm	
Treatment	Bin centre	± 40 mm from centre	Bin centre	± 40 mm from centre
(i) Blunt flat spear	0.099	0.106 a	0.145	0.127
(ii) Flat spear	0.089	0.071 b	0.139	0.119
(iii) Blunt spear	0.107	0.099 a	0.128	0.141
(iv) Sharp spear	0.102	0.108 a	0.146	0.136
P =	0.757	0.038	0.826	0.748
L.S.D. (P<0.05)	ns	0.027	ns	ns

A blunt flat spear opener (Treatment (i)) resulted in significantly lower soil water content at 50-100 mm soil depth in the Yacka dry establishment conditions (Experiment 6d) (Table 6.13). There were no other significant opener effects on soil water content in the Yacka Experiments 6c and 6d.

Table 6.13 Effects of spear opener shape on soil water content of Yacka soil of experiments in 1996.

Treatment	Soil water content θ ($m_w m_s^{-1}$)			
	Wet establishment conditions Sampled 10 days post seeding		Dry establishment conditions Sampled 11 days post seeding	
	Sample depth (mm)		Sample depth (mm)	
	0-50	50-100	0-50	50-100
(i) Blunt flat spear	0.238	0.301	0.108	0.128 b
(ii) Flat spear	0.224	0.291	0.097	0.191 a
(iii) Blunt spear	0.253	0.313	0.114	0.172 a
(iv) Sharp spear	0.243	0.302	0.102	0.170 a
P =	0.498	0.353	0.662	0.003
L.S.D. (P<0.05)	ns	ns	ns	0.029

6.3.6 Rate of plant emergence and total emergence

A blunt flat spear opener (Treatment (i)) resulted in significantly higher plant emergence results than all other openers in the Stanley Flat wet establishment Experiment 6a and also in the Yacka wet establishment Experiment 6c, although differences were not statistically significant (Table 6.14). Although a sharp spear opener (Treatment (iv)) achieved higher plant emergence than all other openers in both the Stanley Flat and Yacka dry establishment experiments, increased plant emergence was not statistically significant. Although there were significant differences in mean days to emergence in both wet establishment experiments, the magnitude of these differences was very small.

Table 6.14 Spear opener effects on total wheat plant emergence and mean emergence day (M.E.D.).

Stanley Flat	Wet establishment conditions		Dry establishment conditions	
Treatment	% total plant emergence	M.E.D.	% total plant emergence	M.E.D.
(i) Blunt flat spear	69.50 a	6.09 b	76.00	4.98
(ii) Flat spear	56.91 b	6.17 b	71.50	5.36
(iii) Blunt spear	50.09 b	6.73 a	77.00	5.23
(iv) Sharp spear	55.00 b	6.49 ab	82.50	5.47
P =	0.002	0.044	0.343	0.455
L.S.D. (P<0.05)	7.90	0.47	ns	ns
Yacka	Wet establishment conditions		Dry establishment conditions	
Treatment	% total plant emergence	M.E.D.	% total plant emergence	M.E.D.
(i) Blunt flat spear	68.77	8.75	10.52	4.99
(ii) Flat spear	55.02	8.87	5.66	2.43
(iii) Blunt spear	63.11	8.98	13.75	7.21
(iv) Sharp spear	55.02	9.44	17.80	5.28
P =	0.775	0.055	0.456	0.282
L.S.D. (P<0.05)	ns	0.51	ns	ns

6.3.7 Plant root and shoot growth

There were no significant resulting soil opener effects on individual plant shoot or root growth in wet or dry Stanley Flat Experiments 6a and 6b (Table 6.15). In the Yacka wet establishment Experiment 6c, the sharp spear opener (Treatment (iv)) resulted in significantly lower shoot growth compared to the blunt flat or blunt spear opener (Treatments (i) and (iii)). Contrasting this however in the Yacka dry establishment Experiment 6d, the same sharp spear opener resulted in significantly higher shoot growth compared with a blunt flat and flat spear opener (Treatments (i) and (ii)). There were however no significant resulting root growth differences in either Yacka experiment. There was no visual or measured difference in plant rooting depth between resulting from any openers (Plate 6.6). There was also no significant correlation of plant emergence or growth with soil physical properties using complex linear and non linear models using Datafit™ data modelling software (Anon, 1993).

Table 6.15 Spear opener effects on plant growth at 2 leaf stage.

Stanley Flat	Dry matter growth (g plant ⁻¹)					
	Wet establishment conditions Sampled 13 days post seeding			Dry establishment conditions Sampled 13 days post seeding		
Treatment	Shoot	Roots	Total	Shoot	Roots	Total
(i) Blunt flat spear	0.0228	0.0183	0.0420	0.0186	0.0137	0.0362
(ii) Flat spear	0.0232	0.0184	0.0446	0.0178	0.0154	0.0371
(iii) Blunt spear	0.0186	0.0167	0.0383	0.0175	0.0139	0.0376
(iv) Sharp spear	0.0218	0.0179	0.0428	0.0154	0.0126	0.0318
P =	0.605	0.946	0.738	0.269	0.806	0.448
L.S.D. (P<0.05)	ns	ns	ns	ns	ns	ns

Yacka	Dry matter growth (g plant ⁻¹)					
	Wet establishment conditions Sampled 10 days post seeding			Dry establishment conditions Sampled 11 days post seeding		
Treatment	Shoot	Roots	Total	Shoot	Roots	Total
(i) Blunt flat spear	0.0091 a	0.0050	0.0188 a	0.0035 b	0.0039	0.0149 b
(ii) Flat spear	0.0065 ab	0.0045	0.0157 ab	0.0077 b	0.0026	0.0178 b
(iii) Blunt spear	0.0083 a	0.0039	0.0169 ab	0.0088 ab	0.0042	0.0205 ab
(iv) Sharp spear	0.0047 b	0.0038	0.0131 b	0.0137 a	0.0039	0.0251 a
P =	0.016	0.478	0.047	0.016	0.397	0.038
L.S.D. (P<0.05)	0.0028	ns	0.0039	0.0057	ns	0.0068



Plate 6.6 Soil bin Stanley Flat plant root growth. Left; (ii) Flat spear opener wet establishment (Experiment 6a).; Right (iv) Sharp spear opener dry establishment (Experiment 6b).



Plate 6.7 Blunt flat spear opener (Treatment (i)) soil smear groove in a Yacka wet sown soil core (Experiment 6c).

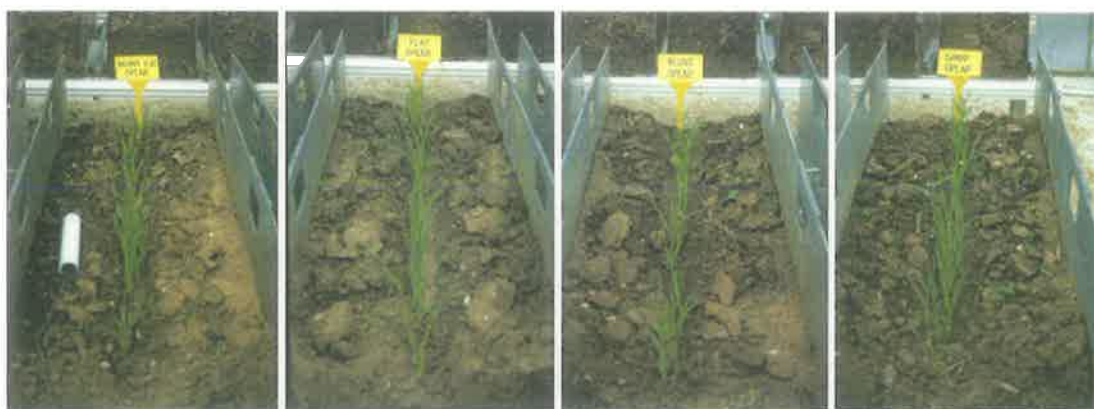


Plate 6.8 Soil bin Stanley Flat dry establishment (Experiment 6b) plant growth. Left to right; (i) blunt flat spear, (ii) flat spear, (iii) blunt spear, (iv) sharp spear.

6.4 Discussion

Use of a soil bin and soil core technique was very effective in enabling greater control over rainfall events and collection of plant root samples. Measurement of soil penetration resistance in a soil bin or soil core in a controlled environment enabled a

significant window of opportunity to collect detailed data with greater precision and control than would have been possible in the field. Although it would be theoretically possible to collect a series of penetration resistance readings with a 2 mm cone in a field experiment, in reality the prevailing weather conditions and short day lengths during the growing season would severely limit the amount of data collected.

The soil core method did not appear to increase error or influence experiment results any greater than the soil bin method. Logistically and based on operational costs of both methods, the soil core method appeared to be the most effective, particularly as it did not significantly affect soil bulk density of the seedbed as the soil bin method did.

Results of the wet establishment Experiments 6a and 6c of soils from Stanley Flat and Yacka did not produce results expected based upon the conclusions from research in Chapter 5. Possible reasons for these differences include the significant reduction in soil bulk density from a natural field state. It is likely that the much lower bulk density resulting from soil bin sampling procedure masked any treatment effects generated by the different soil openers. In addition, warmer daytime temperatures in the green house than those experienced in the field in Chapter 5 resulted in extremely rapid mean days to emergence results of 6 days and 9 days for Stanley Flat and Yacka respectively. This is in contrast to mean days to emergence of approximately 14 and 13 days respectively for Roseworthy and Yacka in a colder field situation described in Chapter 5 and up to 20 or more days the Hart single row experiment described in Chapter 3. A general summary of resulting effects of the soil openers used in these experiments based on specific soil and plant growth criteria is shown in Table 6.16. A general summary of resulting effects of the soil openers used in these experiments based

on specific soil and plant growth criteria is shown in Table 6.15.

Table 6.15 Summary of Stanley Flat and Yacka results in 1996 based on defined criteria.

