THE EFFECTS OF NO-TILLAGE AND SUBSOIL LOOSENING ON SOIL PHYSICAL PROPERTIES

AND

CROP PERFORMANCE

A thesis presented in partial fulfilment of the requirements
for the degree of
Master of Applied Science in Soil Science
at Massey University

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1998

ABSTRACT

Much of New Zealand's lowland agriculture integrates animal and crop production on poorly drained, easily compacted soils. Over the years, conventional cultivation has given rise to degraded soil structure on many farms. No-tillage has been shown to avoid many of these problems but the question remains: "Where soils are compact, what combination of deep tillage and/or drainage systems and no-tillage allow for the most efficient transition from conventional cultivation to no-tillage crop establishment?" The objective of this study was to ascertain if soil properties, and crop (*Brassica campestis* x *Brassica napus* cv "Pasja" followed by wheat *Triticum aestivum* cv "Kohika") establishment and yield on land converted from a conventionally tilled system to a no-tillage system could be improved by various subsoiling and mole plough operations. Plots on a Milson silt loam (Argillic Perch-Gley Pallic Soil) (Typic Ochraqualf) were paraplowed (PP), straight-legged subsoiled (SL), mole ploughed (M) or were left as non-subsoiled controls (C) in the autumn of 1997. Forage brassica was then sown with a Cross-Slot™ no-tillage drill. Wheat was established on the same plots with the same no-tillage drill in the spring of 1997.

Subsoiling initially reduced soil strength by a significant amount. Shortly after subsoiling cone indices showed disruption to 300 mm with PP, 350 mm with SL and 100 mm with M. At the same time, approximately 20% of profile cone indices from subsoiled treatments were greater than 2 MPa, compared to approximately 52% for C and M. At 267 days after subsoiling, PP continued to have lower cone index values than C and M.

Subsoiling initially reduced bulk density. When measured in May, the bulk density of PP plots was significantly lower than SL, M and C although reconsolidation in all plots was observed in February 1998 after the wheat was harvested. Air permeability in PP, SL and M was significantly greater than in C.

Despite the differences in soil strength and bulk density (but not air permeability), subsoiling and mole ploughing did not produce differences in plant populations or yield for either the winter brassica or spring-sown wheat crops. The lack of any differences for brassica crop performance criteria were in spite of the vertical rooting depth being greater in the PP treatment. The lack of differences in plant establishment and yield was thought to be due to the relatively dry autumn and winter soil conditions and the use of the Cross-Slot™ no-tillage opener which is reported to be tolerant of variable soil conditions.

ACKNOWLEDGEMENTS

I would like to extend my sincerest appreciation to my supervisors, Dr D.J. (Dave) Horne, Dr C.W. (Craig) Ross of Manaaki Whenua Landcare Research and Dr C.J. (John) Baker of Baker No-Tillage. Throughout this project all have been extremely supportive and encouraging and have inspired me to undertake this study. Professor Russ Tillman of the Soil Science Department has shown understanding in my desire to undertake higher level study while balancing my employment and career commitments.

Bill and Sharon Ritchie have been close friends for some time and their professional and personal support is gratefully appreciated.

My thanks are also extended to Ross and Helen Maxwell for providing access to both their property and machinery, and for motivational cups of coffee during the bleak winter months. Gavin Milne of Grassline® has made significant contributions to the development of this project and provided flexibility in my hours of employment which greatly assisted my study programme and the compilation of this document. Financial support from AgResearch Grasslands and the Foundation for Arable Research is gratefully acknowledged.

In the field related aspects of this study, the technical expertise of John Dando of Landcare Research has been invaluable.

Noel Humm of AgResearch Grasslands has played a significant role in editing and proof-reading this document. I am extremely grateful for his patience and keen eye for mistakes. Similarly to Joanne Morris for her gracious help with the numerous computer-related problems that arose during this study.

Anthony Smith has freely provided constructive criticism while the manuscript was being prepared and our enduring friendship continues.

Peter and Beverley Brock have both been guiding influences on my life. Their calm counsel and advice have provided me with the motivation to succeed and enjoy life despite the pitfalls that may occur from time to time.

Finally, I sincerely thank my parents, Trevor and Avis and my brother Adrian for their love, support and encouragement and dedicate this work to them.

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1. INTRODUCTION

Soil compaction has reduced crop yields in countries around the world, including the USA (Adams *et al.* 1960; West *et al.*, 1996), Canada (Raghaven *et al.*, 1979; Carter *et al.*, 1996), Australia (Delroy and Bowen, 1976) and New Zealand (Greenwood and Cameron, 1990; Harrison *et al.*, 1994; Sojka *et al.*, 1997). Soils may be compacted by both natural and human-induced processes. Natural processes, such as consolidation and shrinkage, which are largely dependant on moisture regimes, can result in surface crusts, subsurface compaction and pans (Hillel, 1980). In a fine textured soil, the subsoil is often naturally compact and may limit plant growth.

Controllable compactive processes consist largely of trampling, wheel traffic and tillage. Vehicle and implement traffic is considered to be the main source of compaction in arable agriculture with its use of heavy field equipment such as tractors, harvesters and transport equipment. Untimely operation of machinery (*i.e.* when soil moisture corresponds to the plastic state) can deteriorate aggregate stability and give rise to soil compaction. Arguably, the most harmful practice to soil structure is tillage.

Until recently, tillage with mouldboard ploughs and subsequent secondary operations was the only realistic option for farmers seeking to establish new pastures and crops. Such tillage relies on repeated passes with tyned and/or powered machinery to create a suitable seedbed for crop establishment. In so doing, soil aggregates are disintegrated, not shattered and re-arranged along natural lines of cleavage as they would normally be through natural processes (Baker *et al.*, 1996). Such massive aggregate reorientation occurs until ultimately a "plough pan" or compacted layer is formed. Plough pans occur at ploughing depth and result from repetitive smearing as the plough shares slide over the same surface year after year. Some plough pans are not even smeared but are simply a flat sheared surface (Culpin, 1992).

Recent developments in machinery, herbicides and management have re-established no-tillage as an alternative method for establishing crops. Despite its benefits, no-tillage has been identified by some authors (*e.g.* McLaren and Cameron, 1996) as leading to higher soil bulk densities and soil strength. Smaller root systems, and reduced crop vigour and yield, have been observed with no-tillage when compared with crops established by tillage (Baker *et al.*, 1996). It should be noted, however, that the former observations have been reported in soils that have already lost much of their structure through repetitive and untimely tillage. In this case short-term amelioration of soil structure may be necessary until the natural processes by which soil structure is repaired can predominate. Such processes are encouraged by no-tillage. Some authors (*e.g.* Evans *et al.*, 1996) have illustrated the need for deep loosening to alleviate compaction and improve the agronomic performance of crops or pastures established without cultivation. This observation is especially pertinent in finely-textured soils that have been subject to intensive tillage and its inherent problems.

Increased awareness of the problems associated with subsoil compaction has generated widespread interest in subsoiling as this technique has been reported to provide short-term benefits in soil physical properties. A range of subsoiling implements are available for commercial use and include straight-legged subsoilers, slant-legged subsoilers and mole ploughs. While all three types of implement perform some degree of soil loosening and shattering, the latter design has the primary function of drainage and is commonly used in conjunction with subsurface pipe or tile drainage systems. Authors including Evans *et al.*, (1996) and Sojka *et al.*, (1997) have reported subsoiling effects under tilled treatments but none have previously concentrated solely on no-tillage.

The hypothesis tested here was that subsoiling and moling, in combination with no-tillage would improve soil conditions and increase crop yield.

2. REVIEW OF THE LITERATURE

2.1 Introduction

Since the time seed was first planted the soil has been manipulated to create an environment that results in satisfactory seedling emergence and crop growth. Virgil (1991), writing in the last century before the Christian era, described the dual aims of the tillage methods which Julius Caesar brought to Britain: this involved weed destruction, followed by seedbed preparation. Subsequently, in 1794 when Thomas Jefferson, a farmer (and inventor) and later the third President of the United States of America, designed and tested a "Mouldboard plough of least resistance" he unwittingly ushered in the era of mechanised soil manipulation that proceeded, largely unchanged, to this present day.

It has long been recognised that conventional tillage is costly (Luttrell *et al.*, 1964), both in financial terms and in resultant damage to the irreplaceable soil resource through repeated, and often untimely, tillage and the soil-depleting ravages of erosion. Although Edward H. Faulkner levelled criticism at the plough in "Plowman's Folly" (1943), he received very little support from scientific circles. The agricultural sciences, however, seem unable to meet his challenge: "No-one has ever advanced a scientific reason for ploughing."

Research into chemically-assisted minimal tillage was initiated in the 1950s, predominantly by Imperial Chemical Industries[1] (ICI) (Boon, 1966) which discovered the bipyridyl herbicides Paraquat® and Diquat® (Allen, 1981). The later discovery by Monsanto of glyphosates further intensified the interest in no-tillage. No-tillage, as defined by Baker (1985a) is: "The drilling of seeds into an untilled seedbed with no competing vegetation, usually achieved by the removal of resident species with herbicide."

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[1] To further sales of bipyridyl, ICI commercialised the double disc no-tillage opener (*i.e.* "V-shaped" slot) which is still commonly used in many no-tillage applications.

With improvements in technology, notably in opener[2] design and operation, and management, the uptake of no-tillage has been rapid. In the United States alone, the area cropped by no-tillage has increased from 1.5% of the total cropped land area in 1973 (Phillips and Young, 1973) to 13.7% in 1993 (Lessiter, 1993). The primary reason for this increase in the use of no-tillage is the benefits of this technique for crop establishment and erosion control (Baker, 1985a; Sprague and Triplett, 1986).

This review is structured in five parts. The first part identifies the reported advantages and disadvantages of no-tillage directly related to this study. The second section focuses on the required opener design features capable of handling the unique conditions experienced in no-tillage crop or pasture establishment situations. The principles of soil compaction are reviewed in the third section, followed by an overview of subsoiling and its effects on soil physical and hydrological properties. The reported crop and pasture yield improvements from reducing compacted subsoil through deep mechanical loosening are reviewed in the fifth and final section.

2.2 Advantages and disadvantages of no-tillage

Excessive tillage is regarded internationally as a major cause of soil degradation. By way of contrast, no-tillage allows the retention of surface residues (Griffith *et al.*, 1992), reduces soil losses by erosion (Mannering and Fenster, 1983), improves soil structure (Ross and Hughes, 1985), enhances soil moisture retention (Phillips and Young, 1973), and increases both organic matter (Smettem *et al.*, 1992) and nutrient levels. The retention of surface residues is the primary reason behind both the advantages, and the disadvantages, of no-tillage (Baker *et al.*, 1996). Given their importance this section is viewed from the perspective of treating such residues as an asset rather than the "trash" to which they have colloquially, and quite incorrectly been referred.

Tillage has a significant impact on the amount of residue remaining on the soil surface: mouldboard plough-based systems traditionally leave minimal residue, however, significantly greater quantities of crop residue remain on the soil surface with no-tillage. Data from three years of a maize (*Zea mays*) residue experiment is

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[2] For the purpose of this document, the term opener is used to describe the soil-engaging component of a no-tillage drill or planter (often referred to as a coulter).

summarised in Table 1, where Griffith *et al*., (1992) recorded mean residue covers in no-tilled treatments that were over 11 times greater than tilled treatments.

Table 1: Effect of tillage on in-row maize residue cover (%).

	Residue cover (%)			
Tillage system	**1988**	**1989**	**1990**	**Mean**
No-till	75	55	82	71
Disc	38	16	20	25
Chisel	33	15	17	22
Mouldboard	4	2	8	6

(After Griffith *et al*., 1992)

2.2.1 Hydrological properties

Soil water storage is essential for continued plant growth and development between rainfall and/or irrigation events. Maintaining surface residue of 30% or greater (on a surface area basis) generally reduces soil moisture losses from evaporation and runoff. It also increases water infiltration, leading to more stored soil water, and little effect on transpiration rate (Phillips, 1984). As long ago as 1939, Bennet recognised the effects that surface residues have on conserving soil moisture, stating that: "Trash (sic) and crop residues on the surface check runoff and allow more water to be absorbed by the soil". Further work by Unger and Parker (1968) and Phillips and Young (1973) validated the conclusion of Bennet (*loc. cit.*). The use of no-tillage to increase residue cover also enhances soil water reserves by maintaining the natural pore system (Table 2) by protecting unstable soil from rain impact.

Table 2: Effect of tillage on surface residue and water storage.

Treatment	**Residue cover (%)**	**Water stored (% of bare fallow)**
No-till	78	130
Stubble mulch	38	123
Bare fallow	5	100

(After Griffith *et al*., 1992)

Triplett *et al*., (1968) reported a positive correlation between residue and maize yields, and suggested that increased soil water content was responsible for the yield advantage. This is supported by the strong negative relationship between quantity of surface residue and evaporation, reported by Steiner (1989). McIsacc *et al*., (1991) reported a similar negative relationship between residue cover and runoff. No-tillage significantly increases water infiltration (McLaren and Cameron, 1994) owing to surface roughness and/or residue (Table 3). Water runoff is slowed by both roughness and residue, allowing further time for infiltration, and surface residues tend to prevent soil crusting, thus further increasing infiltration (Unger *et al.*, 1988; Griffith *et al.*, 1992). Residue retention provides little or no advantage compared with bare soils in terms of plant available soil water during years with adequate rainfall for crop growth, according to Goss *et al.*, (1978) and Icabakci *et al.*, (1993).

Table 3: Effect of tillage and residue on infiltration and simulated rainfall.

	Total infiltration after one hour (mm)	
Treatment	**Initial run**	**Wet run[a]**
Ploughed (bare)	18.2	10.5
No-till (bare)	12.3	6.4
No-till (40% cover)	23.5	13.6
No-till (80% cover)	44.5	35.1

[a] 24 hours after initial run.

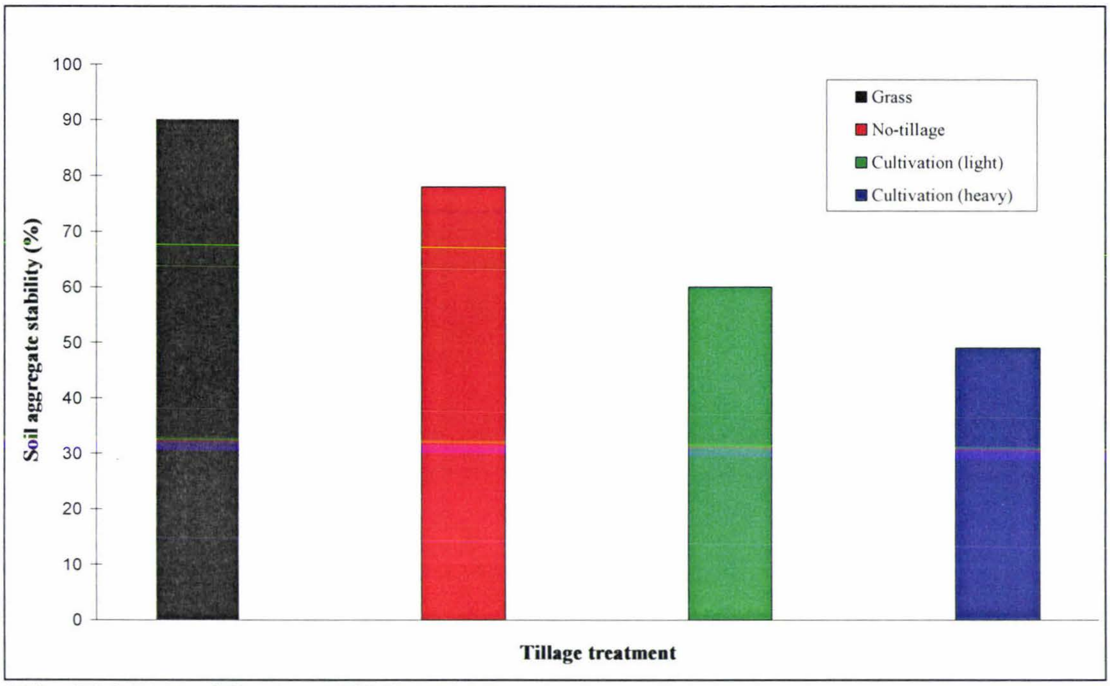
(After Griffith *et al.*, 1992)

2.2.2 Improved soil structure

No-tillage facilitates residue retention which, in turn, helps to increase soil organic matter levels or slow their decline, compared with tillage (Ross and Hughes, 1985; Chan and Mead, 1988). The organic carbon content of soils is related to the tillage intensity, soil aggregation (Figure 1) and stability. Smettem *et al.*, (1992) compared tillage and no-tillage and found that organic carbon (C) was significantly greater under no-tillage, and that aggregate stability was significantly affected by organic C%. This work concluded that a management system which maximised surface cover and increased organic matter return would probably lead to a soil with greater structural stability.

Indeed Weill *et al.*, (1988) found that soil organic matter content was positively correlated with the size of the 1–2 mm aggregate fraction, and was increased by no-tillage, while aggregate stability was also improved. Several other workers (Douglas and Goss, 1982; Blevins *et al.*, 1983; Chan and Mead, 1988; Chan *et al.*, 1992) have reported an increase in organic C under no-tillage, particularly in the top 50 mm of soil, and that this led to a rise, or at least a reduced rate of decline, of aggregate stability. Furthermore, a direct relationship has been reported between the organic matter content and water holding capacity, especially plant available water. Anon. (1994) reported that when organic matter content increased from 2% to 6%, a 65% increase in available soil water could result.

Figure 1: Soil aggregate stability under four tillage treatments.



(After McLaren and Cameron, 1994)

2.2.3 Reduced erosion

An undisputed advantage of no-tillage is its ability to control soil erosion (Unger and McCalla, 1980; Knapp, 1983; Dickey *et al.,* 1990) principally through its retention of crop residue on the soil surface. Mannering and Fenster (1983) outlined three important ways in which residue achieved this:

1. Surface sealing, or crusting, of the soil is minimised resulting in improved rainwater infiltration into the soil.
2. When runoff occurs, the velocity of runoff decreases, reducing its ability to carry sediment.
3. Wind erosion is decreased by reducing wind energy and by protecting the soil surface.

Unger *et al*., (1988) noted that residue retention near the surface dissipates rain energy, minimises aggregate dispersion and retards surface flow, allowing more time for trapped water to infiltrate. Lal *et al.,* (1988) found that the effectiveness of no-tillage in reducing runoff and erosion depended on the quantity of residue available. No other single soil conservation technique has reduced both wind and water erosion in a continuous cropping regime as much as the change from tillage to no-tillage (Baker, 1985a).

2.2.4 Soil fauna

Power and Mastina (1988) stated that crop residue management directly affected soil water, aeration, temperature and nutrient regimes. In addition, these factors defined the soil environment for microbiological activity. A residue-covered soil is likely to have a micro-environment less oxidative than one where residues have been removed or incorporated.

Earthworms are extremely important for the incorporation, distribution and breakdown of organic matter. Earthworm numbers and biomass are significantly increased by no-tillage compared with ploughing because of the elimination of tillage with its negative effects on earthworm populations (Edwards and Lofty, 1972; Carter *et al*., 1988). Pankhurst *et al*., (1995) assessed the effects of tillage and stubble management on earthworm biomass and numbers and determined that crop residue removal significantly reduced both measures. In a short-term residue management trial, Giles (1994) reported that earthworm numbers increased proportionally with surface residues, and at one stage measured 9 t ha^{-1} of earthworm biomass under 11 t ha^{-1} of barley residue after six winter months in a temperate climate.

2.3 Successful plant establishment in crop residues

The fundamental aim of crop establishment is to achieve 100% seedling emergence regardless of prevailing soil, weather or crop residue conditions. If no-tillage is to be widely adopted, the risks associated with stand establishment and growth must be no worse than those of conventional tillage (Saxton and Baker, 1990). A considerable volume of data suggests that plant establishment is associated more with opener design and the effect that this has on soil physical parameters than any other single factor (Baker, 1976a; Baker and Mai, 1982; Choudhary and Baker, 1982; Baker, 1985b; Choudhary *et al.*, 1985; Hamilton-Manns, 1994; Hamilton-Manns *et al.*, 1995). The influence of opener design on soil cover appears to be the key factor. Baker (1976a) showed a strong relationship between cover and seedling emergence and categorised the four classes of slot cover:

In dry soils, vapour-phase soil water has a major effect on the emergence and subsurface survival of the crop seedlings. In-groove soil humidity itself is a function of the nature and amount of groove cover. When the in-groove humidity decreases too rapidly after drilling because of low diffusion resistance through the groove cover, seeds germinate, but many seedlings die before emergence (Choudhary and Baker, 1981a). In wet soils, failure of seeds to germinate is associated with low soil oxygen diffusion rates, which are themselves related to opener design, particularly their ability to manipulate residue in, over, or adjacent to the slot (Chaudhry and Baker, 1988). Earthworm activity and numbers are also affected by opener design and residues and, in turn, have a direct impact on the oxygen diffusion rates in and around the slot (Chaudhry *et al.,* 1986).

2.3.1 No-tillage openers

Baker (1976b) claimed that slot shape, soil cover and residue cover of the seed furrow were the most important biological variables in opener design. In this respect, until recently, most openers have created essentially two shapes of soil slot with some minor variations in between. These are "V" and "U" shapes (Choudhary and Baker, 1981b; Baker and Choudhary, 1988). V-shaped slots are created by openers of either double or triple-disc configuration which, despite their many disadvantages, are the most commonly-used openers worldwide (Baker, 1985a). Among the most advantageous design features are an ability to physically tolerate surface residue without blockages (Baker *et al.*, 1979) and low maintenance. These beneficial attributes, however, are negated by:

1. An inability to optimise the seed-zone micro-environment, particularly water vapour retention and oxygen movement in both dry and wet soils (Baker *et al.,* 1988).
2. A tendency to smear and compact slot walls (Baker and Mai, 1982).
3. A tendency to tuck residue into the slot where it affects germination by releasing phenolic acids upon decomposition (Hyde *et al.*, 1987).

4. A wedging action in the soil which creates little loose covering material (Baker, 1970).
5. A marked dependence on slow speeds to avoid "seed-flick" by the discs (Saxton and Baker, 1990).
6. A relatively narrow operational tolerance of the triple disc opener in dry soils, where reliable seedling emergence is sought (Choudhary and Baker, 1981a).

U-shaped slots are created by a wider range of openers so generalisations become more difficult. These openers produce seed-zone micro-environments somewhat more optimal than V-shaped slots (Baker, 1976b) yet cause tillage, moisture loss and randomised soil-seed contact. They all produce loose soil, however, which can be utilised later for slot cover (Baker, 1970) albeit that little "micro-management" is exercised over surface residues in the vicinity of the slot (Baker and Choudhary, 1988). The residues are indeed often swept aside to avoid opener blockages (Baker *et al.*, 1979), resulting in a loss of moisture control (Baker and Choudhary, 1988; Saxton and Baker, 1990) although this also avoids residue tucking or "hairpinning".

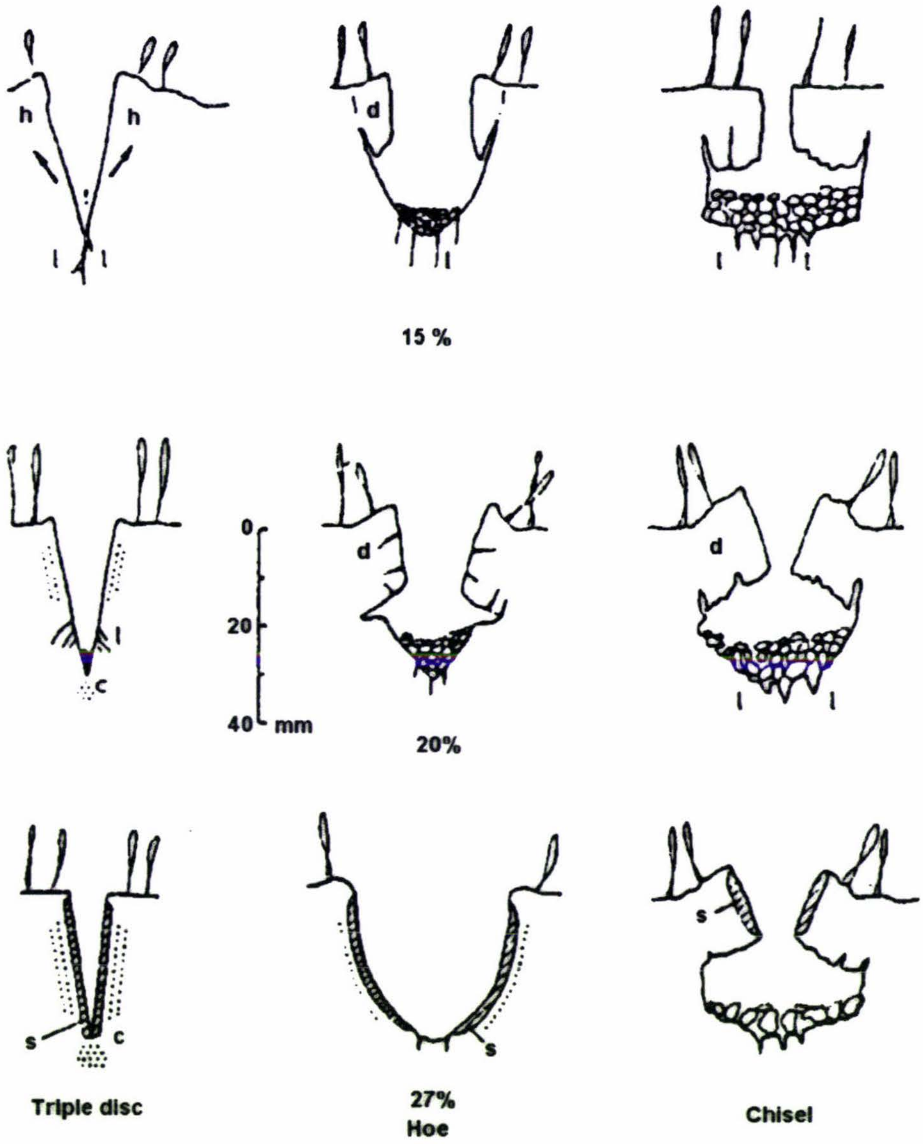
When exploring geometrical options that contrasted with V or U shapes, a new slot shape was first discovered by Baker (1976a). This slot shape reversed the "wide top-narrow base" characteristics associated with V-shaped grooves by inverting them, thus assuming an initial "Inverted-T" (⊥) shaped seed groove (Baker, 1976a, 1976b). The opener was first described in the literature as a "chisel coulter" and became commercially available as the "Baker Boot", a rigid tyne with slightly inclined wings on either side (Baker, 1985a). That simple design underwent further development to become the current plus-shape (+), originally named the Bio-Blade™ but now referred to as a Cross-Slot™ opener. Numerous field and laboratory trials (Baker, 1976a, 1976b; Baker *et al.* 1979; Choudhary and Baker, 1982; Baker and Saxton, 1988; Saxton and Baker, 1990) have all concluded that Cross-Slot™ openers produce significantly better seedling emergence results than either of the alternative openers. The general slot-shape characteristics of the three opener configurations at three different soil moisture levels are illustrated in Figure 2.

Slot shapes based on the inverted-T configuration have especially increased the tolerance of seeds sown into sub-optimal soils (*i.e.* too dry or too wet) (Baker and Saxton, 1988). In dry soil, the enhanced performance of this configuration has been shown to be a function of resistance of the soil and residue slot cover to the diffusion of water vapour. The increased germination and emergence of inverted-T-shaped slots is attributed to the slot's ability to maintain residue-covered soil over the slot, thus controlling the seed zone micro-environment. This is referred to as micro-management of soil and residue (Baker and Choudhary, 1988). Wet soil performance has also been linked to residue retention over the slot and the ability of this opener to prevent the tucking of residue into the seed zone. In this case the residue greatly influences earthworm mobility and numbers, which provide more oxygen diffusion and infiltration into the seed zone than other opener types (Baker *et al.*, 1988).

2.3.2 Opener effects on plant performance

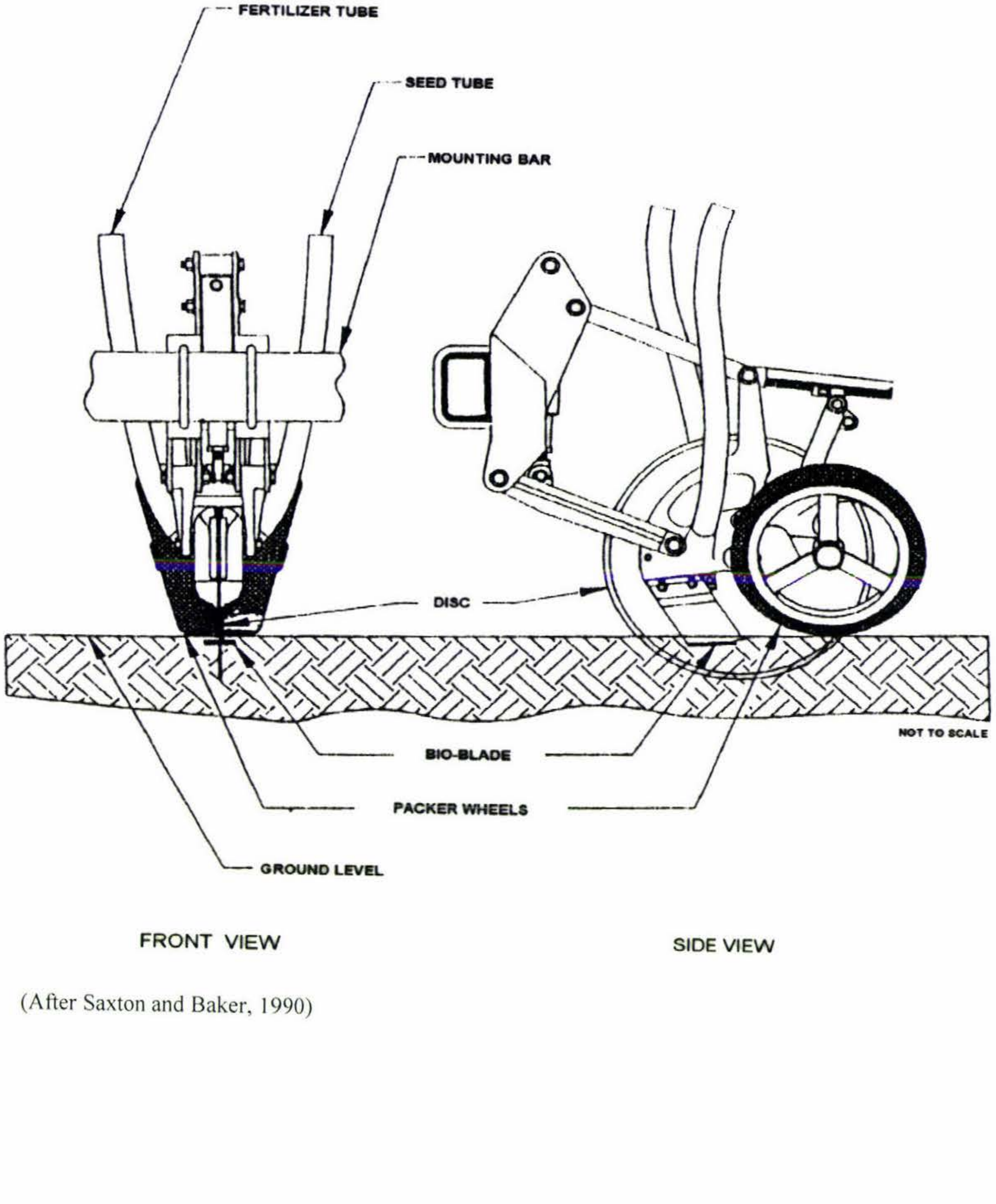
Field experiments encompassing several thousand hectares in New Zealand, Australia and the United States (Baker and Desborough, 1985; Ritchie, 1986; Ritchie and Baker, 1987; Saxton, 1987, 1988) comparing the inverted-T shaped slot with its contemporaries have been conducted since investigations into the then experimental chisel opener were initiated in 1969. In describing the significant biological advantages which all versions of the inverted-T openers possessed, Baker (1976b) stated that: "The chisel coulter, with its apparent ability to protect the seed from the drying elements, appears to sustain seedling emergence and establishment despite the presence of such a smear." Figure 3 illustrates the components of an earlier evolution of the Cross-Slot™ no-tillage opener. Ritchie (1986) reported that attention to the shape of the drilled slot was essential, particularly in drying soil conditions (Figure 2), with the inverted-T shape showing consistently greater tolerance to climatic and soil changes than any other shapes so far encountered (Figure 4).

Figure 2: Principal characteristics of no-tilled grooves in a silt loam at moisture contents of 15%, 20% and 27%.



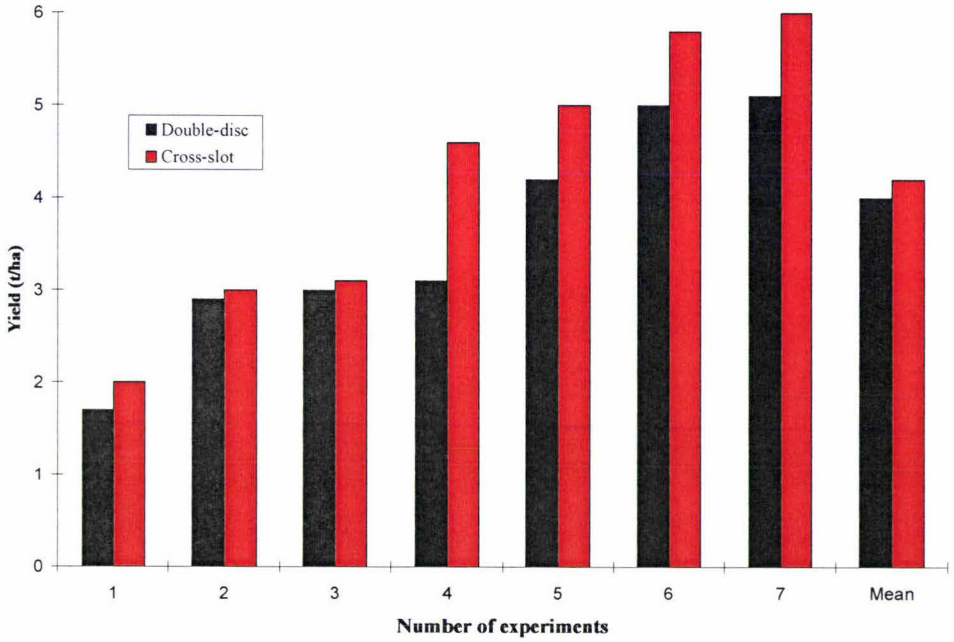
(After Dixon, 1972)

Figure 3: Components of the Cross-Slot™ no-tillage opener.