Treatment	Soil bulk density (Mg m ⁻³)	Total penetration energy (MJ m ⁻²)			Shear Strength (KPa m ⁻²)	Water avail. % vol.	Moisture stressed % vol.	Saturated % vol.	Total plant emerg. (%)	Shoot dry matter (mg plant ⁻¹)
	0-50 mm depth	Above seed	Seed depth	Below seed	0-50 mm					
Criteria:										
High	>1.5	>60	>60	>60	>1000				>70	>40
Moderate					100-1000	15-35	<15	>30	70-50	
Low	<1.2	<20	<20	<20	<100				50-20	<20
Very Low									<20	
Stanley Flat wet establishment conditions										
(i) Blunt flat spear	Low	ns	Mod	ns	Low	High	No	No	Mod	High
(ii) Flat spear	Low	ns	Low	ns	Low	High	No	No	Mod	High
(iii) Blunt spear	Low	ns	Low	ns	Low	High	No	No	Mod	Mod
(iv) Sharp spear	Low	ns	Low	ns	Low	High	No	No	Mod	High
Stanley Flat dry establishment conditions										
(i) Blunt flat spear	Low	ns	Mod	ns	Low	Low	Yes	No	High	Mod
(ii) Flat spear	Low	ns	Mod	ns	Low	Low	Yes	No	High	Mod
(iii) Blunt spear	Low	ns	Mod	ns	Low	Low	Yes	No	High	Mod
(iv) Sharp spear	Low	ns	Mod	ns	Low	Low	Yes	No	High	Mod
Yacka wet establishment conditions										
(i) Blunt flat spear	High	ns	High	Mod	Low	High	No	No	Low	Low
(ii) Flat spear	High	ns	Mod	Mod	Low	High	No	No	Low	Low
(iii) Blunt spear	High	ns	Mod	Mod	Low	High	No	No	Low	Low
(iv) Sharp spear	High	ns	Mod	Mod	Low	High	No	No	Low	Low
Yacka dry establishment conditions										
(i) Blunt flat spear	High	ns	Mod	ns	Low	Low	Yes	No	V Low	Low
(ii) Flat spear	High	ns	Mod	ns	Low	Low	Yes	No	V Low	Low
(iii) Blunt spear	High	ns	High	ns	Low	Low	Yes	No	V Low	Low
(iv) Sharp spear	High	ns	Mod	ns	Low	Low	Yes	No	V Low	Low

It is likely that soil smearing which appears to occur with blunt and flat openers in a wet red-brown earth, becomes a greater problem in cold wet establishment conditions.

It is more likely that seed burst could occur or *Pythium* spp. infection described in the literature by Kirkegaard et. al. (1995) could increase in severity as mean days to emergence increases..

Measurement of soil water content both in the furrow and laterally to the side provided much greater insight into the effects of soil physical properties on soil water content. It is quite likely that a blunt flat spear opener (Treatment (i)) in the Stanley Flat wet establishment conditions (Experiment 6a) created a smear at the base of the seed furrow, reducing water infiltration creating a perched layer of higher water content. This however did not significantly affect plant establishment, and considering the very low soil bulk density of the Stanley Flat experiments, may have actually improved seedbed conditions.

Very low soil water content at 50-100 mm resulting from blunt flat spear opener (Treatment (i)) in dry Yacka establishment conditions (Experiment 6d) may have contributed to crusting at the base of the seed furrow, although it was not evident in penetration resistance results collected post emergence. An earlier measurement of penetration resistance may have found resulting differences between soil openers. A sharp spear opener (Treatment (iv)) resulted in greater plant emergence in the dry Yacka establishment conditions (Experiment 6d), although not statistically significant compared to other openers. The same opener also resulted in significantly greater early shoot growth compared to a flat and blunt flat opener (Treatments (i) and (ii)) in the same experiment. This could potentially contribute to significant grain yield reduction in a field situation based on similar results in Chapter 4.

6.5 Conclusions

The results of this research clearly show that a sharp soil opener is preferable to a blunt or flat opener in dry establishment conditions at Yacka. This supports conclusions from chapter 4. Selection of opener shape for seeding in wet establishment conditions on a red brown earth is not so clear cut with soil bin and core experiments in wet establishment conditions resulting in establishment response from soil openers in complete contrast to results in chapter 5. It is likely that temperature in these experiments using a green house may have accelerated mean days to emergence. It is possible that soil physical effects such as smearing may have greater impact in cold wet establishment conditions rather than warm wet establishment conditions. The following points highlight several key findings from this research which supports comments in the literature on soil moisture and temperature effects in Chapter 2;

- (i) Soil moisture conditions at the time of seeding dominate the effects of sowing points on seedbed properties and subsequent crop response.
- (ii) Extremes of soil temperature may also exert a strong influence over crop response to seedbed conditions.
- (iii) Given the complexity of interactions between the soil opener, soil properties and climatic conditions, it is unrealistic to expect superior performance from one soil opener design over others in all seeding conditions.

7. GENERAL DISCUSSION

7.1 Introduction

In developing an initial outline of this research, it was hypothesised that significant correlations between soil physical properties such as penetration resistance, soil bulk density and water content and resulting crop establishment would exist, whereby response models could be developed. This was not the case with the design parameters tested in this research which could create some doubt as to the importance of small design changes to soil openers on penetration resistance etc., and resulting effects on establishment. There were many other soil physical and soil water factors that could have been measured, but were not in this research. Most importantly however is the overall effect on grain yield, which is of most importance to the farming industry.

7.2 Use of a spear type opener in contrast to other soil opener types

This research has shown that the type of soil opener and covering device used on a seed drill can significantly improve cereal crop establishment and grain yield. The research also found that the combination of soil opener and covering device should be selected carefully for each particular situation (soil and climate) to optimise establishment.

Commercial inverted-T type soil openers presented difficulty in optimising establishment in some conditions in this research, although design improvement may reduce problems such as seed placement and seed-soil contact. The research by Baker and co-workers clearly has less direct relevance to seeding systems in Australia,

principally due to the low operational speed requirement of this seeding equipment compared to that in current use by Australian farmers, and the poor resulting seed furrow characteristics if this speed is exceeded. The very high purchase and operating cost of the Cross-Slot[®] soil opener which overcame much of the problems with the standard inverted-T soil opener, prohibits commercial use. This research by Baker and others is exceptional however, in developing a soil opener to improve crop performance as a primary focus rather than concentrating on engineering related performance criteria.

Based on conclusions from Chapters 3 and 4, row aligned preceding tillage 50 mm deeper than a seed row is recommended in direct seeding systems as long as seed placement is not significantly compromised. This significantly reduced penetration resistance in a red-brown earth, but did not necessarily improve crop establishment or grain yield. Crop establishment growth and grain yield response is more greatly influenced by shape of the following opener placing seed and fertiliser. Press wheels used in combination with accurate seed placement, clearly improved crop establishment, plant growth rate and grain yield, particularly if soil crusting occurs as shown in Chapter 3.

The cast spear type opener has performed extremely well in testing of different generic seed drill opener types and seeding machine configurations as long as adequate soil tilth is present at seeding and plant emergence, or created by additional deep cultivation during the seeding process. Grain yield results from direct drilled experiments on well structured red-brown earths, indicate significant yield improvements can be achieved with spear points and press wheels in comparison with

openers and covering devices such as finger tine harrows that most farmers currently use in their seeding programs. This is in addition to reduced soil disturbance from spear points in comparison to some other opener types.

Use of a spear type opener and press wheel in a 3 rank tine configuration, would provide significant improvement to trash handling, crop establishment and grain yield, compared to a current farming industry standard of a full cut 6 rank seeder with 125 mm wide shares and trash finger tine harrows.

The use of spear type soil opener technology as a basis for further soil opener design to improve crop establishment and growth addresses several key criteria required by the farming industry:

- (i) Ensures accurate seed placement when used with an integrated seed delivery tube (Slattery and Rainbow, 1995).
- (ii) When a sharp leading edge is maintained, minimises the impact of soil smear in the seed furrow.
- (iii) Enables farmers to maintain seeding speed of up to 10 km hr⁻¹.
- (iv) Can easily be adapted for attachment to a deeper seed row aligned soil opener to create deeper seed-bed tilth and band fertiliser.
- (v) Is relatively small and cheap to manufacture as a consequence of this, allowing the cost of more exotic manufacturing materials to be justified.
- (vi) This research has demonstrated results in South Australian red-brown earth soils, crop establishment, growth and grain yield at least the same or greater than that achieved with the use of other soil openers currently available.

7.3 A matrix of spear opener design effects on crop establishment

The aim of this research was to quantify the effects of different design parameters that spear type soil openers have on soil physical properties and crop response. Indirect significant effects of soil openers on crop establishment and growth were found. However, a simple correlation with soil physical properties, linking these changes was not found. The research also highlighted that soils used in soil opener studies should be determined if they are compactive or non-compactive. Triaxial testing of soils in the literature in Chapter 2 would have provided greater insight as to why soil openers achieved soil physical responses documented. If the soils were compactive, then the anecdotal observations of soil smear resulting from the use of a blunt soil opener, or one that has a flat area compressing against the base of the seed-bed, would be more readily explained.

This research presents several suppositions:

- (i) That there is a relationship between spear type opener width, the relative bluntness of a cutting edge, and the flat underside area of an opener in contact with the soil, affecting soil compaction resulting in plant establishment effects.
- (ii) That resulting soil physical effects may result in significant grain yield responses, only when extremes of wet or dry soil water content, and soil temperature occur during seedling establishment.

Modelling of soil openers, resulting soil physical properties, and plant response data is required to effectively fast-track improved design. Results show however, a clear lack of significant correlation between soil physical properties and plant establishment and growth. . Modelling plant response data to soil physical property changes of this

research was therefore not possible, although results show improved crop emergence clearly can lead to significant grain yield improvement. In light of this difficulty, a simple matrix of crop establishment response to different soil moisture and temperature conditions and soil opener design was developed (Table 7.1). The matrix is simply a summary of research data from Chapters 4 to 6, considering both crop establishment and growth factors.

Table 7.1 Plant establishment response to spear soil opener design factors at Roseworthy/ Stanley Flat and Yacka under wet (water content θ ($m_w m_s^{-1}$) > 0.28) or dry (water content θ ($m_w m_s^{-1}$) $0.15-0.20$) soil, and warm to cool ($>10^\circ C$) or cold ($<10^\circ C$) soil temperature at 100 mm.

Soil opener design parameter	Roseworthy/ Stanley Flat				Yacka			
	Wet soil		Dry soil		Wet soil		Dry soil	
	Cold	Warm to cold	Cold	Warm to cold	Cold	Warm to cold	Cold	Warm to cold
Sharp	Good	Good	Good	Good	Good	Poor	Good	Good
Blunt	Poor	Poor	Good	Good	Good	Good	Poor	Poor
Flat	Poor	Poor	No data	Good	Good	Poor	No data	Poor
Narrow (<40 mm)	No data	No data	Poor	No data	No data	No data	Poor	No data
Blunt/flat	Poor	Good	No data	Good	Good	Good	No data	Poor

The matrix in Table 7.1 highlights the importance of a sharp soil opener for optimum plant establishment. The matrix also highlights the contrasting effect of blunt and flat openers in the Yacka and Roseworthy/ Stanley Flat soils. Soil opener design features were not a critical factor in dry establishment conditions at Roseworthy and Stanley Flat, nor in wet establishment conditions at Yacka. This is likely due to the compressive behavior of these soils, which is highlighted by the triaxial soil test results from Roseworthy and Yacka (Appendices 10.3.1 and 10.3.2).

More extensive comparative field testing in a wider range of soil types under a variety of establishment conditions would improve and generate greater confidence in this response matrix. Greater manufacturer and farmer confidence in the performance of a particular seed drill soil opener can only be obtained from wider testing and/or monitoring of commercial experience.

No significant correlation was found in this research between penetration energy below the seed and crop emergence and growth. At no point in this research, did penetration resistance 30 mm below the seed zone exceed 3 Mpa, except in dry establishment conditions at Yacka in 1994 (Chapter 4). Penetration resistance at the same depth during the first days of emergence did not exceed 1.5 Mpa in any experiment, except dry establishment conditions in the Stanley Flat and Yacka soil bin and core experiments in 1996 (Chapter 6). It is likely, as suggested by Bengough and Mullins (1990), that the penetrometer data collected, although significant, may have overestimated any potential direct effect leading to plant emergence and growth differences. Based on the literature on optimal penetration resistance for crop establishment and growth in Chapter 2, the conditions predisposing reduced root growth in the soils considered in this research, would be likely to be only found in extreme conditions of low soil moisture resulting in very high soil strength.

Shahidi (1996), concurrently undertook related research to this subject during the progress of this research. He adopted a similar approach to the research outlined in this thesis, but had a greater magnitude of change in soil opener shape, both in terms of opener width (18 mm or an additional width to 40 mm wide as an inverted-T type opener), depth (0 mm or 50 mm cultivation depth below the seed) and rake angle (45°

or 90° to the direction of travel). His work did show some effects of shape on soil physical properties and he also used more physical parameters to characterise the seed-bed. However, he also showed that a wide range in the values of various physical properties did not have a dramatic influence on wheat emergence or growth.

It is possible that the soil physical properties measured as a result of the various soil openers, had a significant effect on soil water availability to the plant as suggested by the research of Prebble (1970), Eavis (1972), and Taylor and Box (1961). Continuous measurement of water availability in the seed furrow was not done in this research, only water content was directly measured. It is also likely that compaction by soil openers may have significantly affected water flux in the small region of the soil matrix below the seed, as suggested in Chapter 6. In hindsight, greater consideration of these effects should have been made in this research as described by Bristow *et al.* (1995). Unfortunately, continuous measurement of soil suction and soil temperature during establishment in this research was not done. Collection of this data is not really a practical option except under very limited and restricted conditions. It would be very difficult to collect this data in a replicated field or green-house experiment as used in this research. It is possible that continuous soil suction and temperature data could be collected in a very small experiment in future research using technology described by Weaich *et al.* (1994). Reduction in soil bulk density of the soil bin experiments in Chapter 6 probably contributed to increased seed-bed tilth for these experiments, and this could also be considered a factor in the establishment response matrix in Table 7.1. This soil bin study should be considered as an experiment with a lower soil bulk density, rather than a flawed experiment. It is clear that the subject of this research is complex, and simple explanation of these results is unrealistic and

could possibly be misleading. The interaction of the soil opener and the process of soil crusting or hardsetting, particularly under conditions of rapid drying should perhaps been of greater focus in this research. Research by Gusli *et al.* (1994a and 1994b) on the impact of the wetting and drying process on a hard setting soil foreshadowed the impact of these events on soil strength.

7.4 An ideal spear type soil opener

Spear type opener width and sharpness of the leading edge had a significant impact on crop establishment and growth. The research reported in Chapters 3 and 4 concluded that wide and sharp type spear openers should be used in preference to narrow and blunt spear openers on the red-brown earths used in these experiments. Use of sharp spear openers may significantly increase grain yield compared with blunt or flat spear openers in dry establishment conditions on a non-compactable poorly structured soil. Sharp spear soil openers may result in increasing grain yield by greater than 8.2% as found in Chapter 5. Seeding on a compactable soil such as Roseworthy, at water contents greater than the plastic limit, may reduce grain yield by up to 20% with a blunt or flat spear opener compared to a sharp spear opener. Although this is limited data, this research indicates that some degree of grain yield benefit can be obtained from the use of sharp spear soil openers on a red-brown earth.

Research reported in Chapter 5 showed that soil opener shape factors such as a flat underside and a blunt leading edge increased penetration resistance and penetration energy because of increased soil bulk density. This can lead to a reduction in total plant emergence. These changes in soil opener shape lead to a significant reduction in

plant emergence, which correlated significantly with grain yield on the compactable red-brown earth at Roseworthy.

It is interesting to note that the early seeding technology developed 5000 years ago essentially has what appears to be a sharp spear type soil opener (Figure 1.1). In considering this, it has to be questioned how far research into seeding technology has been taken.

7.5 Implications for the manufacturing industry

The development of soil opener design is complicated by factors such as manufacturing costs, range of soils for operational use, and a lack of clear correlation between soil physical property measurements and plant response data. Variable factors such as the influence of water content on soil strength, soil suction, and soil temperature, compound the difficulty in determining clear guidelines for optimum soil opener design for seeding.

In light of these comments, soil opener manufacturers targeting red-brown earths should have an aim of manufacturing soil openers that are as sharp as possible. Poor seed placement has been clearly drawn out as a significant factor in reduced soil opener performance. Seed delivery tubes should be integrated with the soil opener design to optimise seed placement.

Tungsten carbide should be mounted in such a way as to prevent creation of a soil cone in response to a blunt leading edge, leading to soil compaction effects below the opener as described by Payne (1956), and Willatt and Willis (1965). Tungsten

carbide can also be manufactured in many complex shapes and sizes, enabling novel methods of attachment and manufacture of a sharp leading edge. Yield improvements found in this research provide a significant justification towards increased investment in the initial cost of manufacturing a soil opener. However, given the other benefits of no-tillage seeding systems using narrow points such as soil conservation and options for deeper tillage and fertiliser banding in one pass achieving labour and cost savings, it is not imperative that they surpass traditional seeding technology in grain yield also.

7.6 Implications for the farming industry

The farming industry principally requires a soil opener on a seed drill that will outlast an entire season of seeding operations. This can determine the choice of soil opener, sometimes foregoing establishment performance opportunity for wear life. The additional factors of cost, draft force requirement, longevity in abnormally stony soils and crop establishment performance in high surface residue all contribute toward a farmers choice of soil opener.

As discussed in the literature review, introduction of tungsten carbide in the manufacture of soil openers has had a significant impact on wear life. This research has implications for farmers in two ways. Firstly, improved integrity of soil opener shape during soil opener wear life would suggest that soil opener performance in terms of crop establishment and growth should be maintained at optimum performance for much longer. Secondly, a soil opener manufactured with a sharp tungsten carbide tip can significantly improve crop establishment in at least some years on a red-brown earth. In contrast, a blunt manufactured tip or an opener

wearing to a flat underside may retard establishment as found by Rainbow and Stevens (1995). This provides justification for additional expenditure and/ or labor cost for replacement of seed drill soil openers, particularly under establishment conditions which would produce poor establishment results as outlined in Table 7.1. For example, a farmer on a well-structured compressible soil would achieve significant production and economic benefits by simply replacing flat worn or blunt openers with sharp openers if cool wet establishment conditions prevail.

This research has provided some answers to very fundamental questions being asked by the farming industry. The fundamental philosophy that a sharp soil opener would be preferable to a blunt soil opener to optimise crop establishment and grain yield would on the surface seem to have a simple answer. This research however has given significant grounds for this philosophy based more widely than just for the benefit of reducing draft force requirements, but that there may also be benefits to crop establishment and grain yield.

The research has addressed objectives (i) to (iv) as outlined in the introduction, but has only been able to define a simple matrix of spear soil opener design parameters in addressing objective (v) to maximize wheat plant establishment, growth and grain yield on a red-brown earth.

As a result of this research, the manufacturing industry has much more detailed and precise information on which to design improved soil openers for seeding. Principles that farmers should consider include:

- (i) Ensuring that seedbed penetration resistance is < 1.5 Mpa.
- (ii) Simply ensuring that sharp soil openers are used in cold wet seeding conditions ($< 10^\circ$ C, water content θ ($m_w m_s^{-1}$) > 0.28).

In addition, farmers adopting no till farming can do so with the confidence that crop establishment and grain yield need not suffer, indeed may even improve, if these principles are followed.

8. CONCLUSIONS

Based on this research, it is now clear, that the effect of opener shape on emergence and early growth is not an immediate event. Rather it is a long-term effect on soil properties such as development of tillage pans and changes in structural stability. Even then, the system requires catastrophic events such as high temperatures combined with soil desiccation (drought) or heavy rainfall (flooding). These conditions will produce anoxic conditions or develop surface crusting or hardsetting to stress seedlings to the point where the fine physical distinctions created by tillage come into play to determine survival or sufficient growth to draw one set of conditions ahead of others. In the experiments reported in this research, these conditions did not develop or developed only slightly. Where these slight perturbations developed, some resulting effects were found, although muted. This suggests that future work should look at the effect of various soil openers in more extreme conditions, where the systems are taxed more heavily. In light of these conclusions, the cast spear type opener has performed extremely well in testing of different generic seed drill opener types and seeding machine configurations as long as adequate soil tilth is present at seeding and plant emergence, or created by additional deep cultivation during the seeding process.

Spear type opener width and sharpness of the leading edge resulted in a significant impact on crop establishment and growth in the soil and moisture conditions used in this research. This research suggests that wide sharp type spear openers should be used in preference to narrow blunt spear openers on the red-brown earths of southern Australia. Use of sharp spear openers may result in significantly increased grain yield

compared with blunt spear openers if soil smear occurs. Seed row aligned deeper cultivation has a significant effect of reducing soil penetration resistance, however resulting crop establishment growth and grain yield response is more greatly influenced by shape of the following opener placing seed and fertiliser.

Grain yield results from direct drilled experiments in this study on well structured red-brown earth soils, indicate significant yield improvements can be achieved with spear type soil openers and press wheels in comparison with openers and covering devices such as finger tine harrows that most farmers currently use in their seeding programs. This is in addition to reduced soil disturbance from spear points in comparison to some other opener types. Use of a spear type soil opener and press wheels when used on a 3 rank tine spacing, would provide significant improvement to trash handling, crop establishment and grain yield, compared to a current farming industry standard of a full cut 6 rank seeder with 125 mm wide shares and trash finger tine harrows.