(After Saxton and Baker, 1990)

Figure 4: Wheat yield comparison between double-disc and Cross-Slot™ no-tillage openers in eastern Washington (USA).



(After Saxton and Baker, 1990)

2.4 Soil compaction

2.4.1 Principles of compaction

Soil compaction is defined as the decrease in volume of a given mass of soil, or alternatively the increase in soil density (Marshal and Holmes, 1979; Hillel, 1980). The degree of compactness increases as a result of air or water expulsion during the failure and closer packing of aggregates (Marshall and Holmes, 1979) and during the forced rearrangement and closer packing of soil particles within the aggregates (Harris, 1971).

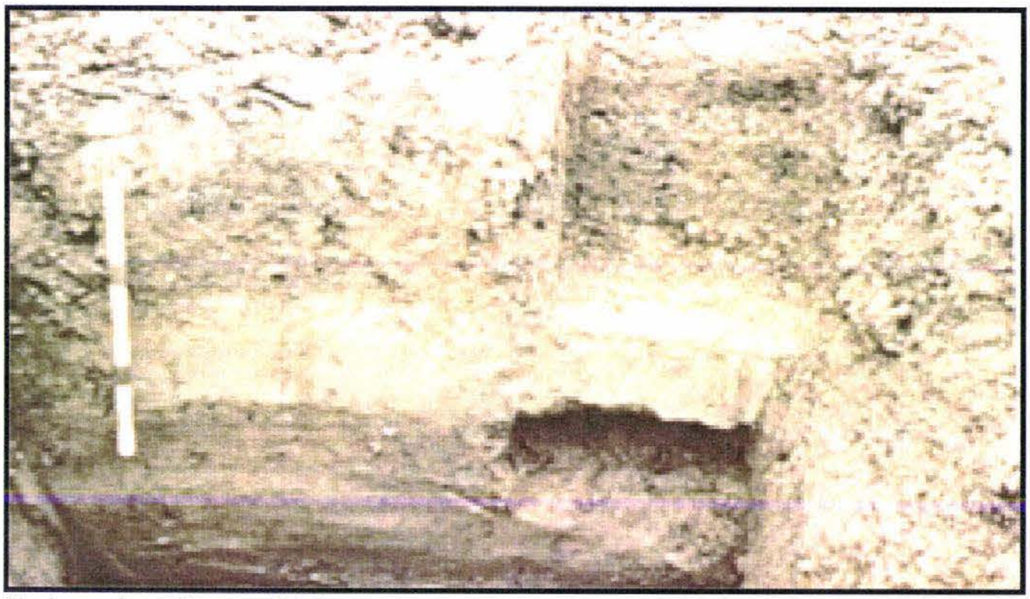
A change in the state of compactness is usually described quantitatively using parameters of soil packing such as bulk density and porosity. Quantitative descriptions of the compaction process are difficult because of the complexities of many combinations of soil conditions and forces acting upon the soil. Those forces may be of internal (*e.g.* freezing, drying, swelling) or external (*e.g.* animal treading, tillage implements, wheel traffic) origin. Traffic, however, is considered to be the primary source of those forces in tilled agricultural soils as it produces both vertical (uniaxial) and horizontal (shear) forces. Figure 5 illustrates the nature of subsoil compaction.

2.4.2 Influence of soil properties on compaction

Laboratory compactibility tests have shown that, given the same level and pattern of loading, resultant bulk densities are largely a function of particular soil properties (Soane *et al.,* 1981a) and soil water is clearly the most dominant of these. As soil water content increases, cohesion between soil particles is reduced and movement of those particles is lubricated (Baver *et al.*, 1972; Akram and Kemper, 1979; Hillel, 1980). At very high water contents, water prevents close particle packing and reduces the volume of air available for displacement, thus limiting further compaction (Hillel, 1980).

The water content at which maximum bulk density is attained is described as the "optimum" for compaction in the Proctor test and is commonly used in agricultural compaction studies (Soane *et al.*, 1972). Optimum water contents for compaction have been shown to be near the plastic limit of soils (Soane *et al.*, 1981a). Soane *et al.*, (1972) reported that, in 58 soils, compaction was strongly influenced by organic matter content, a finding later confirmed by Carter *et al.*, (1996). Soil strength also affects soil compactibility (Hillel, 1980), with weakly-structured, low-strength soils being most prone to compaction. Carter *et al.*, (1996) reported that soils are particularly at risk of compaction when in a tilled condition.

Figure 5: Subsoil compaction with evidence of a plough pan.



(Redrawn from Haynes, 1995)

2.4.3 Effects of compaction on soil physical properties

Changes in soil physical properties including soil strength and the content and transmission of air and water are of considerable importance to crop growth, and thus are of practical use in describing compaction.

2.4.3.1 Soil strength

Strength is an important soil property as it influences the ease of tillage, root growth and compactibility (Marshall and Holmes, 1979; O'Sullivan and Ball, 1982; Horne *et al.*, 1992). Shear strength is often used to describe soil strength because it is considered physically relevant to soil failure by plant roots (O'Sullivan and Ball, 1982). Penetrometers are widely used to measure mechanical impedance, an indirect measure of soil strength, because measurements are simple and rapid, and relationships have been found between impedance and root penetration (Barley and Greacen, 1967; Greacen *et al.*, 1968; Eavis, 1972; Vazquez *et al.*, 1991; Unger and Kaspar, 1994). The "penetration resistance", often called the "cone index", provides an empirical measure of soil strength resulting from a combination of shear failure, compression, plastic flow, cutting of the soil, and metal-soil and soil-soil friction (Marshall and Holmes, 1979; Hillel, 1980). Interpreting results is difficult, however, because the same values of penetration resistance can result from different combinations of soil properties (Dexter and Woodhead, 1985). Several authors have drawn attention to a number of problems which make interpretation of the data, and comparisons of data between experiments, difficult (Russell and Goss, 1974; Cassel, 1982). The main problems reported are:

1. Penetrometer movement through the soil does not resemble that of roots.
2. Penetration resistance does not account for small numbers of continuous pores which, in compact soils, act as important pathways for root penetration.
3. Soil water content and bulk density have large interacting influences on penetration resistance, making it difficult to compare resistances measured at different times, or to compare treatments with different water contents and bulk densities.
4. Penetrometer geometry and mode of use, particularly speed of insertion into the soil, strongly influence recordings.

Measurements of mechanical impedance made with penetrometers should therefore be regarded only as comparative, not absolute, guides to the forces which roots encounter in penetrating soil (Unger and Kaspar, 1994). At a given water content, soil strength increases with increasing bulk density (McLaren and Cameron, 1996). As soil compaction causes increased aggregate and particle packing, it increases soil strength through increased soil cohesion and friction (Chancellor, 1971; Bowen, 1981).

The variation in reported critical values of mechanical impedance (MI) for root growth, as measured with penetrometers, was wide. Critical MI varied between 0.3 MPa (Carter *et al.*, 1965) and 6.0 MPa (Gerard *et al.*, 1982), the difference mainly reflecting effects of penetrometer geometry and mode of use, soil water content at the time of measurement, particle size distribution, and type of crop.

2.4.3.2 Porosity

Soil compaction reduces the volume and continuity of pores, particularly those of larger diameters (Becher, 1991). For this reason, states of compactness are often quantified by measures of porosity, particularly macroporosity. When large pores collapse with compaction, smaller pores are produced (Becher, *loc. cit.*). Consequently, soil compaction affects a wide range of pore sizes. While the size affected depends on the degree of compaction, and thus on the increase in bulk density, compaction usually reduces the volume of pores larger than 10–30 μm equivalent spherical diameter, and increases the volume of smaller pores, usually those less than 6–10 μm (McLaren and Cameron, 1996).

Bulk density varies widely between sites and soils, and particularly depends on particle size distribution (Becher, 1991) and organic matter content. Although a single critical bulk density may be inappropriate for general use, critical values of 1.50–1.60 g cm^{-3} commonly appear to describe bulk densities that are restrictive to root growth (Barley *et al.*, 1965).

2.4.3.3 Aeration

Sufficient transfer of gas, particularly oxygen (O_2) and carbon dioxide (CO_2), between the soil and atmosphere is necessary to maintain aeration for plant and microbial activity (Langer, 1990); as soil compaction can reduce the size and continuity of soil pores, and it may reduce or even stop gaseous exchange. Macroporosity is often used to describe aeration status (Erickson, 1982), however, O_2 diffusion rate and gas diffusivity are considered more relevant (Greenwood, 1975; Erickson, 1982). Oxygen diffusion rate in particular, has been reported to be the best descriptor of soil-air-plant relations (Erickson, 1982), and compaction has been found to reduce the rate to levels below those thought to be critical for plant growth (Erickson, 1982; Sojka *et al.*, 1997).

Air permeability is often measured in compaction studies to characterise the volume and continuity of the large pores available for diffusion and mass flow of air, and compaction can significantly reduce rates of air permeability (Eriksson *et al.*, 1974). Ball and O'Sullivan (1982), for instance, measured rates in a wheeled soil three orders of magnitude less than those in an unwheeled soil.

Erickson (1982), in reviewing soil aeration in relation to tillage, identified the approaches to defining critical soil aeration as capacity (porosity measures), intensity (oxygen concentrations) and rate (gas diffusion rates). Macroporosity is most often used to define minimum soil porosities for root growth, probably because it is easily determined. A critical value of 10% of the total soil volume is commonly thought to define limiting conditions of aeration (Grable, 1971) while an O_2 concentration approaching 20% is generally regarded as necessary for root growth (Wolkowski, 1990). Greenwood (1975), however, considered that unless O_2 concentrations somewhere in the root zone are near zero, plant growth will be unimpeded. Erickson (1982) determined that O_2 diffusion rate is the most appropriate measure of soil-air-plant relations and oxygen diffusion rates of 0.2–0.4 g cm^{-2} min^{-1} are thought to represent critical values for crop growth.

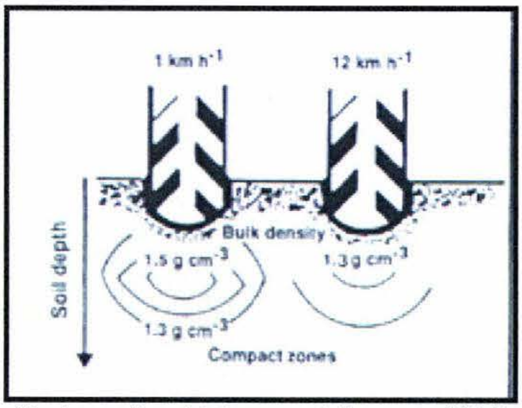
2.4.4 Occurrence of soil compaction

Soils may become compacted both naturally and by processes induced by land use. Natural processes, such as consolidation and shrinkage, that depend largely on moisture regimes, can result in surface crusts and subsurface compaction and pans (Carter *et al.*, 1996). Subsoil bulk densities are commonly high (1.7–1.8 g cm^{-3}), and are considered restrictive for root growth (Gradwell, 1984).

Controllable compactive processes arising from land use consist largely of trampling, wheel traffic and tillage. The occurrence of such compaction is widespread and diverse, although traffic is considered to be the main source of soil compaction in arable and pastoral agriculture (Hillel, 1980; Hakansson *et al.*, 1988; Wolkowski, 1990), and is discussed further below.

While some tillage operations (*e.g.* rolling) purposely compact (only lightly) the tilled zone sufficiently for optimum seed germination, the passage of wheeled vehicles required for tillage, transport, spraying and harvesting, often results in serious compaction problems (Ball *et al.*, 1997). The importance of traffic compaction has long been recognised (Amos, 1918) and is reflected in the literature. Topsoil and subsoil compaction increases with vehicle load through an increase in average tyre contact pressure (Soane *et al.,* 1981b; 1982) (Figure 6). At high loads, however, the weight of the load itself is more important than contact pressure (Soane *et al.,* 1981b) and can result in compaction of the soil to depths of 500 mm or more (Canarache *et al.*, 1984; Hakansson *et al.*, 1988). Such deep compaction may be very persistent as it is below the depth of normal tillage, natural freezing and drying, and most biological activity (Hakansson *et al.*, *loc. cit.*).

Figure 6: Effect of vehicle speed on compaction.



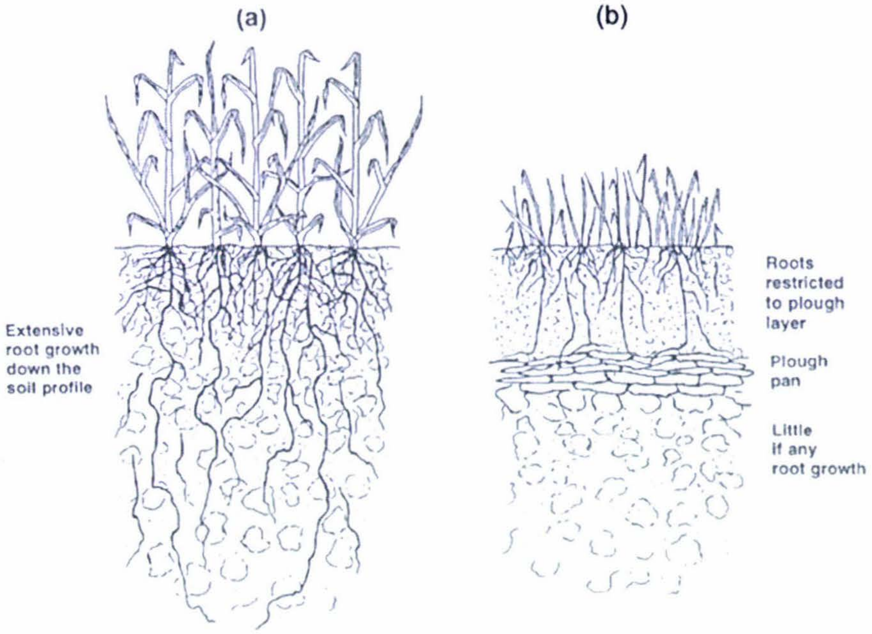
(Redrawn from McLaren and Cameron, 1994)

Wheel coverage of the soil surface during seedbed preparation and harvesting may be high. Soane (1975), for example, reported that traditional seedbed preparation (including fertiliser spreading, harrowing twice, sowing and rolling) using medium-sized tractors may result in 90% coverage of the soil surface, while the harvest of a cereal crop followed by straw disposal can give 60% coverage. Soane *et al.*, (1982) cited an observation in which the traffic associated with cereal cropping totally covered the ground four to five times in one year.

If a soil is subjected to continuous cultivation over a number of years, especially when the soil water content is outside the acceptable moisture content (Davies *et al.*, 1972), the friable, heterogeneous nature of the soil colloids is re-arranged to form a homogeneous, compacted layer often referred to as a "plough pan" (Figure 7). In addition, chemical and physical conditions that give rise to compaction are associated with tillage include:

1. Organic matter oxidisation of (the entire carbon content of a wheat crop was reported as being oxidised within 19 days) (Reicosky, 1996).
2. Tillage aggregate pulverisation along mechanically created shear planes as compared with natural lines of cleavage (Hughes, 1975).

Figure 7: Plant rooting characteristics in loose and compacted soils.



Growth of wheat in (a) a well-structured soil and (b) a soil containing a compacted subsoil layer

(Redrawn from Haynes, 1995)

2.4.5 Reducing compaction and loosening compacted soil

2.4.5.1 Methods of reducing compaction

Soil compaction may be limited by improved farm management practices. These include: drainage and timely tillage to avoid field work in wet conditions; incorporation of organic matter; and crop rotations which avoid successive years of intensive traffic (Batey and Davies, 1971). Traffic management practices which may reduce compaction have been comprehensively reviewed by Eriksson *et al.*, (1974).

2.4.5.2 Methods of loosening compacted soil

Several authors have suggested that freeze/thaw cycles are likely to loosen compacted soils in areas where winter freezing often occurs. Similarly, wet/dry cycles have been shown to result in shrinkage and cracking of compacted soils, especially those of high clay content (Akram and Kemper, 1979). Most such natural alleviation of compacted soil usually occurs within the 0–150 mm depth (Akram and Kemper, *loc. cit.*) and may be very slow.

Since subsoil compaction largely occurs below natural freeze/thaw and wet/dry activities, most evidence suggests that natural alleviation does not loosen compacted subsoil, even when conditions favour such processes. Earthworms may create channels through compacted soil (Bowen, 1981), although tillage reduces earthworm populations such that numbers of deeply burrowing earthworms may be low under the tillage systems normally associated with arable agriculture.

Particular plants such as lucerne (*Medicago sativa* L.) have been grown for their abilities to improve soil structural conditions (Bowen, 1981). In describing specific effects of roots on structural regeneration, Goss (1987) suggested that rapid growth of fibrous root systems during moist conditions when soils are mechanically weak, may result in the disruption of compacted layers.

Loosening of compacted topsoils is a generally accepted (and arguably incorrect) role of tillage. Unless no-tillage is practised, concern is mostly with the disruption of compacted zones beneath the depth of normal tillage.

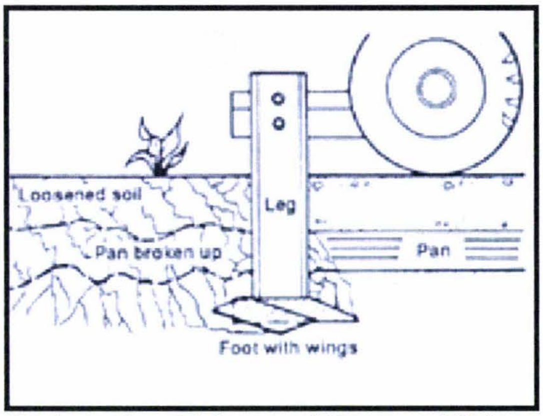
In general, it appears that compaction which occurs below the normal tillage depth and natural regenerative processes may be very persistent (Blake *et al.*, 1976). In such situations, deep mechanical loosening has been employed to alleviate the adverse effects of compaction.

2.5 Subsoiling

Deep tillage has long been practised to loosen compacted soils and improve their physical state. It has been performed with a wide range of equipment designed to loosen subsoils, and often to mix topsoils and subsoils together (Figure 8). Such equipment can be broadly grouped into three categories:

- Mouldboard, disc and slip ploughs.
- Rotary tillage, ditching and digging machines.
- Tyned implements.

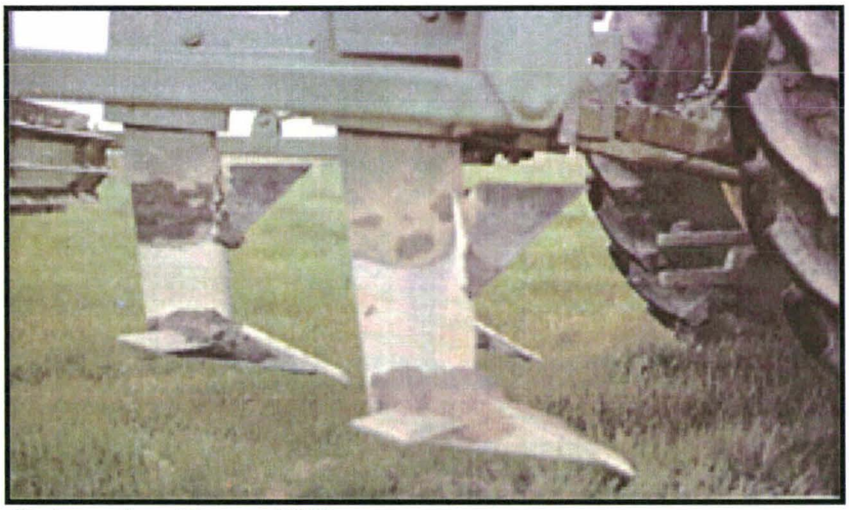
Figure 8: Loosening a compacted plough pan with a winged-tyne subsoiler.



(Redrawn from McLaren and Cameron, 1994)

Many different tyned implements have been used to loosen compacted soil with minimal vertical mixing (Figure 9). Such implements are known as subsoilers, chisels or rippers (Loveday *et al.*, 1970). Subsoiling refers to the loosening, by tyned equipment, of soil below the normal depth of tillage, and it has been widely researched overseas. It is becoming a commonly accepted practise to improve soil physical conditions.

Figure 9: Typical tyned subsoiler with lateral wings.



(Redrawn from Haynes, 1995)

2.5.1 Subsoiling principles and equipment

A wide range of subsoiling equipment, comprising varying numbers, configurations and modifications of chisel, conventional and winged tynes, has been used to loosen compacted soil. Descriptions of those implements, their energy requirements and soil failure achieved in given soil conditions, have been published and reviewed by many authors (Davies *et al.*, 1972; Swain, 1975; Spoor and Godwin, 1978; Bowen, 1981). Studies have shown that the degree of soil loosening achieved by subsoiling is highly dependent on the design and operation of the implement (Spoor and Godwin, 1978).

2.5.1.1 Types of soil disturbance and critical operating depth

Spoor (1982b) defined two types of soil disturbance created by subsoilers:

1. Significant disruption of the zone affected by the subsoiler, with reorientation of the soil fragments produced, creating large pores between those fragments.
2. "Opening up" of the soil along existing planes of weakness, creating large fissures between the disturbed soil fragments, but without significant reorientation of the latter.

Compared to complete disruption (*i.e.* type (1) above), the loosening created usually results in minimal soil surface disturbance (Spoor, 1982b; Pidgeon, 1983) and a higher risk of immediate re-compaction by traffic (Spoor, 1982b). Spoor and Godwin (1978) considered that the most effective and permanent soil disturbance is achieved through rearrangement of the disturbed soil fragments relative to one another. The direction of soil movement during subsoiling depends on the relative resistance to soil flow in different directions, with movement always occurring in the direction of least resistance (Spoor, 1982a).

At shallow operating depths the soil is moved forward, sideways and upwards by a subsoiler ("crescent failure"). This effectively loosens the soil by shear and tensile failure along well-defined rupture planes which radiate from just above the share tip to the soil surface at an angle of about 45° to the horizontal (Spoor and Godwin, 1978). Soil failure is progressive, occurring first with the share, followed by the leg and finally with the "wing" if present (Spoor, 1982b). As the operating depth increases, soil resistance to upward movement also increases until a particular depth is reached (the "critical depth"). The soil then flows forwards and sideways only ("lateral failure"), resulting in little overall disturbance, and compaction at depth (Spoor and Godwin, 1978).

2.5.1.2 Effects of soil water content and strength

For maximum soil loosening, subsoiling should be performed when the soil is drier than the plastic limit, or friable, so that brittle failure can occur (Batey and Davies, 1971). Spoor (1982b) reported that fragment reorientation was greatest at low inter-fragment cohesion, the latter reaching a maximum near the plastic limit. Pidgeon (1983) recommended subsoiling at a soil matric potential of 100 kPa for most effective loosening. It is apparent that the range of soil depths and moisture conditions over which satisfactory loosening can be achieved may be widened by loosening strong surface layers, either in a separate operation prior to subsoiling, or by using shallow widely-spaced leading tynes on the subsoiling implement (Spoor, 1982a).

2.5.1.3 Effects of tyne shape, spacing and depth

The degree of surface and subsurface soil disturbance achieved by subsoiling is strongly influenced by a number of tyne design parameters. Spoor and Godwin (1978) reported that the addition of wings, or "sweeps", to conventional subsoilers improves their performance. Although winged subsoilers have a higher draught than do chisel tyne or conventional implements, total soil disturbance is significantly greater, and the draught/disturbance ratio (specific resistance) is therefore reduced (Spoor and Godwin, 1978).

The same authors also considered that winged tynes produce the most effective soil rearrangement at depth. Soil, already disturbed by the share, flows up and over the wings and is further disturbed and reoriented as it falls behind them. The degree of fragment reorientation, and both surface and subsurface disturbance, increases with wing width and lift height (Spoor and Godwin, 1978; Spoor, 1982b). Wings generally increase critical depth, although the degree of that increase depends on wing width and lift height, and soil conditions (Spoor and Godwin, 1978). Other tyne properties also influence the degree of soil disturbance and critical depth. Spoor (1982b) reported that vertical subsoiler legs split the already loosened soil zone, causing reorientation of the loosened fragments, and surface disturbance. Sideways inclined legs ("slanted legs", usually at 45° to the vertical) create little surface disturbance. Share width, inclination and lift height also influence subsoiler effectiveness, with wider shares and greater inclination and lift height resulting in increased soil disturbance (Spoor and Godwin, 1978). Under given soil conditions, wider shares generally increase the critical depth (Spoor and Godwin, *loc. cit*).

The arrangement of tynes on subsoiler frames has been found to affect both soil disturbance and specific resistance (Spoor and Godwin, 1978; Godwin *et al.*, 1984). For tynes working at wide spacings and a common depth, Spoor and Godwin (1978) reported that loosening is incomplete and a furrowed soil surface is formed. At close spacings loosening occurs to a more uniform depth and little soil surface disturbance is produced. For complete loosening, Spoor and Godwin (1978) recommend maximum tyne spacings which depend on the particular tyne disturbance pattern (Table 4). Godwin *et al.*, (1984) recommended similar spacings for conventional implements. Earlier subsoiling summaries have recommended that, as a general rule, the distance between tynes should roughly equal the working depth (Davies *et al.*, 1972; Swain, 1975).

Table 4: Recommended tyne spacings for complete soil disturbance.

Type of subsoiler	Spacing in terms of working depth (d)
Conventional	1.0 – 1.5
Winged	1.5 – 2.0
Winged + shallow leading tynes	2.0 – 2.5

(After Davies *et al.*, 1982)

2.5.1.4 Subsoiling depth

Because of the large number of variables involved, accurate predictions of critical working depths under field conditions are impractical (Spoor and Godwin, 1978). Similarly, the design of a single implement able to operate efficiently at any depth, and over a wide range of soil strength and moisture conditions, has not yet been achieved. Progress in design has resulted in implements which operate well over a satisfactory range of soil depths and conditions. Some of these implements are adjustable in the field.

Although wings may substantially improve subsoiler performance (Spoor and Godwin, 1978), non-winged subsoilers of varying configurations are commonly used (Swain, 1975). The latter consist of a number of chisel or conventional tynes operating at the same depth which are usually wider than the tractor to avoid immediate wheel re-compaction. Bowen (1981) suggested that such subsoilers may typically be operated at greater than their critical depths, resulting in inadequate loosening, high specific resistance, and compaction and smearing at the share depth. Spoor and Godwin (1978) also reported that non-winged implements may result in only minimal disturbance. They further considered that, for persistent loosening, the loosened soil units should be significantly rearranged, and reported that chisel tyne and conventional subsoilers often may not achieve this. It is not unexpected that many authors have concluded that the use of chisel and conventional subsoilers often results in minimal soil disturbance (Spoor and Godwin, 1978; Spoor, 1982a).

For soils with thin compacted layers ("pans"), however, localised loosening with chisel tyne and conventional implements has often achieved success (Unger, 1979; Unger *et al.,* 1981; Busscher *et al*., 1988; Carter *et al*., 1996). Such subsoiling provides weakened slots at intervals through the pans, often allowing adequate root penetration into a more favourable soil environment. Conversely, if the compacted soil to be loosened is too deep for total penetration by the subsoiler, general, rather than localised, loosening is probably required for adequate deep root development. Chisel tyne and conventional subsoilers are unlikely to consistently achieve such loosening to a uniform depth and winged implements are often used for general loosening of compacted horizons, as well as for disrupting thin pans (Davies *et al*., 1982).

2.5.1.5 Subsoiling implements

The slant-legged "Paraplow®" represents a less conventional approach to subsoiler design. It was developed to loosen the soil, using minimum energy and without total disruption, whilst maintaining a level soil surface (Pidgeon, 1983). It has been used successfully to loosen conventionally cultivated soils as well as those under no-tillage and minimum tillage systems (Davies *et al.,* 1982; West *et al*., 1996). Adjustable flaps enable changes to be made to the effective thickness of the legs and to the degree of soil lift, allowing some field control of the degree of loosening by changing the extent of fragmentation and fragment reorientation achieved (Spoor, 1982b; Pidgeon, 1983). This feature of the Paraplow® is likely to widen the range of soil strength and moisture conditions over which satisfactory loosening may be achieved.

Spoor (1982b) reported that slanted subsoiler legs may produce only minimal soil disturbance and create fewer voids than vertical legs. Pidgeon (1983) considered that moderate lifting and fissuring of the soil along natural planes of weakness by the Paraplow® is sufficient to significantly improve soil physical conditions and crop growth. Such disturbance is achieved by the Paraplow® with minimum flap lift, although wider flap adjustments can be made to substantially increase disturbance (Pidgeon, 1983). Contrary to the views of Spoor (1982b), Pidgeon (1983) reported that fissures produced by minimal soil disturbance may be more persistent than the voids produced by total disruption, and that such disturbance by the Paraplow® may be less energy demanding than significant soil disruption by conventional subsoilers.

2.5.2 Effects of subsoiling on soil physical properties

The following soil physical properties have been studied in subsoiling experiments:

1. Mechanical impedance.
2. Bulk density.
3. Porosity.
4. Water infiltration and transmission.
5. Aeration.

2.5.2.1 Mechanical impedance

Since the main objective in loosening such soils is to increase deep root development (Swain, 1975), much attention has been focused on the effects of subsoiling on soil mechanical impedance. Despite the many drawbacks to their use, penetrometers have usually been used to assess impedance. Numerous experiments have shown that subsoiling significantly reduces penetration resistance to levels considered by the authors to be below those restricting root growth (Kaddah, 1976; Busscher *et al.*, 1988; Unger and Kaspar, 1994). Reductions usually occur to about the depth of subsoiling, and are the most pronounced in soils with high initial penetration resistance (Ellington, 1986).

2.5.2.2 Bulk density

Subsoilers loosen soil by fissuring and fragmenting the compacted soil, and often reorientating those fragments (Spoor, 1982b). Soil structural units are likely to be smaller and less closely packed after subsoiling, resulting in a lower bulk density. Indeed, reductions in bulk density soon after subsoiling have been widely reported (Allmaras *et al.,* 1977; Carter *et al*., 1996; Evans *et al*., 1996). Soane *et al*., (1987), for example, reported 4–23% reductions in bulk density after subsoiling 13 sites with a winged implement. The soils varied widely in particle size distributions and undisturbed bulk densities, and the authors considered that significant reorientation of the soil fragments was achieved. Subsoiling experiments in which there were no significant changes in bulk density have also been reported. Possible reasons for the lack of response in those particular studies are:

1. Bulk density measurement occurred too long after subsoiling and was therefore affected by re-compaction.
2. Using a single tyne implement resulting in re-compaction by tractor wheels during subsoiling.
3. Using a tyne spacing too wide for uniform loosening.

Although, in some cases, re-compaction may occur soon after loosening, the effects of subsoiling on bulk density have frequently been measured several months, and even years after subsoiling (*e.g.* Ellington, 1986). Although authors of such studies often report reduced bulk densities after subsoiling (Ellington, *loc. cit.*) (Figure 10), the individual effects of subsoiling and re-compaction cannot be determined. The influence of implement design and soil conditions on reported reductions in bulk densities are also difficult to assess because sampling techniques and times varied widely.

2.5.2.3 Porosity

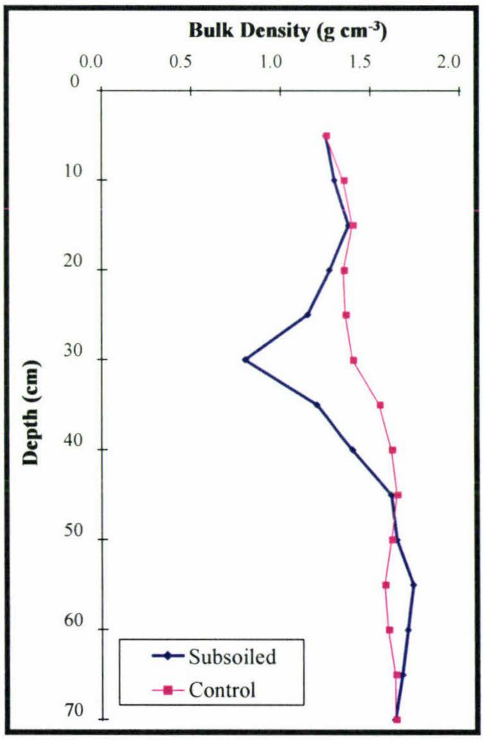
Concomitant with reductions in bulk density, increases in total porosity have been reported to result from subsoiling (Loveday *et al*., 1970; Hill, 1990). Although increased volumes of pores larger than 20–30 μm ESD usually accounted for those increases (Allmaras *et al.,* 1977), it is apparent that the influence of subsoiling on the volume of pores of different size ranges (Figure 11) varied widely (*e.g.* Chapman and Allbrook, 1987).

No comprehensive description of pore shapes created by tyne subsoilers has been reported. It is likely that, because subsoiling induces shear and tensile failure (Koolen and Kuipers, 1983), much of the resultant increase in porosity may comprise mainly large fissures. If significant soil disruption and fragmentation occurs, large packing voids of varying size are also likely to be produced (Kooistra, 1987). Fissures and packing voids are unlike the channels formed by biological activity (Bullock *et al.*, 1985), however, and may be less permanent.