The research philosophy implicit in this thesis is that a narrow range of soil openers (narrow in the sense that design features were very similar), will have different effects on soil physical properties in the immediate seed-bed created by the opener. These research results have shown that is not the case given the sophistication and accuracy of the measurements performed.

Given the level of experimentation chosen in this research, using both field and large soil monolith experiments, the very best efforts were made to characterise the various resulting soil physical properties and their impact on plant establishment and growth, both under normal and abnormal seed bed temperature and soil moisture conditions.

For this reason, the results, limited as they were, stand as a further contribution towards the development of improved soil openers for use in the seeding of field crops.

9. RECOMMENDATIONS FOR FURTHER WORK

More extensive comparative field testing in a wider range of soil types under a variety of establishment conditions would improve and generate greater confidence in the response matrix developed from this research in Chapter 7. Greater manufacturer and farmer confidence in the performance of a particular seed drill soil opener can only be obtained from wider testing and/or monitoring of commercial experience.

Greater differentiation of resulting soil opener effects under ideal seeding conditions would be found in future research if the magnitude of soil opener design differences were larger than those contained in this research, such as width and angle of soil entry. Resulting effects of small design changes in future soil opener research, in particular cutting edge effects, are more likely to be found in the extremes of temperature and soil water in the seed-bed.

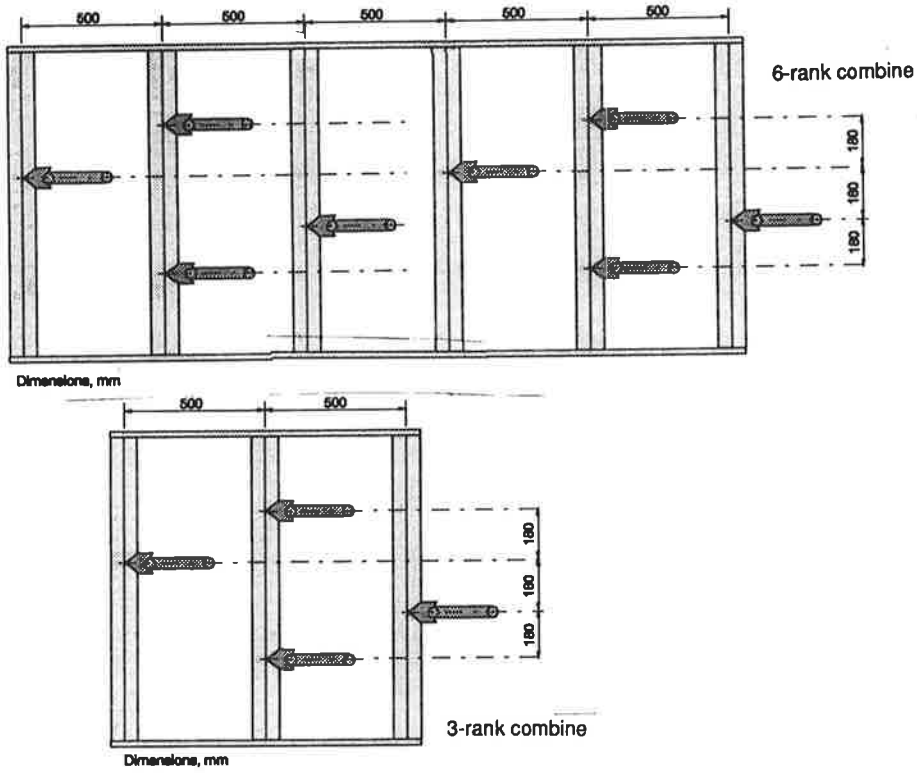
This research highlighted benefits from the use of triaxial testing of the soils in explaining their behaviour in reaction to a soil opener. The calculation of the angle of internal friction and cohesion factors is essential to enable the prediction of soil failure patterns of an opener to be made when modelling soil response data. As it is also likely that compaction by soil openers may have significantly affected water flux in the small region of the soil matrix below the seed. It is possible that continuous soil matric suction and temperature data could be collected in a very small experiment in future research of this type.

The use of the soil bin experimental methodology should be used in future studies of this type as it is a cost effective and efficient method of early crop establishment measurement. Future work should be carried out in controlled temperature and light environments to more effectively simulate Australian winter sowing conditions. The use of the micro-cone penetrometers and image analysis software was a very effective method of data collection as was the root measurement methods as used in Chapter 6. Future research into the impact of soil opener effects on soil smear should concentrate on cold wet seedbed conditions. There is opportunity to expand this work into soils of higher clay content than the red-brown earths included in this study.

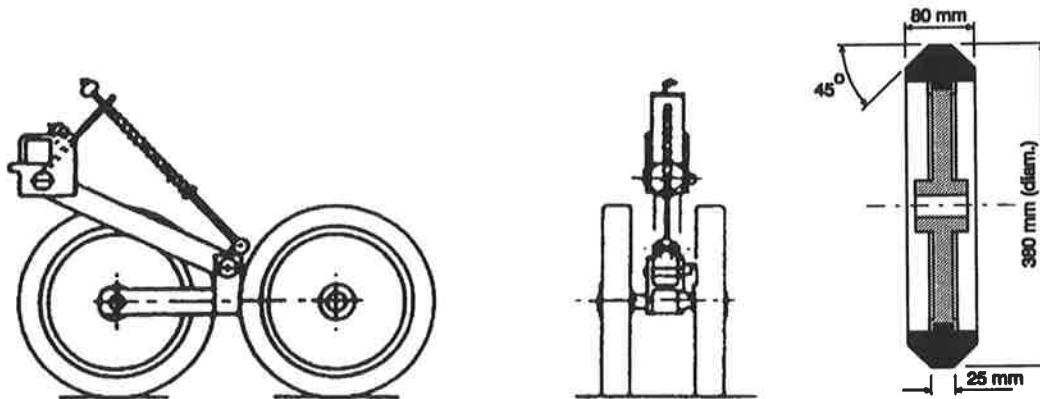
10. APPENDICES

Appendix 10.1 Seeding equipment

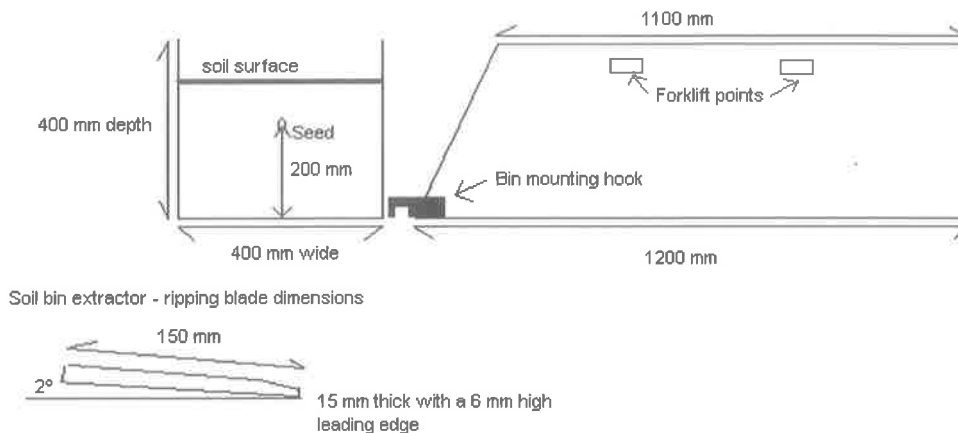
A10.1.1 Tine layouts used in spear seeding type seed drill soil opener experiments.



A 10.1.2 Solid rubber Manutec 80 mm wide banked press wheel and walking type frame used in spear type seeding point experiments.



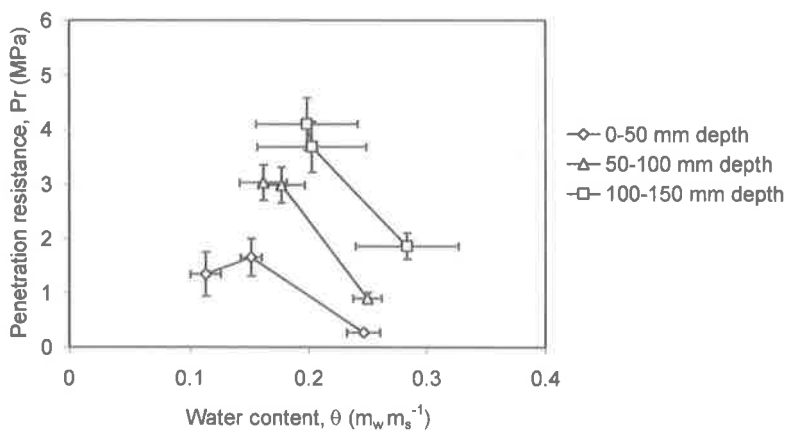
A10.1.3 Soil bin and extraction unit dimensions.



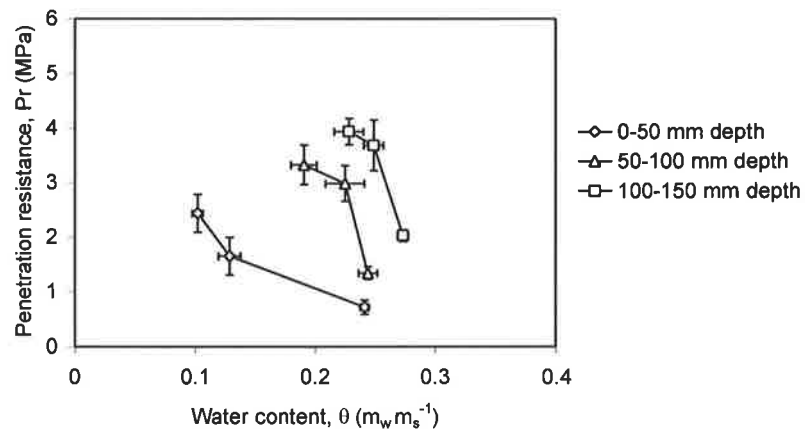
Appendix 10.2 Soil penetrometer resistance with soil water content change.

Uncultivated soil of the experimental sites were watered with 100 mm rainfall equivalent using tap water in 4 locations contained by the soil cores described in chapters 5 and 6. Penetrometer recordings and soil water content were recorded at 3 weekly intervals using the methods described in chapter 4.

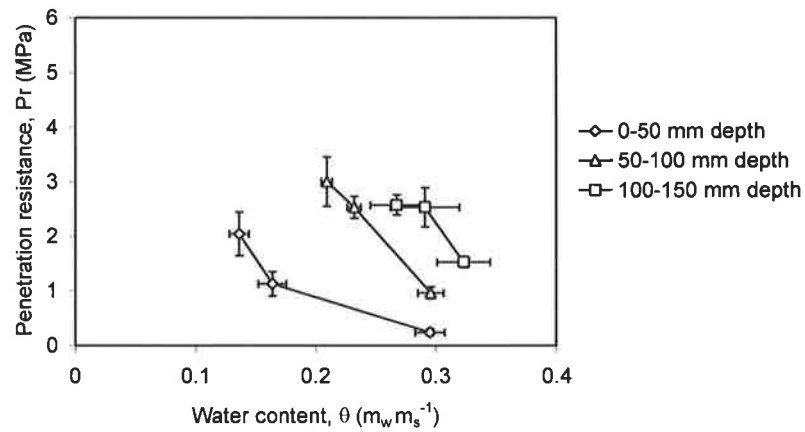
A 10.2.1a Roseworthy soil penetrometer resistance with soil water content change 1994.



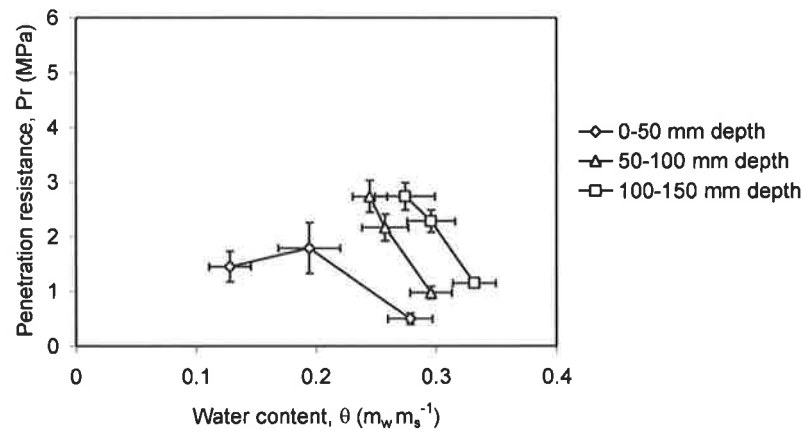
A 10.2.1b Roseworthy soil penetrometer resistance with soil water content change 1995.



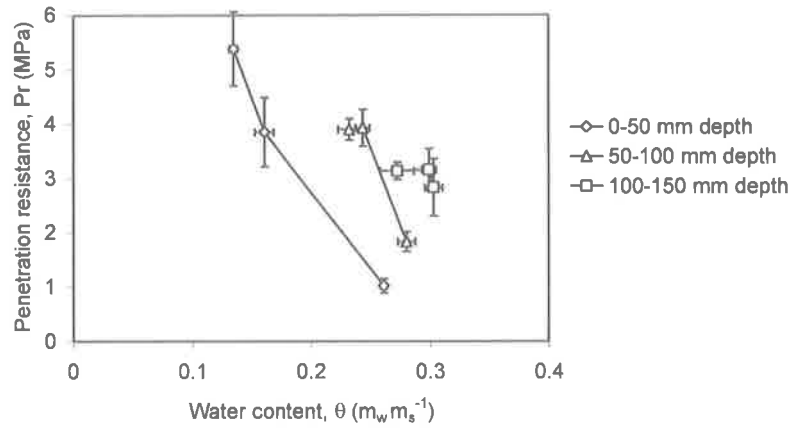
A 10.2.2a Yacka soil penetrometer resistance with soil water content change 1994.



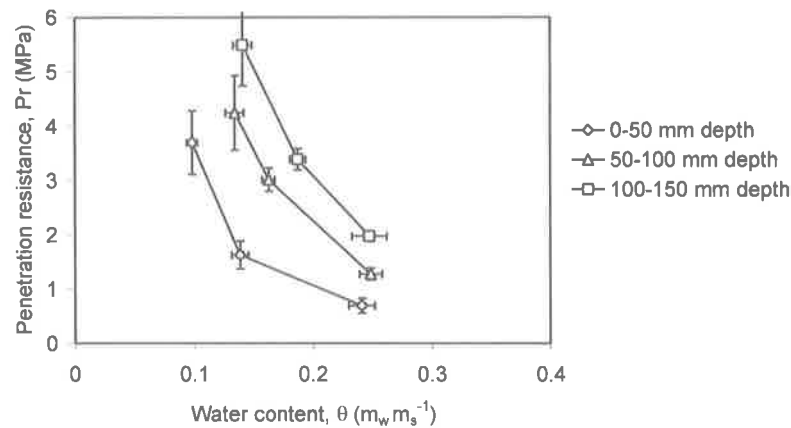
A 10.2.2b Yacka soil penetrometer resistance with soil water content change 1995.



A 10.2.2c Yacka soil penetrometer resistance with soil water content change 1996.



A 10.2.3 Stanley Flat soil penetrometer resistance with soil water content change 1996.

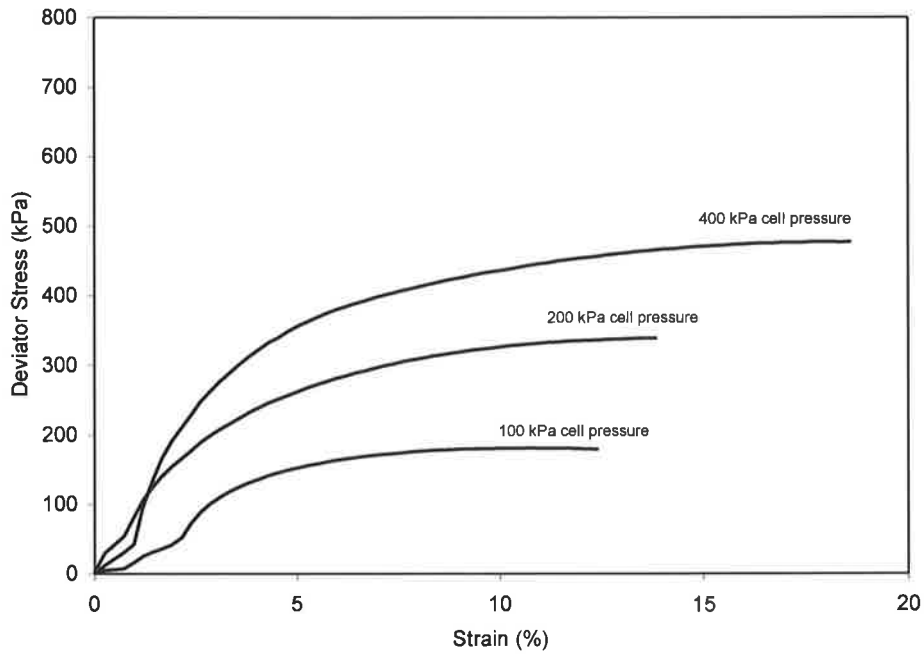


Appendix 10.3 Triaxial compression tests

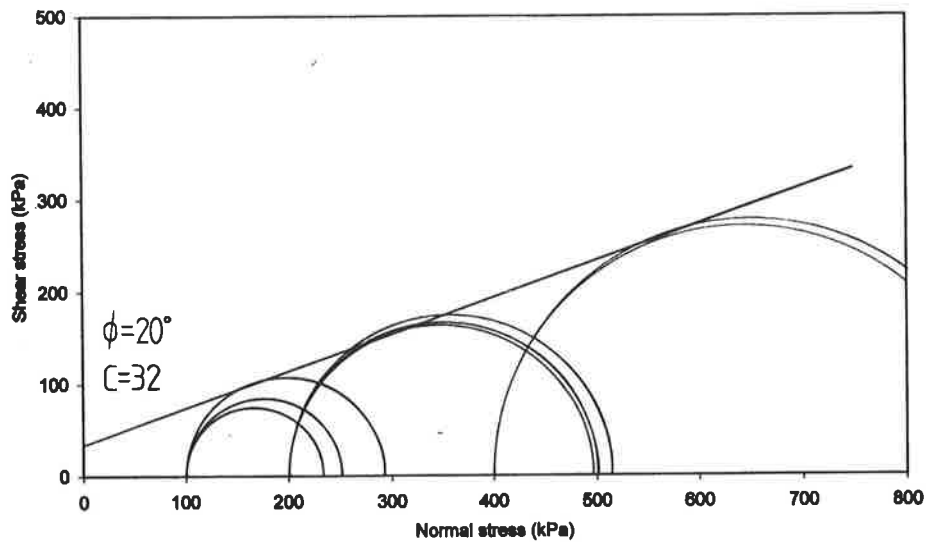
Triaxial compression tests were performed on un-worked soil of the Roseworthy and Yacka 1994 sites with dry soil cores 46 mm \varnothing of 105 mm length. Water content was increased with addition of a measured dose of tap water of 20 ml and 40 ml to obtain moist and wet soil respectively. The tests were conducted with automated ELETM triaxial test equipment according to AS 1289.F4.1-1977 “Determination of compressive strength of a specimen tested in undrained triaxial compression without measurement of pore water pressure” (Anon, 1977). Measurements were repeated 2 times, or repeated a

3rd time if results appeared inconsistent. Deviator stress versus strain curves generated from the triaxial tests was used to calculate the soil cohesion (C) and angle of internal friction (ϕ) using Mohr's circles with the line of best fit fitted by eye.