2.5.2.4 Water infiltration and transmission

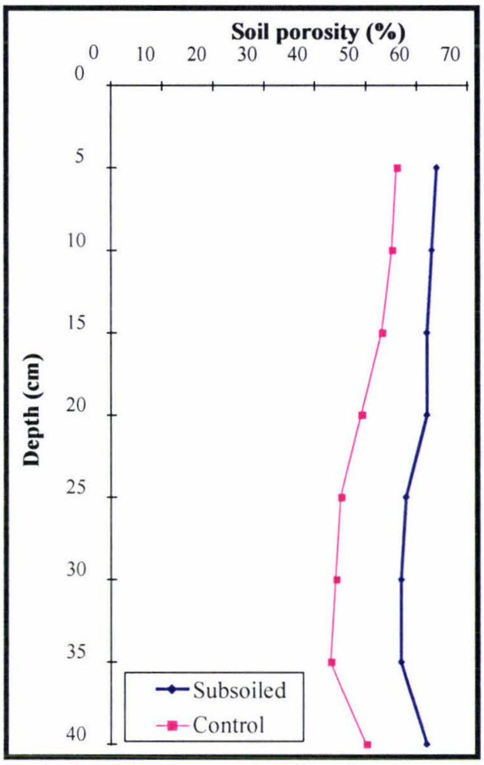
A frequently reported objective of subsoiling is to improve downward water movement through compacted soil (Davies *et al.*, 1972; Swain, 1975; Unger, 1979; Carter *et al.*, 1996). The rate of water transmission depends on the pore space geometry which, in turn, is determined by the soil structural arrangement. Subsoiling may substantially modify that arrangement and therefore significantly affect soil hydraulic properties. Several authors have emphasised that improvements in water infiltration and hydraulic conductivity may have important consequences in terms of reduced runoff, waterlogging of the root zone and increased water intake and storage (Davies *et al.*, 1972). If subsoiling is to improve drainage of the soil profile, the soil underlying the loosened zone should be well drained (Carter *et al.*, 1996).

Figure 10: Effects of subsoiling on bulk density.



(After Harrison *et al.*, 1994)

Figure 11: Comparison of soil porosity between treatments.



(After Chapman and Allbrook, 1987)

2.5.2.5 Aeration

Spoor and Voorhees (1986) reported that air permeability may be a satisfactory criterion for determining the need for soil loosening. Due to the dynamic nature of aeration, improvements in response to soil loosening may only be realised during wet conditions (Erickson, 1982; Sojka *et al.*, 1997). Consequently, most workers have focused on improvements in water transmission assuming concomitant improvements in aeration. As a result, while subsoiling is often performed to reduce the incidence of waterlogging, and thus avoid reductions in crop yield resulting from anaerobic conditions (Swain, 1975), there is little direct evidence of improvements in soil aeration after subsoiling.

2.5.3 Persistence of the effects of subsoiling

Continued measurements of soil physical properties and crop yield for several years after loosening have shown that improvements resulting from subsoiling are not permanent (Burnett and Hauser, 1967; Carter *et al.*, 1996; Evans *et al.*, 1996; Sojka *et al.*, 1997). Reviews of earlier work, together with reports of recent studies, show that the persistence of those improvements varies widely (Burnett and Hauser, 1967; Eck and Unger, 1985; Soane *et al.,* 1987).

There have been few reported instances of very persistent (ten years or more) changes in soil physical conditions resulting from soil loosening. It is generally recognised, however, that the loosened structure may rapidly collapse, and improvements in soil physical conditions may be transient. Adeoye (1982), for example, reported that 15 weeks after loosening, the macropores created by subsoiling were lost. A number of workers have reported that mechanical impedance and bulk density increased to pre-loosening levels within one to two years after subsoiling and consequently, annual or biennial subsoiling has been recommended for some soils (Carter *et al.*, 1996).

Most studies have shown more gradual reductions in the effects of subsoiling over periods of three to five years, although the effects of subsoiling were often imperceptible after that length of time (Unger, 1979). In view of such results, recommendations to loosen compacted soils every three to five years are common (Davies *et al.*, 1972). Persistence of subsoiling effects depends on the stability of pores created during loosening. Poor persistence of that porosity has been attributed mainly to:

- Re-compaction by traffic.
- Soil slaking during wet conditions.

Loosened soil, particularly that of low clay content, is mechanically very weak, and thus susceptible to re-compaction by traffic (Spoor, 1982a; Soane *et al.*, 1987; Wolkowski, 1990). Studies have conclusively demonstrated that traffic soon after loosening can rapidly re-compact the soil to its original state (Trouse, 1983; Soane *et al.*, 1987; Ball *et al.*, 1997). Soane *et al.*, (1987), for example, reported significant re-compaction with a single pass of high and low pressure tyres. They concluded that subsoiling followed by ploughing and random surface wheelings can cause significant subsoil re-compaction. They further considered that if subsoiling is performed on ploughed land, the soil surface may be unable to support even a low pressure tyre without deep re-compaction.

Subsoiling which results in a level soil surface is likely to reduce the need for further tillage prior to sowing. That was one of the design criteria in the development of the Paraplow® (Pidgeon, 1983). Such a soil surface allows no-tillage to be employed, thereby reducing the number of wheelings subsequent to subsoiling and increasing the persistence of subsoil loosening effects (Pidgeon, 1983; Ellington, 1986).

2.6 Agronomic effects of subsoil compaction and subsoiling

2.6.1 Root penetration and proliferation as a function of soil aeration

Trouse, (1971) determined that roots require O_2 for respiration in order that.

1. Rapid cell division and enlargement can occur.
2. Root tips can penetrate the soil.
3. Roots can penetrate the soil.
4. Roots can absorb and transmit water and nutrients.

Anaerobic conditions may occur in the soil when the entry rate of atmospheric O_2 is less than the requirements of roots, bacteria, fungi, and other soil organisms (Russell, 1977). The restricted O_2 supply, together with many biological, chemical and physical changes, can significantly reduce crop root and aerial growth (Grable, 1966; Trouse, 1971; Cannell, 1977; Busscher *et al.*, 1988). Those changes include the production and accumulation of toxins, mainly CO_2 and ethylene, and soluble nitrate loss by denitrification (Wolkowski, 1990).

Although high CO_2 concentrations may be toxic to roots, it diffuses more readily in solution than O_2. Toxic concentrations of CO_2 are a minor source of injury to plant roots compared to O_2 deficiency (Russell, 1977). Low concentrations of ethylene, an endogenous growth regulator, promote lateral root cell expansion at the expense of elongation growth, resulting in less efficient, stunted and thickened roots (Cannell, 1977; Dawkins *et al.*, 1983). At any given temperature, plant growth rate can be related to the soil O_2 level. Most plants show a decreased growth rate at low O_2 levels although some species are more sensitive than others. Plant yield is reported as being lower in an anaerobic soil because the rate of plant water uptake is restricted.

Poor soil aeration can also reduce the rate of plant nutrient uptake as there is generally a higher nutrient concentration within their roots than in the surrounding soil solution. To actively uptake nutrients against this gradient, energy must be supplied by the process of root respiration. When low soil O_2 levels cause the respiration rate to slow then consequently less energy is produced to assist in nutrient transportation, and the subsequent uptake rate decreases.

By reducing the volume and continuity of the larger soil pores, compaction restricts the transmission of air and water through soils. This results in waterlogging during wet conditions, and a restricted O_2 supply to plant roots (Trouse, 1971). As O_2 diffuses 10^4 times more slowly in water than in air (Cannell, 1977), the presence of water-filled pores is the main restriction to aeration. Anaerobic conditions are likely to occur not only in the compacted zones, but also in looser overlying soil which becomes waterlogged due to low hydraulic conductivity of the soil below.

Research by Greenwood and Cameron (1990) illustrated that the macropores created by subsoiling greatly increased the rate of air transmission (k_a). Below the cultivated depth, k_a was low in the non-subsoiled treatments. Within the depth of loosening, however, this factor was increased significantly. Measurements of k_a to the full depth of subsoiling showed that there was a disruption in macropore continuity caused by surface tillage after subsoiling.

Improvements in root growth are largely a function of the creation of large, continuous macropores. Air permeability reflects that macroporosity, and therefore has considerable potential for estimating whether subsoiling has resulted in sufficient soil disruption to significantly improve root growth. The results of Greenwood and Cameron (1990) suggest that, in terms of practical improvements in root growth, measurements of air permeability are likely to be useful in predicting the requirement for subsoiling.

2.6.2 Effects of subsoiling on root penetration

Soil physical properties influence root growth (Nye and Tinker, 1977). Soil horizons with a high penetration resistance often have high bulk densities, and a low percentage of large continuous macropores which may be used as pathways for root growth (Russell, 1977). These factors have been widely reported as significant limitations to root penetration of a wide range of crops (Dawkins *et al.*, 1984a; Ide *et al.*, 1984; Barraclough and Weir, 1988; Unger and Kaspar, 1994)

Roots must, in consequence, force their way into a soil so they can grow only in soils which are compressible (Russell, 1980). Many attempts have been made in the literature to measure the effects of compaction or shear strength of a soil on root elongation. Plant roots will rarely enter a light-textured soil if its bulk density exceeds 1.7–1.8 g cm^{-3}, or a heavy textured soil if it exceeds 1.5–1.6 g cm^{-3}. It is possible that the roots of large-seeded plants such as peas (*Pisum sativum*), with well-developed tap roots, can exert a maximum pressure as high as 5 – 10 MPa, but cereal roots appear to have their growth affected by much smaller soil pressures.

In most experiments involving subsoil loosening, plant root growth has increased compared with treatments in compacted subsoils. Greenwood and Cameron (1990), for example, recorded an increase in root depth from 300–400 mm to 600–700 mm after subsoiling. Other local researchers including Harrison *et al.*, (1994) and Chapman and Allbrook (1987) have found similar differences. Harrison *et al.*, (1994) determined that significant differences had developed in root length by the first spring of autumn subsoiled treatments. In these treatments, pasture roots at 20–30 cm depth were significantly longer than control plots. Similarly, in the first summer, the differences in root depth were obvious further down the soil profile, this time in the 300–400 and 400–500 mm depths.

Harrison *et al.*, (*loc. cit.*) concluded that a greater rate of root growth was evident in the loosened soil compared with the control treatment. Furthermore, increased root growth rates occurred largely in depths that were previously inaccessible to root growth because of the high bulk density of the soil. In this experiment 35% of the total root length in the subsoiled plots was present below 250 mm depth. By contrast, in the nil and aerated treatments only 25 and 28% of the root length respectively was within the 250 mm depth.

Chapman and Allbrook (1987) concluded that the depth of plant roots growing within a 10 cm band either side of the subsoiler slits were deeper than roots in the non-subsoiled plots (Table 5). Greenwood and Cameron (1990) concurred with this result in determining that 35–40% of roots were located within 50 mm of the share plane and 50–60% within 100 mm of that zone. They emphasised the need to determine the spatial variability of soil physical properties prior to developing a procedure for estimating root growth.

Table 5: Rooting depth of subsoiled and control plots in a compacted soil.

	Subsoiled	Control
Maximum rooting depth (mm)	285	235

(After Chapman and Allbrook, 1987)

2.6.3 Effects of subsoiling on hydraulic properties

Plants need to uptake a considerable amount of water to satisfy their transpiration demand. Some data suggests that 200–500 litres of water are required for a plant to produce one kilogram of dry matter (kg DM) (McLaren and Cameron, 1996). For a crop yielding 10,000 kg DM ha^{-1} this represents a minimum of 2,000,000 $l\ \text{ha}^{-1}$ of water. Compaction alters the soil structure, which determines water content and water transmission in soils (Walkentin, 1971). Water content and transmission are affected most by the changes in pore size distribution and compaction is the most important change affecting agronomic practice (Langer, 1990). The volume of water flowing through a tube per unit of time, according to the Poiseuille equation (Equation 1), is proportional to the fourth power of the radius.

Equation 1

$$Q = \frac{r^4 \text{ x } i}{5037}$$

Where Q is the flow, d is the pore diameter and *i* is the hydraulic gradient.

Halving the tube size (*i.e.* porosity) decreases the flow volume by a factor of 16 (Studman, 1990). Compaction, therefore, in decreasing macroporosity has a large effect in decreasing water transmission in saturated soil (McLaren and Cameron, 1994). The maximum amount of water retained by the soil at saturation is decreased by compaction (Walkentin, 1971). Depending on the rate of transpiration, water movement into roots is caused by two different forces:

1. Active absorption (osmosis) — occurs at slow transpiration rates.

2. Passive absorption (mass flow) — occurs at high transpiration rates.

Absorption (F) may be described by the following equation

Equation 2

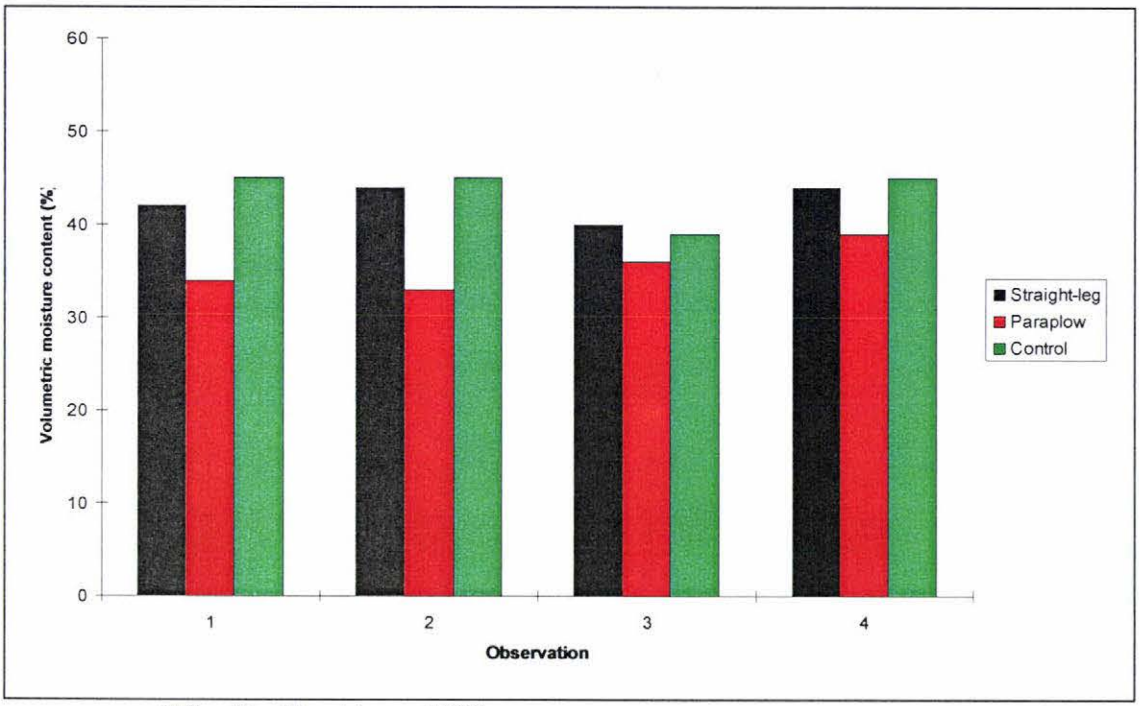
$$F = \frac{(\psi_m + \psi_s)\text{soil} - (\psi_p + \psi_s)\text{plant}}{r_s + r_p}$$

Where ψ_m is the soil matric potential, ψ_s is the solute, ψ_p is the plant pressure potential and r is the resistance to flow in both the plant and soil.

Subsoiling can significantly increase water use by dryland crops. At soil water contents near saturation, large continuous macropores conduct most of the water moving through a soil (Bouma *et al.*, 1982; White, 1985). Consequently, the macropores created by subsoiling improve water transmission through the root zone. Dye studies by Greenwood and Cameron (1990) showed that many of the newly-created pores were indeed vertically continuous between the topsoil and almost the full depth of loosening. This is believed to reduce the incidence of root-zone waterlogging which can result in significant crop yield losses in some yellow-grey earths.

Subsoiling has further been shown to increase the rate of transmission of water (K_{sat}). Greenwood and Cameron (*loc. cit.*) compared non-subsoiled treatments with deep loosening and concluded that, after subsoiling, an increase in K_{sat} of 2–4 orders of magnitude was apparent. Hamilton-Manns (1993) observed a similar trend with volumetric water content, with the plots subsoiled with a Paraplow® experiencing a significantly lower soil volumetric water content than the other treatments
(Figure 12).

Figure 12: Soil volumetric moisture content (%) of three subsoiling treatments.



(After Hamilton-Manns, 1993)

Harrison *et al.*, (1994) concluded that subsurface loosening treatments resulted in significant increases in hydraulic conductivity at 200–300 mm deep. During the first spring of this experiment, the soil profile (0–700 mm) in the subsoiled treatment was significantly drier than the control. This was considered by the authors to be the result of more moisture being retained in the control treatment and the increased drainage in the loosened soil, as shown by the increased hydraulic conductivity values (Table 6).