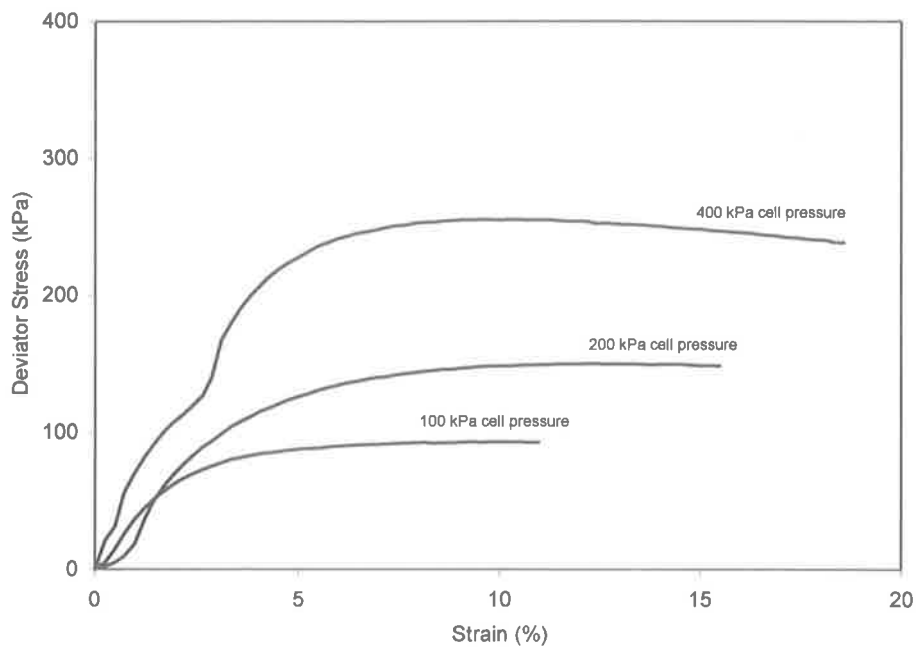
A 10.3.1 Typical deviator stress vs strain curves for Roseworthy 1994 soil, water content θ ($m_w m_s^{-1}$) = 0.21.



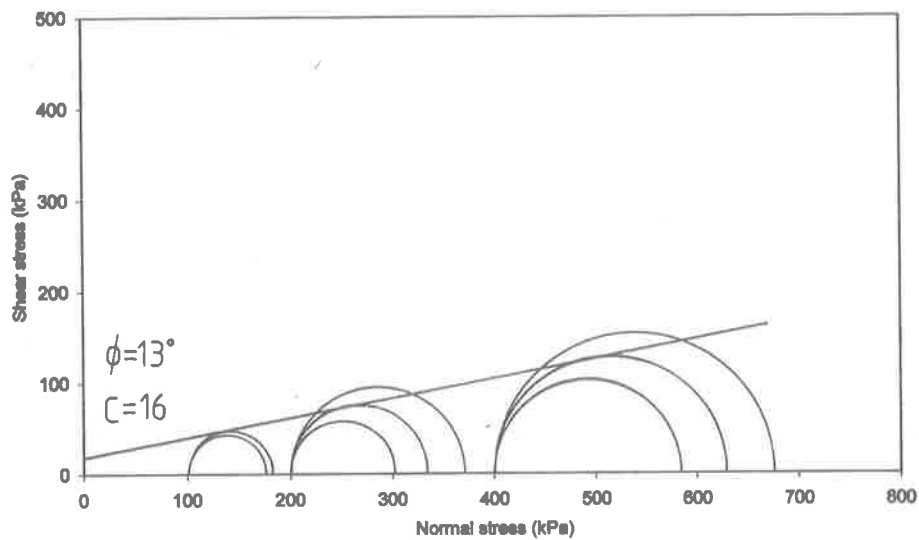
A 10.3.2 Diagram of Mohr's circles for triaxial compression of Roseworthy 1994 soil, water content θ ($m_w m_s^{-1}$) = 0.21.



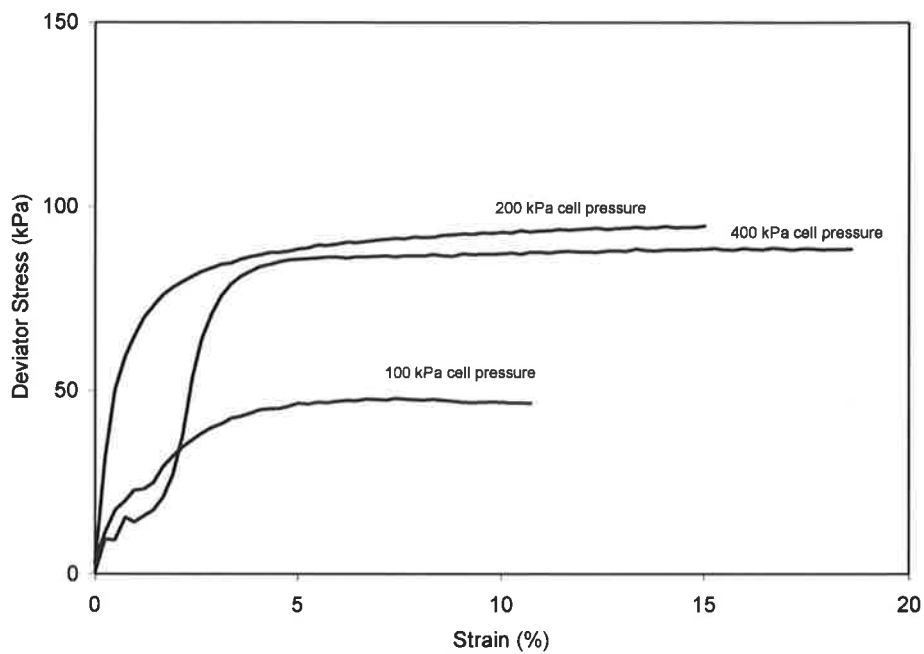
A 10.3.3 Typical deviator stress vs strain curves for Roseworthy 1994 soil, water content θ ($m_w m_s^{-1}$) = 0.37.



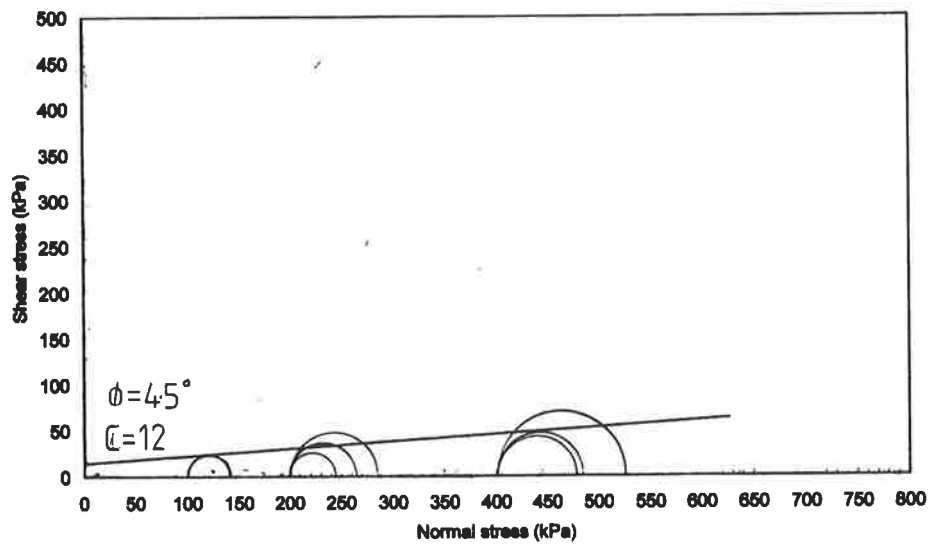
A 10.3.4 Diagram of Mohr's circles for triaxial compression of Roseworthy 1994 soil, water content θ ($m_w m_s^{-1}$) = 0.37.



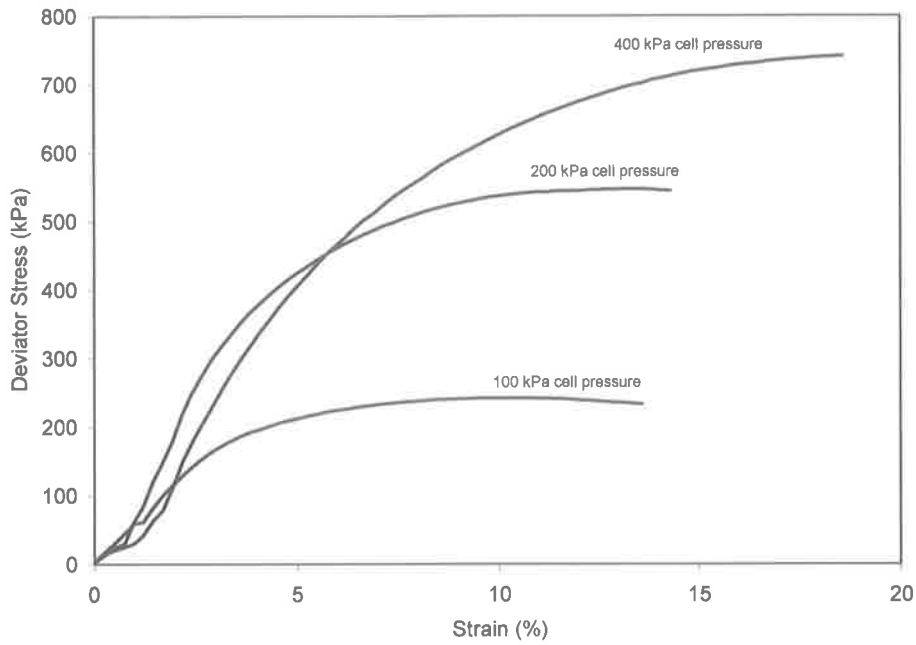
A 10.3.5 Typical deviator stress vs strain curves for Roseworthy 1994 soil, water content θ ($m_w m_s^{-1}$) = 0.49.



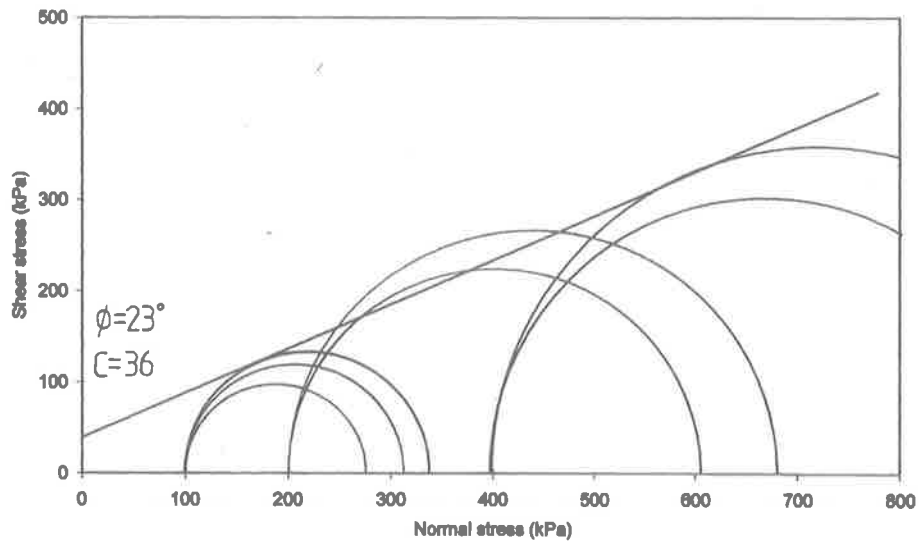
A 10.3.6 Diagram of Mohr's circles for triaxial compression of Roseworthy 1994 soil, water content θ ($m_w m_s^{-1}$) = 0.49.



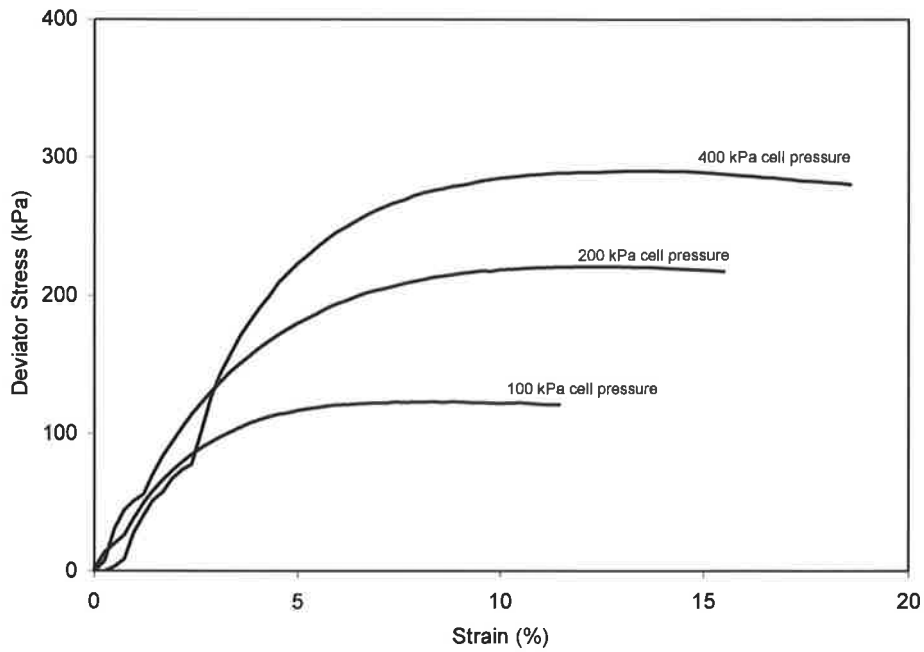
A 10.3.7 Typical deviator stress vs strain curves for Yacka 1994 soil, water content θ ($m_w m_s^{-1}$) = 0.18.



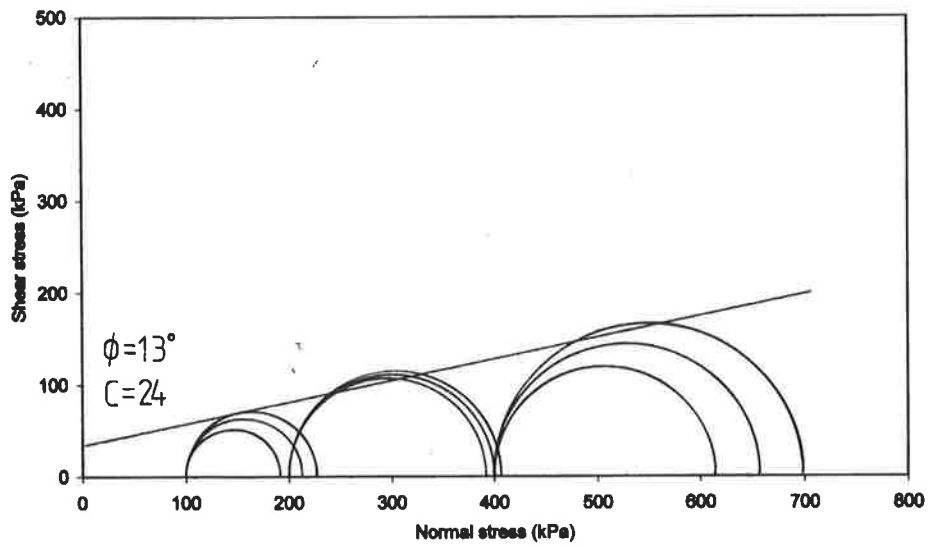
A 10.3.8 Diagram of Mohr's circles for triaxial compression of Yacka 1994 soil, water content θ ($m_w m_s^{-1}$) = 0.18.



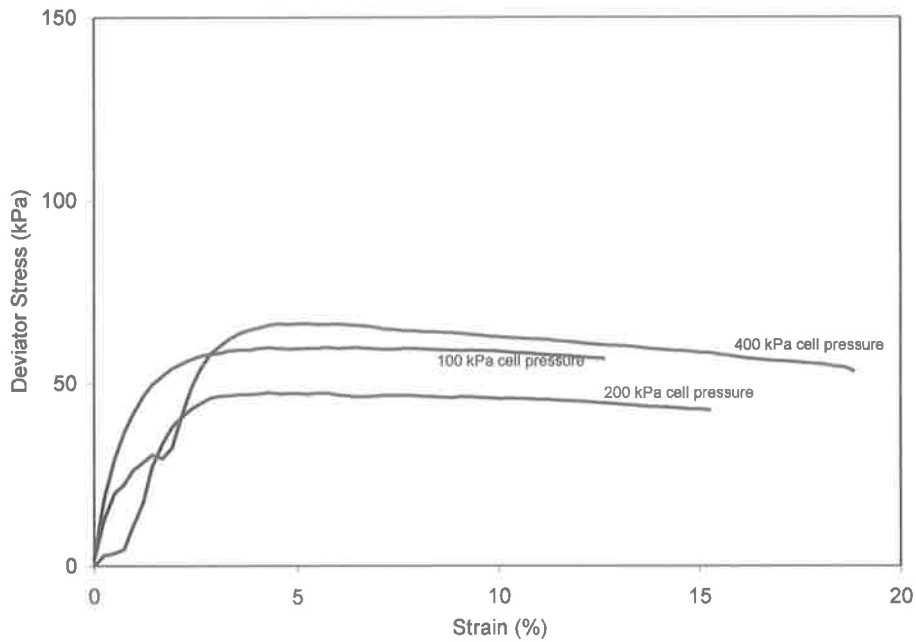
A 10.3.9 Typical deviator stress vs strain curves for Yacka 1994 soil, water content θ ($m_w m_s^{-1}$) = 0.29.



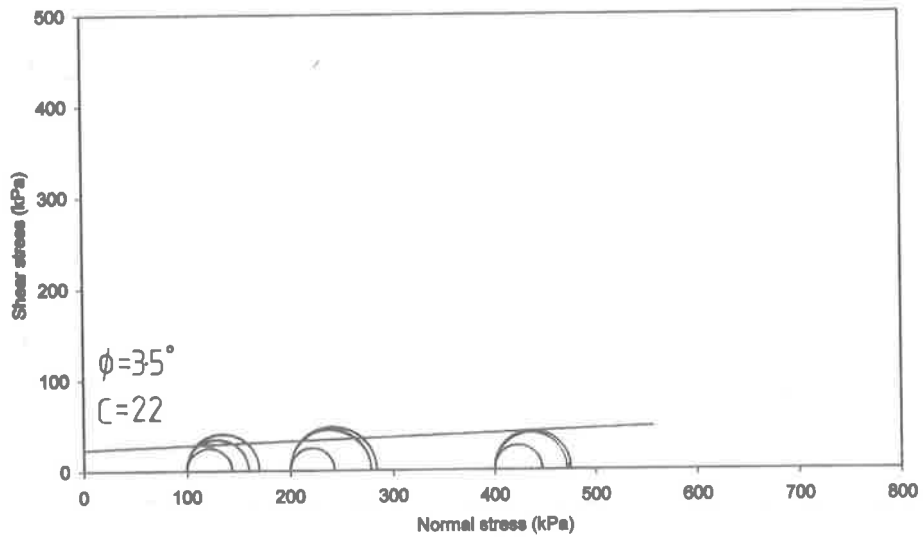
A 10.3.10 Diagram of Mohr's circles for triaxial compression of Yacka 1994 soil, water content θ ($m_w m_s^{-1}$) = 0.29.



A 10.3.11 Typical deviator stress vs strain curves for Yacka 1994 soil, water content θ ($m_w m_s^{-1}$) = 0.43.