Table 6: Saturated hydraulic conductivity (mm h^{-1}) as affected by loosening treatment.

Depth (mm)	Nil	Aerated (270 mm)	Subsoiled (470 mm)
0–100	37.9	-	290.6
100–200	36.5	163.3	83.6
200–300	51.3	380.2	138.0
300–400	17.9	47.2	130.6
400–500	1.4	-	6.3

(After Harrison *et al.*, 1994)

It has been widely acknowledged that large, surface-connected macropores can have a significant effect on the downward water movement (Thomas and Phillips, 1979; White, 1985). In macropores continuous to depth, macropore flow enables water to move rapidly downward from the surface and upper layers of the soil profile. This is often a major objective of loosening soils which contain slowly-permeable zones, because, during rain or irrigation, such zones may cause surface erosion, root-zone waterlogging and poor recharge of plant-available soil water (Swain, 1975; Unger, 1979).

Improvements in hydraulic conductivity resulting from subsoiling have had marked effects on irrigation water penetration into the soil. Greenwood and Cameron (1990) reported a difference in penetration of about seven orders of magnitude between subsoiled and control treatments. During irrigation or rain, such improvements in water transmission may lead to a reduced incidence of transient waterlogging in the root zone (Greenwood and McNamara, 1987).

Subsoiling can significantly increase water use of dryland crops. Greenwood and Cameron (1990) reported that subsoiling at 350 mm deep increased total water use of peas by 22 mm, while deeper subsoiling at 500 mm increased water use by 42 mm. These increases were associated with increased root length of 40–80% over control treatments. Estimates of plant-available water capacity (PAWC) by Greenwood and Cameron (*loc. cit.*) indicate that increases in maximum rooting depth (Z_{max}) increased PAWC from 65 mm to 85 mm by subsoiling to 350 mm depth, and to 98 mm by subsoiling to 500 mm depth. In most studies, subsoiling has usually resulted in substantial increases in the amount of soil water which is potentially available for crop uptake.

In addition to increases in Z_{max}, however, subsoiling also increases subsoil root densities both above and below the maximum rooting depths of the non-subsoiled control. Since the ease of water uptake from a given soil zone increases with root density or with homogeneity of root distribution (Passioura, 1985), subsoiling therefore improves water extraction from above, as well as below, the rooting depth of non-subsoiled treatments. By increasing subsoil root densities, subsoiling enabled the pea crop of Greenwood and Cameron (1990) to withdraw water from a significantly deeper and larger volume of soil. Such an effect of subsoiling has been widely reported for a range of crops (Ide *et al.*, 1984; Chaudhary *et al.*, 1985; Marks and Soane, 1987; Steed *et al.*, 1987). Under irrigation, however, extensive root systems are unnecessary, and even when root growth is restricted by compacted soil, crops may not suffer water stress if the water supply to those crops is sufficient to meet its demands.

2.6.4 Crop responses to subsoil loosening

The increase in bulk density and the decrease in macroporosity which occurs during compaction can restrict root development, inhibit air and water movement. This decreases plant growth (Climo and Richardson, 1984; Naeth *et al.*, 1990; Mulholland and Fullen, 1991) although ethylene toxicity may often play a significant role (Dawkins *et al.*, 1983; 1984b). Changes in states of compactness, and resultant differences in crop yield, have been reported in many publications which show that compaction can substantially reduce yield (*e.g.* Batey and Davies, 1971).

Richardson *et al.,* (1990), although largely focusing on the drainage effects of subsoiling on Northland soils, reported average yield differences of 21% between subsoiled treatments and control plots. In the first year, pasture responses were recorded at 26.5% and declined to 17% yield increases in years two and three. Such improvements in pasture production shown in this work was consistent with those found in mole drainage experiments (Horne and Tillman, 1984; Horne, 1985), shallow aeration (Davidson, 1986) and deep subsoiling (Ross, 1988). From a practical perspective, most of the additional production occurred when it is most valuable, during winter and early spring. Subsoiling in this experiment, however, by improving the rate of downward percolation of soil moisture, resulted in a yield decline in the dry summer months, presumably as a response to declining plant-available water during this period.

In a similar environment, although located in Canterbury, Greenwood and Cameron (1990) reported substantial increases in the seed yields of pea and cereal crops following subsoiling. In the season following subsoiling, seed yields increased by 18–43% (0.5–1.2 t ha^{-1}). The following cereal crops grown, however, exhibited diminishing responses to subsoiling in each of the successive three years.

2.7 Conclusions

The review of the literature has clearly identified the benefits of maintaining crop residues intact upon the soil surface where they lay after harvest. Traditionally crop residues, often incorrectly referred to as "trash", have been burnt, baled or swept aside to alleviate the potential problems it creates for successful no-tillage to proceed. Recent research would suggest that this has been the incorrect approach and that the focus should have been placed on creating a biologically superior no-tillage opener. Such an opener should be capable of handling a wide variety of crop residues with germination and emergence results as good as if not better than conventional tillage, the basis for all such comparisons.

Conservation tillage systems allow the retention of "valuable" crop residues which provide benefits across a range of soil physical, biological, chemical and hydrological properties. Crop residues are capable of improving soil structure, create conditions conducive to earthworm and other soil fauna to function, return valuable nutrients to the organic pool, and increase the soil water storage capabilities. In addition, and perhaps most importantly in erosion prone areas of the world such as the United States, residue management is an effective mechanism against both wind and water erosion. No other single soil conservation technique has reduced both wind and water erosion in a continuous cropping regime as much as changing from tillage to no-tillage.

Recent developments in machinery, herbicides and management have re-established no-tillage as an alternative method of successfully establishing crops. Despite its benefits, no-tillage has been identified by some authors as leading to higher soil bulk densities and soil strength. Smaller root systems, and ultimately reduced crop vigour and yield, have been observed with no-tillage when compared with crops established by tillage. Indeed some authors have illustrated the need for deep loosening to alleviate potential compaction and improve the agronomic performance of crops or pastures established without tillage. This observation is especially pertinent in finely-textured soils that have been subject to intensive tillage and its inherent problems cited earlier, where subsoiling has been reported as improving physical conditions in these situations.

Subsoiling can overcome the effects of soil compaction by improving soil physical conditions which, in certain circumstances, may lead to substantial increases in crop yield. Most previous studies, however, have been largely agronomic, and relatively few have comprehensively assessed the effects of loosening on soil physical properties. Generally, there has been little integration of soil and plant responses. Descriptions of soil conditions before and after loosening, and of the subsoiling equipment used, have generally been vague, while the pattern and type of loosening achieved was seldom described. In such situations, the effects of loosening on crop yield cannot be interpreted in terms of soil physical conditions.

When soil aeration is limited within the soil solution, root penetration and proliferation is decreased. Root growth is directly related to soil oxygen levels and where this essential compound is limiting (associated with a low respiration rate) their growth and permeability to nutrient uptake is low. Subsoiling improves both the volume and continuity of macropores resulting in improved air transmission. In some instances the downward water transmission is also improved and the presence of water-filled pores is the main restriction to aeration.

Roots will seldom enter soil horizons with high penetration resistances or bulk densities and will instead either become shallow rooted or adopt a lateral distribution. Either situation impairs plant moisture and nutrient uptake. Subsoiling improves plant root depth, usually by a factor of two when compared with compacted soils. The amount of water retained by the soil is decreased by compaction as the total porosity is reduced. After subsoiling, however, downward water movement is often increased and the plant available water content is reduced in dry periods.

3. Method and Materials

3.1 Description of trial site

3.1.1 Location

The field experiment described in this chapter occupied a section of a paddock on the property of Ross and Helen Maxwell at Taonui (lat. S401/5238, long. E175/38143), 13 kilometres north-east of Palmerston North, New Zealand. The plains of the Manawatu region support a range of land uses including intensive mixed livestock and cropping farms.

3.1.2 Climate

The region is classified as "moist temperate" (Brougham, 1979) with an average air temperature of 17°C. The area does not experience extreme temperatures; the daily temperature range is 8–9°C throughout the year. Temperatures exceeding 30°C are seldom recorded (Burgess, 1988) but regularly reach over 25°C in summer. Frosts may occur between March and November but are usually only light (-1 to -2.9°C) with some (30–40%) being of moderate intensity (-3 to -5.9°C). Rainfall is reliable with a 30 year average of 958 mm (S. Burgess, pers. comm., 1997)

3.1.3 Soil type

The soil at the trial site, Milson silt loam series (Cowie and Rijkse, 1977), is an Argillic Perch-Gley Pallic Soil (Hewitt, 1992) according to the New Zealand genetic classification (formerly referred to as a Yellow Grey Earth) and would be classified as a Typic Ochraqualf soil using the American Taxonomy. The Milson silt loam is derived from loess, and is poorly drained in its natural state (C.W. Ross, pers. comm., 1997). A full profile description is provided in Appendix 2.

Between 1992 and 1995, the paddock was cropped in a rotation of spring-sown cereals and winter forage crops using conventional tillage (*i.e.* a mouldboard plough and secondary cultivation). In November 1996, a crop of peas (*Pisum sativum* L.) was sown using no-tillage.

3.2 Experimental design

The experimental design was a "randomised, complete block" as described by Fowler and Cohen (1992), with four treatments and four replications. Figure 13 is a diagrammatic representation of the experimental layout.

The treatments were:
1. Mole plough (M).
2. Straight-legged subsoiler (SL).
3. Paraplow® (PP).
4. Control (C).

Plots measured 8 by 40 m. No-tillage was performed across all treatments to sow the crops. Treatments were assigned to plots on a random basis.

3.2.1 Seed drill

Crops were sown using a Cross-Slot™ no-tillage drill. The advantages of this opener configuration are discussed in Section 2.3.1. The particular Cross-Slot™ drill used in this study had 13 openers at 150 mm row spacings to give a sowing width of 1.95 m, and was capable of sowing seed, fertiliser and insecticide (Figure 14).

Figure 13: Experimental plan (not to scale) showing plots and position of drainage line.

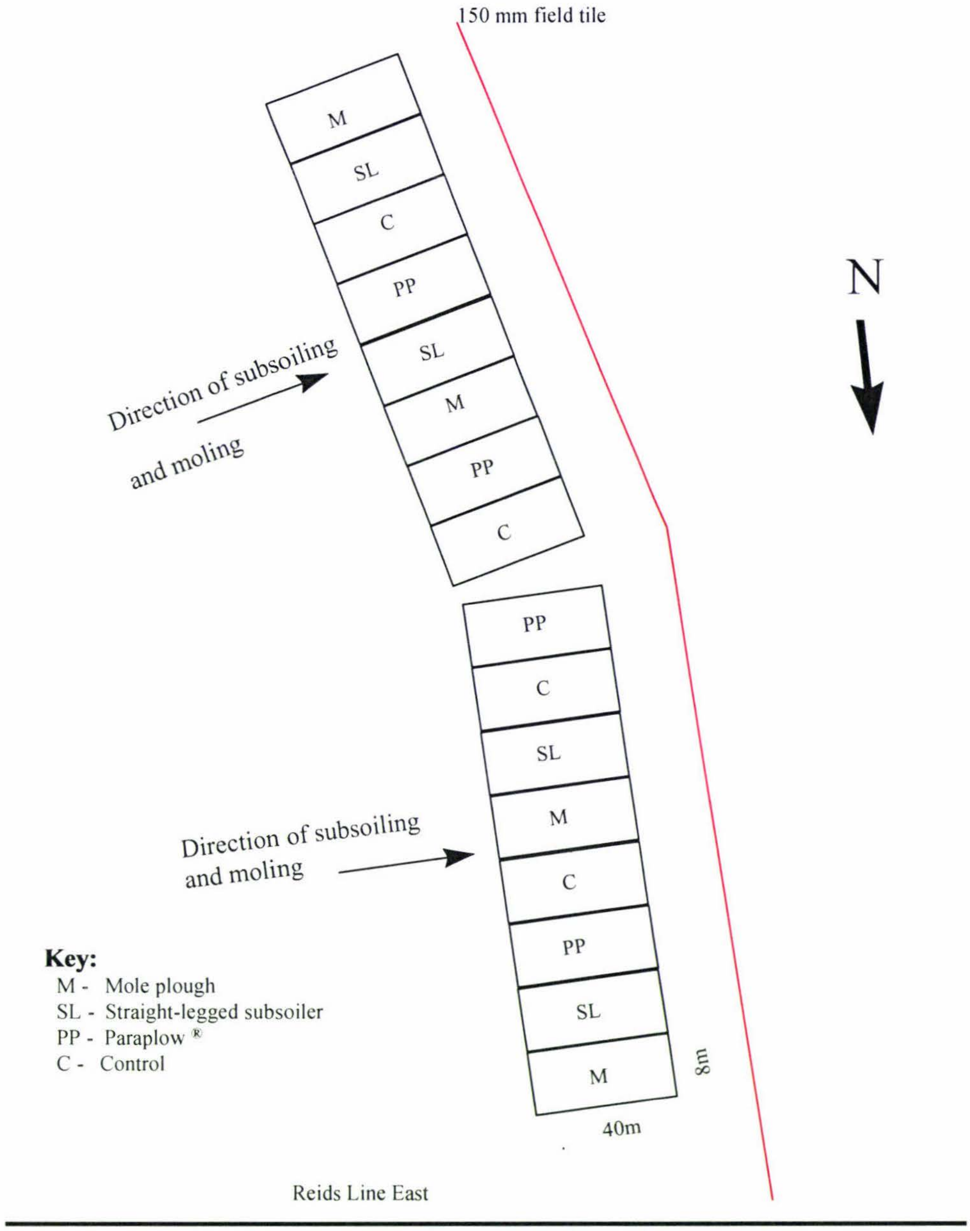


Figure 14: Cross-Slot™ no-tillage drill used for crop establishment.

3.2.2 Subsoiling and moling

Two subsoiling implements and one mole plough were used in the experiment:

1. A Klough semi tractor-mounted mole plough similar to that described by Bowler (1980) (Figure 15).
2. A four-legged Aitchison straight-legged subsoiler (Figure 16).
3. A two-legged Paraplow® as described by Pidgeon (1983) (Figure 17).

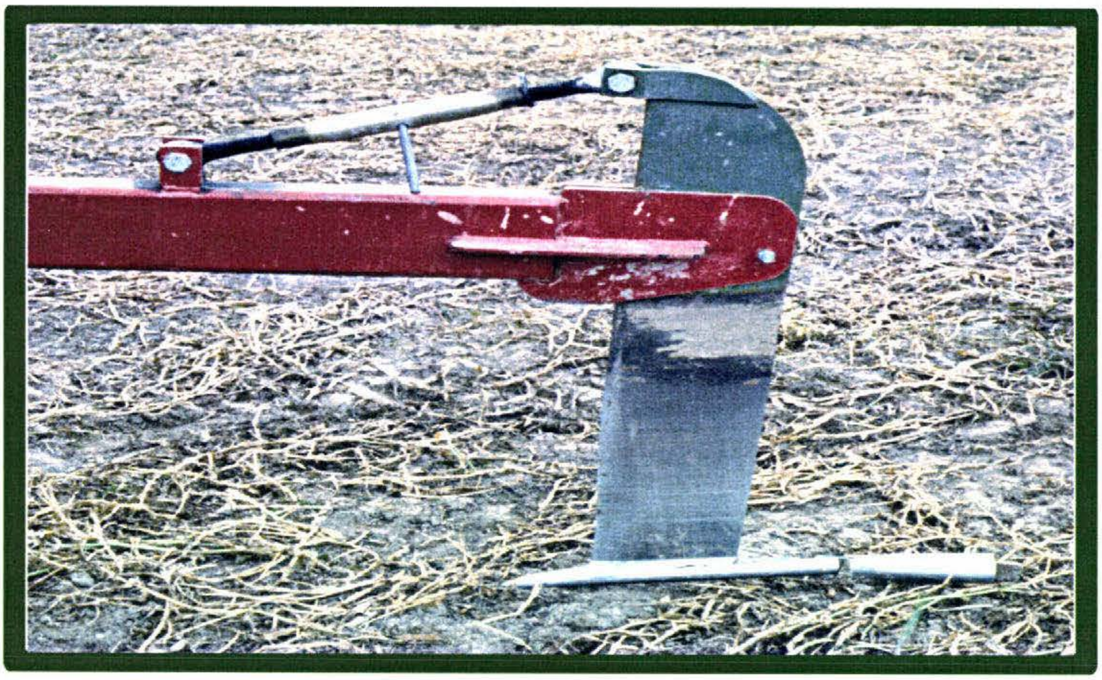
Mole channels were installed at 2 m intervals at a depth of 450 mm. The mole drains were later junctioned vertically with the tile drain (600 mm depth) using a spear of 20 mm diameter.

The Paraplow® treatments were subsoiled to a depth of 450 mm with 500 mm between the shank lines. Difficulty was experienced in obtaining and maintaining the correct working depth of 450 mm due to the dry soil conditions at the time of subsoiling. A total of 500 kg of steel ballast was required to assist the penetration of the rear leg into the soil. Some fluctuations in operating depth were experienced across the length of the plots. No attempt was made to junction the slits created by the tynes with the tile drain.