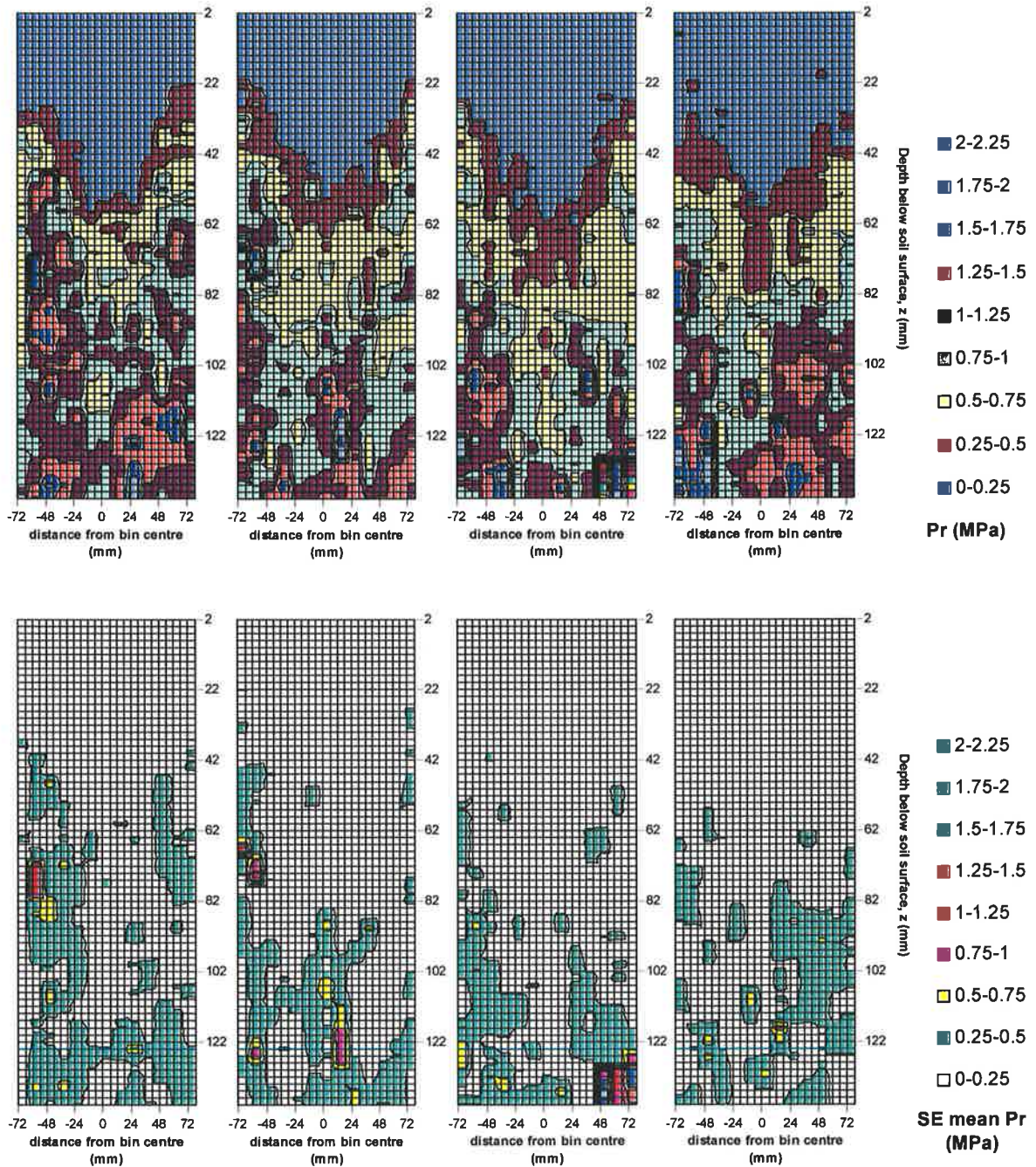


A 10.3.12 Diagram of Mohr's circles for triaxial compression of Yacka 1994 soil, water content θ ($m_w m_s^{-1}$) = 0.43.

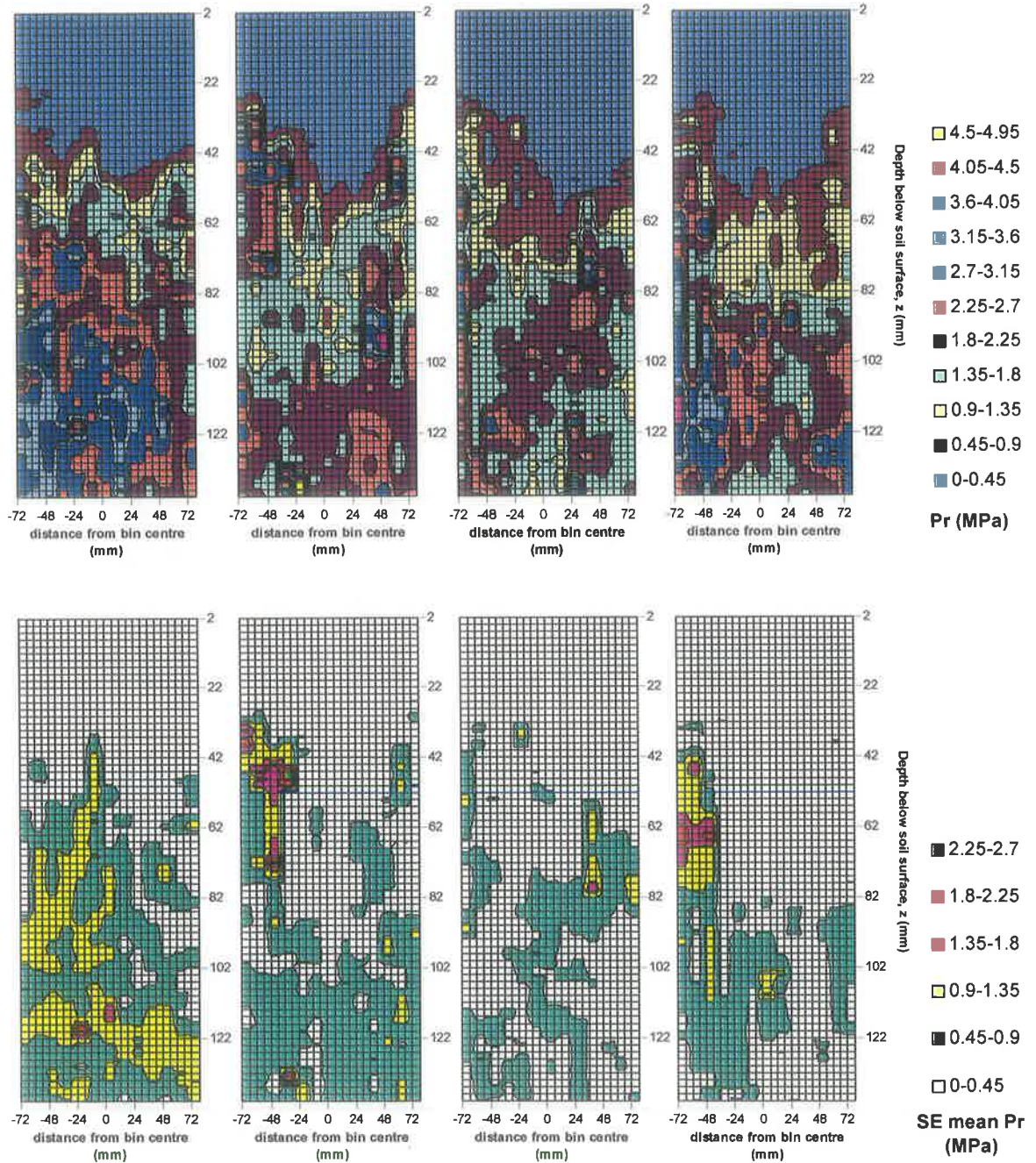


Appendix 10.4 Chapter 6 complete soil bin and soil core penetrometer recordings and standard error measurements 1996

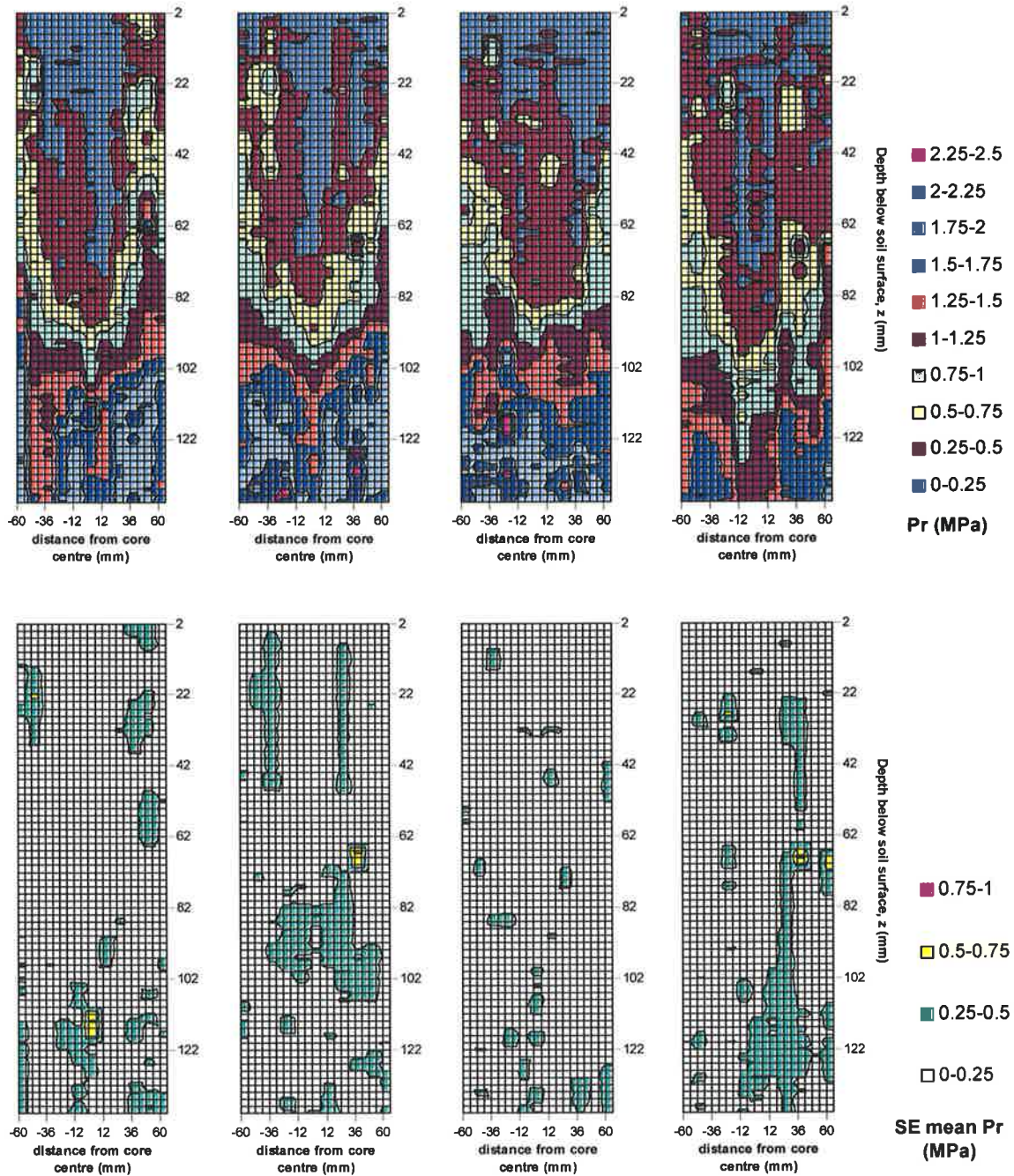
A10.4.1 Spear opener (left to right; (i) blunt flat spear, (ii) flat spear, (iii) blunt spear, (iv) sharp spear) effect on penetrometer resistance (Pr) of a 2 mm cone in Stanley Flat soil bins in wet establishment conditions (top) and standard error of mean (SE mean) Pr results (bottom).



A10.4.2 Spear opener (left to right; (i) blunt flat spear, (ii) flat spear, (iii) blunt spear, (iv) sharp spear) effect on penetrometer resistance (Pr) of a 2 mm cone in Stanley Flat soil bins in dry establishment conditions (top) and standard error of mean (SE mean) Pr results (bottom).



A10.4.3 Spear opener (left to right; (i) blunt flat spear, (ii) flat spear, (iii) blunt spear, (iv) sharp spear) effect on penetrometer resistance (Pr) of a 2 mm cone in Yacka soil cores in wet establishment conditions (top) and standard error of mean (SE mean) Pr results (bottom).



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