The straight-leg subsoiled treatments were loosened to a depth of 250 mm with 500 mm between the shank lines. As for the Paraplow® treatments, the straight-legged subsoiler implement had difficulty in reaching the desired working depth. Two of the tynes were removed from the implement, reducing its draught requirement by 50%, to allow a constant working depth to be achieved. No attempt was made to junction the slits created by the tynes with the tile drain.

All subsoiling and moling operations were performed on 17 February 1997, about 11 days after the pea crop was harvested.

Figure 15: Semi tractor-mounted mole plough.



3.2.3 Crop establishment

A winter forage crop, *Brassica campestis* x *Brassica napus* cv "Pasja" was sown at a rate of 3 kg ha^{-1} on 24 February 1997. A high analysis N–P–K fertiliser (8–15–15) was placed with the seed at a rate of 200 kg ha^{-1}.

On 3 October 1997, the brassica crop was sprayed with glyphosate (360 g l^{-1} glyphosate as active ingredient) at a rate of 2 l ha^{-1} in 100 l ha^{-1} of water. To increase penetration and plant uptake of the translocated herbicide, a surfactant (Pulse®) was used at a rate of 100 ml per 100 *l* of water. A penetrant is commonly applied with glyphosate to enhance plant uptake and herbicide translocation (O'Connor, 1990).

A spring wheat crop, *Triticum aestivum* cv "Kohika", was sown at a rate of 160 kg ha^{-1} on 30 October 1997. A high analysis N–P–K fertiliser (15–10–10) was placed with the seed at a rate of 250 kg ha^{-1}. A molluscicide, "Slug Out" (18.0 g kg^{-1} metaldehyde), was broadcast behind the drill at a rate of 8 kg ha^{-1}.

Figure 16: Straight-legged subsoiler.

Figure 17: Howard two-legged Paraplow®.

3.3 Parameters measured

3.3.1 Soil strength

A Bush recording penetrometer with a standard ASAE 30° 12.83 mm cone was used to monitor soil strength. Cone index readings were taken at 100 mm intervals on a 2 m lateral transect at right angles to the direction of subsoiling and moling. Readings down the soil profile were at depths of 10, 30, 50, 70, 90, 110, 130, 180, 230, 280, 330, 380, 430 and 480 mm, giving a total of 294 cone index values for each profile. This procedure was replicated twice per plot at randomly selected sites.

Soil penetrometry was performed on three occasions, the first on 20 February 1997 (three days after subsoiling operations), the second on 30 June and the third on 11 November (12 days after the wheat crop was established). On each occasion, gravimetric soil moisture contents in the 0–100, 100–200, 200–300, 300–400 and 400–500 mm horizons were measured using the "core technique" to qualitatively describe the relationship between soil strength and soil moisture. Samples were bulked according to treatment.

3.3.2 Soil moisture content

Volumetric soil water content was monitored with Time Domain Reflectometry equipment (TDR) (Soil Moisture Equipment Corp, Santa Barbara, CA, USA). This instrument utilises microwave pulses travelling down two parallel soil probes. The speed with which pulses travel along the probes is a function of the dielectric constant (K) of the soil which, in turn, is determined by the soil moisture content (Topp and Davis, 1985). Soil volumetric water content was measured at regular intervals from mid-July until the end of August. Three lengths of wave guide were used (150, 300 and 450 mm) and replicated twice per treatment. This allowed the soil water content to be measured over the range of disturbance patterns created by the soil loosening treatments.

3.3.3 Bulk density

Soil bulk density was measured using the "core technique" described by (McLaren and Cameron, 1996). On May 10, soil samples were taken at three depths, 0–150, 150–300 and 300–450 mm, using cylindrical aluminium cores measuring 75 mm long with an internal diameter of 100 mm (mean volume of 589 cm^3). Holes were dug randomly in the plots and cores inserted in the middle of the three horizons before being extracted. This process was replicated twice per plot.

A Troxler Model 3440 (Anon., 1991) gauge was used as an alternative and non-destructive means of measuring soil bulk density. A source, containing Caesium–137 which produces gamma rays, is lowered into the ground. Gamma photons reaching the detectors in the base of the unit must pass through the soil, resulting in a large number of photons colliding with soil electrons. These collisions reduce the number of photons reaching the detectors and thus allow the soil density to be calculated. Bulk density was measured with the Troxler density gauge within the 0–300 mm horizon on May 12 and again on February 28. Ten replicates were performed per plot at locations chosen randomly.

3.3.4 Air permeability

One approach to characterising soil aeration is to measure the air permeability (the coefficient governing convective transmission of air through the soil in response to a total pressure gradient) (Hillel, 1980). This measurement can provide useful information on the effective sizes and the continuity of air-filled pores. Grover (1956) used falling-pressure devices in the field and found them useful for assessing the "openness" of the surface layer to the entry of air, as affected by cultural practices such as tractor traffic and tillage. A "falling-head" permeameter similar to that described by Hillel (1980) was used in this experiment.

Readings of air permeability were taken across all plots on 15 August at locations selected randomly. Ten measurements were taken within each plot by inserting the pressure probe into the soil to its operating depth of 50 mm. The pressure cylinder was pressurised to a constant pressure (40 kPa) before evacuation. The time taken for the pressure in the cylinder to fall by 20 kPa was measured with a stop watch and later converted to air permeability using an algorithm to form the permeability data reported in the next section.

3.3.5 Plant population counts

At 27 days after sowing (23 March 1997), plant establishment counts of the brassica crop were performed by counting emerged plants along 1 m of row. This process was replicated at ten sites chosen randomly within each plot. Plant populations per square metre were subsequently calculated. At 30 days after sowing (30 November 1997), plant establishment counts of the wheat crop were performed using the same process as described above

3.3.6 Crop yield

Two pasture exclusion cages measuring 1.17 m x 0.54 m (0.63 m^2) were placed on each plot on 1 July. Forage brassica growth from 1 July to 21 July (21 days) was hand harvested, washed and oven dried at 80°C for 12 hours before weighing. Yield was calculated on a kilograms of dry matter per hectare (kg DM ha^{-1}) basis. On 27 February the cereal plots were harvested at 14.3% moisture with a plot-sized harvester and yield calculated on a kilograms per hectare (kg ha^{-1}) basis.

3.3.7 Brassica root depth and weight

To measure plant root depth, profile pits measuring 1m wide by 300 mm deep were dug at right angles to the direction of travel of the subsoiling and moling implements. A fresh profile wall and plant roots were exposed by using a fine water spray to wash a 5 mm layer of soil away. Maximum rooting depth was measured *in situ*. This process was replicated at two sites chosen randomly within each plot in July.

Blocks of soil were then carefully removed so as not to break the roots before being washed to remove excess soil. Further washing to remove additional soil followed before the remaining root mass was oven dried at 80° C for 24 hours and weighed.

No root studies of the cereal were performed due to time constraints placed upon the completion of this work.

3.4 Statistical analysis

Much of the statistical analysis was performed by computer using the statistical software package SAS® (Statistical Analysis Systems Institute, Carey, NC, USA). Analyses of the experimental data were carried out under the assumption of a randomised complete block (Fowler and Cohen, 1992) and presented as the SAS® "ANOVA" and "GLM" output. Analyses of variance, in conjunction with appropriate T-tests, were used to determine the significant differences between treatments.

4. Results and Discussion

4.1 Surface roughness

Soil conditions at the time of subsoiling and moling were very dry (Table 7). Additional ballast was added to the Paraplow® to facilitate its entry into the soil and to help maintain the correct working depth. The soil surface of the plots subsoiled with the Paraplow® and the straight-legged subsoiler was very uneven due to the substantial soil disturbance that occurred during the loosening operations.

Table 7: Gravimetric soil moisture content three days after subsoiling and moling in the autumn of 1997.

	Gravimetric moisture content (%) 20 February			
Depth (mm)	**PP**	**SL**	**M**	**C**
0–100	11	11	11	10
100–200	12	12	11	11
200–300	11	12	11	12
300–400	11	12	12	13
400–500	12	13	13	13

4.2 Climate

The 1997 winter was exceptionally dry and mild. Total rainfall during the brassica experiment (*i.e.* February to August inclusive), measured at the site, was 465 mm, 13% less than the 30 year mean of 525 mm (Figure 18). Rainfall during May, June and July in 1997 was only 48% of the long-term average for this period.

Mean daily air temperatures for 1997 were similar to the 30 year mean (Table 8), but daily temperatures for May, June and July were approximately 19% warmer than average.

Figure 18: Monthly rainfall for 1997 and the 30 year average.

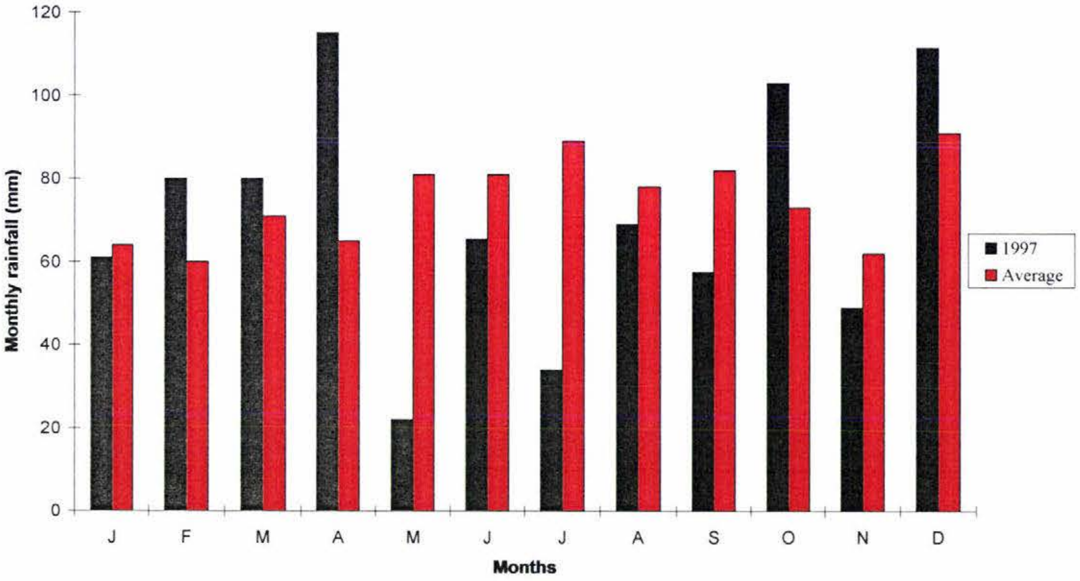


Table 8: Mean daily air temperature for 1997 and the 30 year average.

Month	Mean daily air temperature in 1997 (°C)	30 year mean daily air temperature (°C)
January	16.4	17.7
February	18.2	17.9
March	16.1	16.7
April	12.6	13.9
May	12.9	11.1
June	13.5	9.1
July	7.8	8.3
August	9.3	11.8
September	10.5	11.0
October	12.3	12.4
November	14.4	14.4
December	16.8	16.4

4.3 Soil volumetric moisture content

There were no consistent differences in soil moisture content between treatments. M had a lower volumetric moisture content ($P \leq 0.05$) in the 0–150 mm horizon than PP, SL or C on 3 August (Figure 19) less than 24 hours after a rainfall event of 8.5 mm. This difference may have been due to improved drainage from this depth on M plots. This was the only occasion that moisture measurements were made immediately after substantial rainfall. Given the low rainfall experienced throughout the brassica trial, a lack of differences in soil moisture content is not surprising. The volumetric moisture content of this soil at saturation (θ_{sat}) in undisturbed (C) plots was estimated to be 0.53 for the 0–150 mm depth, while the mean value recorded for this depth was only 0.41.

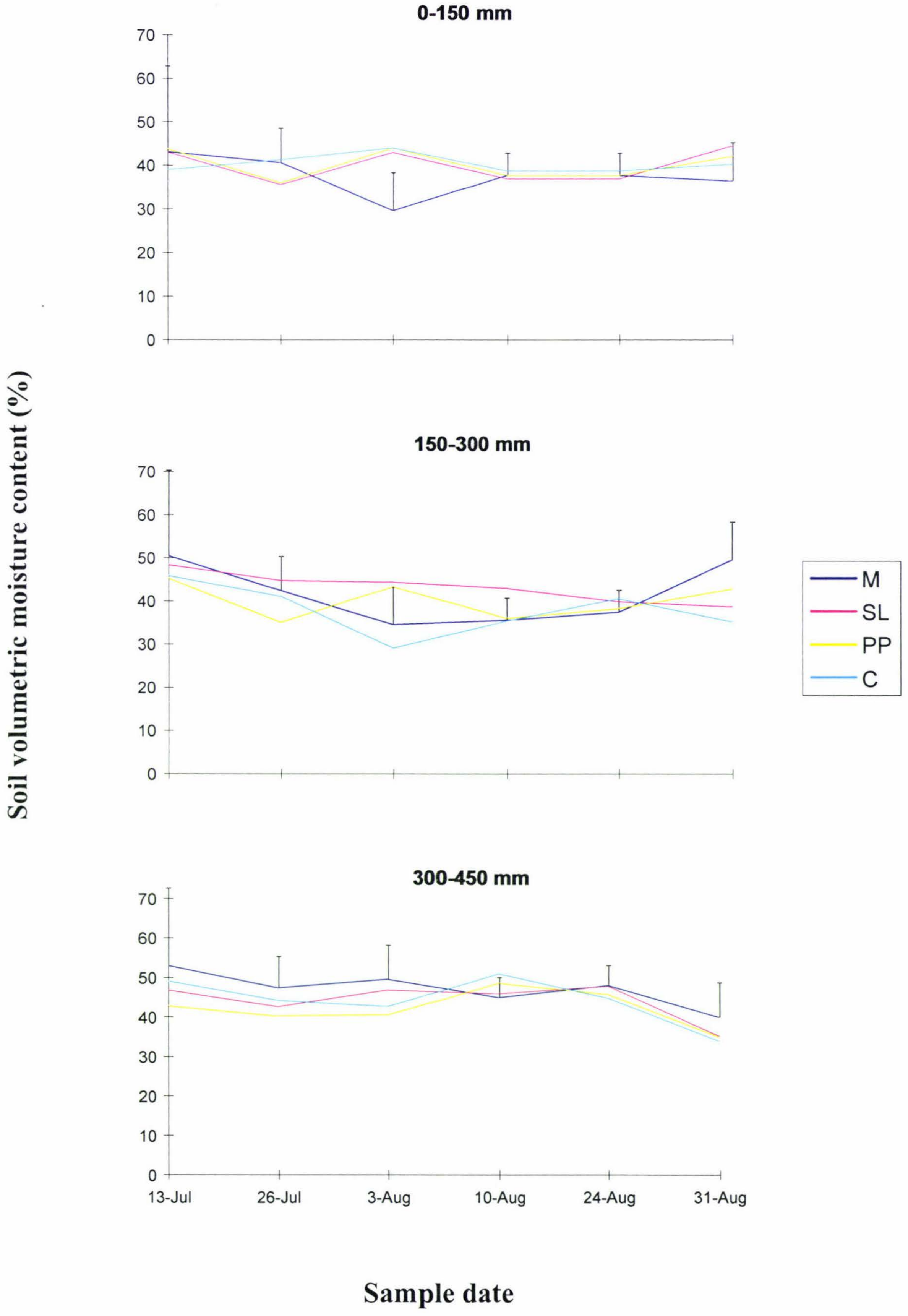
4.4 Bulk density

Bulk density, as measured by the corer procedure, in the 0–150 mm depth was 8% ($P \leq 0.05$) greater in PP, SL and C compared with M. The low value measured in M is surprising and could be an aberration of the sampling procedure used. The M treatments did, however, have a large degree of variation in bulk density values as is reflected in the high standard deviations (Table 9). There were no significant differences between either of the subsoiling treatments and C in the 0–150 mm depth. There were no differences between any of the treatments in either the 150–300 or 300–450 mm depths.

Table 9: Bulk density measured by hand-sampling on 10 May 1997.

	Bulk density (g cm^{-3}) (mean ± standard deviation)			
Depth (mm)	**Paraplow (PP)**	**Straight-legged (SL)**	**Mole (M)**	**Control (C)**
0–150	1.27b ± 0.06	1.24b ± 0.09	1.15c ± 0.22	1.23b ± 0.08
150–300	1.40a ± 0.06	1.43a ± 0.05	1.39a ± 0.21	1.41a ± 0.04
300–450	1.45a ± 0.05	1.44a ± 0.02	1.43a ± 0.06	1.44a ± 0.02
LSD	0.0619			
Unlike letters within a column or row denote significant differences at ($P \leq 0.05$)				

Figure 19: Volumetric moisture content in the 0–150, 150–300 and 300–450 mm depths (I = LSD at P≤0.05).



Many authors, including Baker *et al.*, (1996), McLaren and Cameron, (1996) and Sojka *et al.*, (1997), have stated that bulk density, as measured by the core technique, is a relatively insensitive measure of tillage effects. An alternative, non-destructive technique, a Troxler moisture/density probe, was used to obtain a relatively large (in comparison to the core technique) number of readings of bulk density.

Bulk density data obtained with the Troxler density probe revealed that, in the 0–300 mm range, SL and PP had significantly ($P \leq 0.05$) lower bulk densities than either M or C. At this depth, PP had a significantly ($P \leq 0.05$) lower bulk density than any other treatment (Table 10), averaging 6% less than M and C, and 2% less than SL. This possibly reflects the greater amount of soil loosening achieved with the Paraplow® compared with the other treatments. Although these differences seem small it should be remembered that the values given in Table 10 are the mean values of a large depth increment (0–300 mm): there are probably quite large differences between treatments in some points of this horizon. The relatively high standard deviation for M experienced in the hand-sampled bulk density analysis (Table 9) was also observed with this technique. This is probably due to the comprehensive but very localised fracturing pattern created by mole ploughing (Culpin, 1992). An obvious and noteworthy observation is that the Troxler method enabled both the standard deviation and LSD to be reduced by, on average, a factor of three for all treatments.

Table 10: Bulk density measured by the Troxler moisture-density gauge on 12 May 1997.

	Bulk density (g cm^{-3}) (mean ± standard deviation)			
Depth (mm)	**Paraplow (PP)**	**Straight-legged (SL)**	**Mole (M)**	**Control (C)**
0–300	1.26c ± 0.02	1.29b ± 0.01	1.34a ± 0.08	1.35a ± 0.01
LSD	0.022			

Unlike letters between a column or row denote significant differences at ($P \leq 0.05$)

The loosening effects of subsoiling and mole ploughing, as measured by decreases in bulk density on May 12, were not apparent after cereal harvest (28 February 1998), 376 days after subsoiling and moling (Table 11). There were no differences in bulk density between treatments at this time ($P \leq 0.05$), and all treatments had undergone some consolidation since May 12. In February 1998, PP and SL treatments had bulk density values measuring 4.5% and 2.2% greater than the values measured in May, respectively. The differences in bulk density for both M and C between measurement dates were negligible. The compactive effects of grazing livestock (Climo and Richardson, 1984), vehicles and tillage traffic over winter and spring (Baker *et al.*, 1996) may have been partly responsible for the increase of bulk density values over time.

Table 11: Bulk density measured by the Troxler moisture-density gauge on 28 February 1998.

	Bulk density (g cm^{-3}) (mean ± standard deviation)			
Depth (mm)	**Paraplow (PP)**	**Straight-legged (SL)**	**Mole (M)**	**Control (C)**
0–300	1.33a ± 0.018	1.32a ± 0.019	1.35a ± 0.017	1.36a ± 0.015
LSD	0.04			
Unlike letters between a column or row denote significant differences at ($P \leq 0.05$)				

4.5 Soil Strength

4.5.1 Cone index grand mean values

C plots had the highest mean value of cone indices throughout the study (Table 12). On two of the three sampling occasions, the grand mean for C was equal to or greater than 2 MPa, implying that, on these plots, soil strength was potentially limiting plant root penetration. The cone index value of 2 MPa is widely recognised by researchers as being the critical value for root growth restriction (Unger and Kaspar, 1994).

PP treatments experienced the lowest cone index values, indicating reduced soil strength. At the first sampling (20 February, 3 days after subsoiling and moling), the cone index values for C were significantly greater ($P \leq 0.05$) than all the other treatments. Both PP and SL recorded the lowest cone index values, a 54% reduction in mean profile cone index compared to C. These measurements of soil strength are indicative of the thorough loosening caused by PP and SL treatments. The mean value for M fell between those for the subsoiled and C treatments and suggest that a significant amount ($P \leq 0.05$) of soil loosening occurred with mole ploughing but not as much as through traditional subsoiling.

At the second sample date (30 June, 163 days after subsoiling and moling), the cone indices of PP were significantly smaller ($P \leq 0.05$) than M and C. Interestingly, the means calculated for SL, M and C were not significantly different. However, at the third sample date (11 November) both PP and SL again recorded significantly ($P \leq 0.05$) lower cone index values compared with C. None of the differences in penetration resistance discussed here can be attributed to differences in soil moisture content between treatments (Table 7).

Table 12: Treatment grand mean cone index values (MPa) for the three sample dates.

	Cone index (MPa)		
	20 February	30 June	11 November
Paraplow (PP)	1.68c	1.46b	1.68c
Straight-legged (SL)	1.62c	1.68ab	1.78bc
Mole (M)	2.33b	1.93a	1.86ab
Control (C)	2.54a	1.86a	2.00a
LSD	0.20	0.26	0.17
Unlike letters within a column denote significant differences at ($P \leq 0.05$)			

4.5.2 Cone index profiles

At the first penetrometry (20 February), PP and SL had significantly lower cone index values than C and M tended to be higher (Figure 20). The critical value of 2 MPa was experienced within 70 mm depth in M and C, while it was reached at a depth of about 180 mm in PP and SL.

On 30 June, when soil strength was measured again, there was evidence of reconsolidation in most plots. PP continued to have lower cone index values than M and C. Despite the increases in soil moisture, cone index values for M and C reached 2 MPa near the surface (50 mm) while PP and SL plots achieved this value at a depth approaching 230 mm.

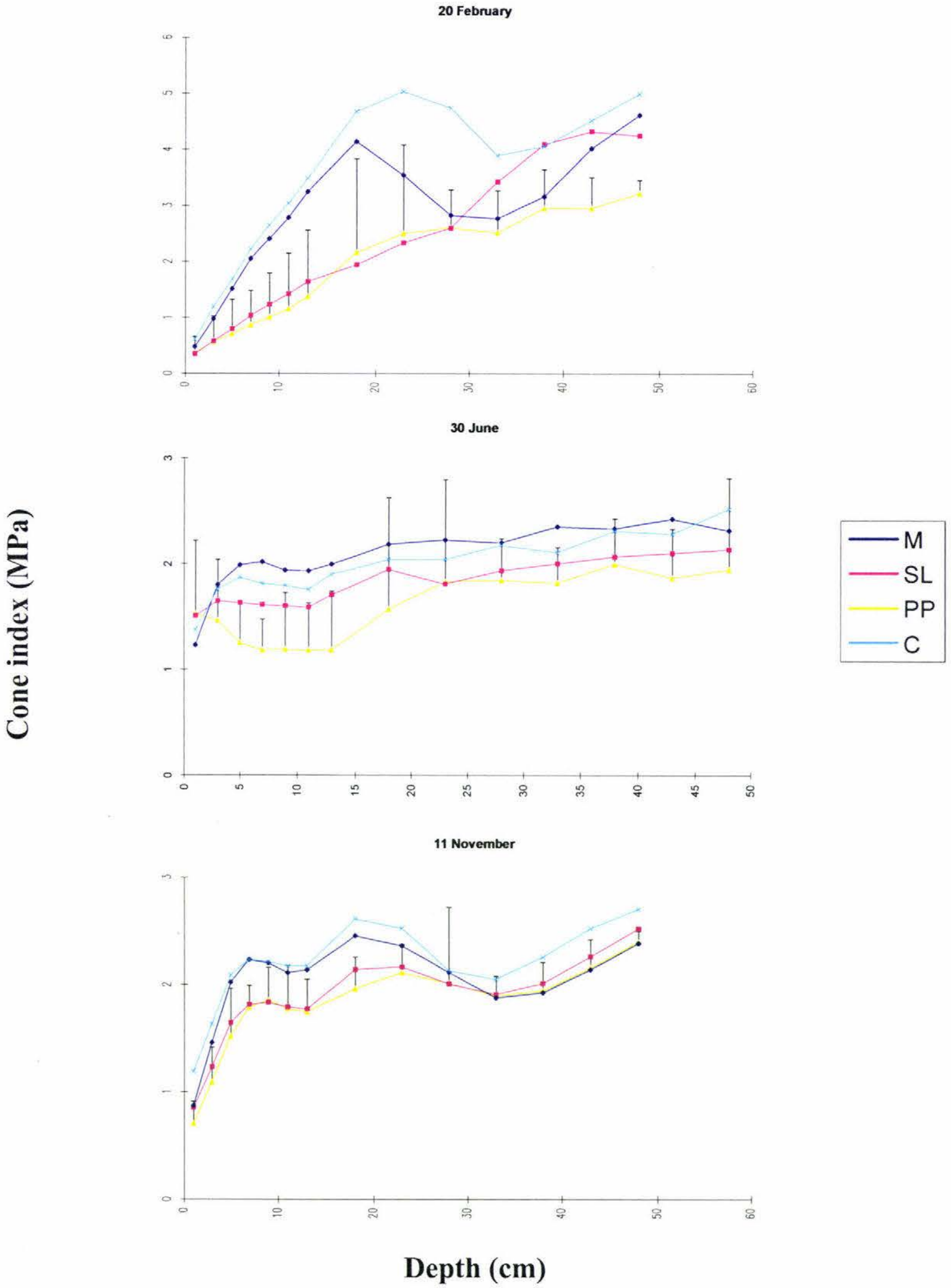
A similar trend was observed for the third and final penetrometry on 11 November. PP and SL still had lower values than C at this time, especially between 90–230 mm depth. All plots had a greater incidence of cone values above 2 MPa and clearly displayed the effects of reconsolidation. This probably resulted from animal treading and vehicular traffic as the paddock had been intensively grazed over the winter and then sprayed and the crop established.

The persistence of loosening for the PP treatments was obvious throughout the trial. This result concurs with Sojka *et al*., (1997) who also found no advantage in terms of loosening to one particular implement but reported that the Paraplow® plots showed a greater persistence of profile loosening than the other treatments.

Table 13: Gravimetric soil moisture content (%) sampled at time of penetrometry.

	Gravimetric moisture content (%) 20 February			
Depth (mm)	**PP**	**SL**	**M**	**C**
0–100	11	11	11	10
100–200	12	12	11	11
200–300	11	12	11	12
300–400	11	12	12	13
400–500	12	13	13	13
	30 June			
0–100	33	34	28	35
100–200	31	29	27	37
200–300	32	30	30	39
300–400	36	30	29	41
400–500	38	31	29	42
	11 November			
0–100	27	29	27	28
100–200	27	29	28	27
200–300	22	21	22	21
300–400	26	25	24	23
400–500	27	27	25	26

Figure 20: Cone index profiles for the three sampling dates (I = LSD at P≤0.05).



4.5.3 Cone penetrometer cumulative frequency distribution

The first time that soil penetrometry was performed (20 February), both C and M had more high cone index values than either PP or SL. Treatments C and M had 55.5% and 49.5% of their cone indices above 2.0 MPa respectively, while only 22.41% (SL) and 18.6% (PP) of cone indices values for the other two treatments were greater than 2.0 MPa (Figure 21). The cumulative frequencies of cone indices for M and C followed similar trends. The M treatment had more low value indices than C, illustrating that moling resulted in a significant amount of soil disturbance and loosening compared with the control (Table 12).

The slope of the frequency distributions for the first penetrometry is noteworthy: the steepest slope for the distributions was between 0–1.2 MPa for the PP and SL plots, where there are three times as many values compared with M and C in the same range. This illustrates the comprehensive nature of the loosening that occurred on PP compared with M and C.

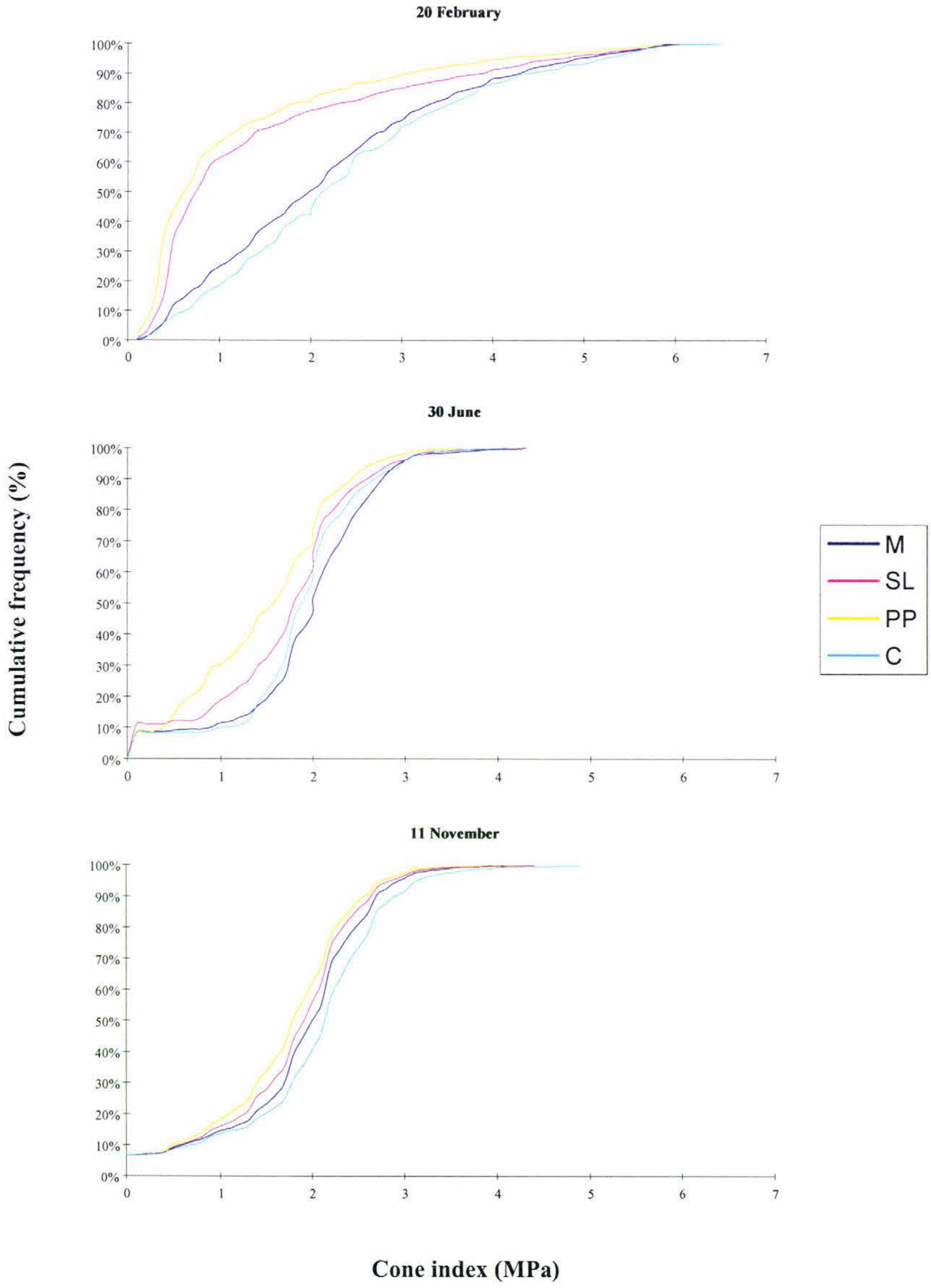
Cone index frequency distributions for PP and SL at the first penetrometry were similar, and this is supported by the treatment grand mean cone index values (Table 12).

The second time penetrometry was performed (30 June), the maximum cone index value was 4.3 MPa compared with the earlier penetrometry where 6.5 MPa was the peak value. This is explained primarily by the increase in soil moisture content between measurement dates (Table 13).

At the second penetrometry, the cumulative frequency distribution for all four treatments followed a similar trend. However, as for the earlier penetrometry, M and C had more high cone values than PP and SL. The C and M treatments had 37.8% and 48.2% of their cone indices above 2 MPa respectively, while 33.4% (SL) and 25.9% (PP) of the cone indices for the other two treatments were greater than 2 MPa. Perhaps the most notable observation was the "coming together" of the cone index values. The wide range in values between treatments is not as evident as it was in the earlier penetrometry (Figure 21).

On 11 November (*i.e.* 12 days after the cereal crop was established) the third and final penetrometry was performed. C and M plots continued to display more high cone values than PP or SL. Treatments C and M had 61% and 50% of their cone indices above 2.0 MPa respectively, while PP recorded 38% and SL 46%. The increased soil strength on C and M is undesirable at this time given that a newly-sown crop is attempting to become established and a soil profile in the drying phase. There was still some evidence of soil loosening nine months after the subsoiling operations were performed. The peak cone index value recorded was 4.9 MPa (C) while the other three treatments varied between 4.3 and 4.4 MPa.

Figure 21: Cone penetrometer cumulative frequency distribution for the three sampling dates.



20 February

30 June

11 November

4.5.4 Cone index profile isopleths

Profile soil strength patterns reveal the spatial distribution of subsurface soil disruption associated with each treatment. Some of these disruption patterns are presented and discussed below. At the first penetrometry (20 February), the C plots had the most extensive area of high cone index values near the surface of the profile (Figure 25). This changed on 30 June as cone index values decreased, presumably as a response to increased soil moisture. On 11 November, cone index values once again increased with corresponding decreases in soil moisture (Figure 33).

Disruption patterns for SL showed the greatest overall profile loosening to the greatest depth of about 350 mm (Figure 23) on 20 February. Distinct disruption patterns associated with shank placement were evident. However, the lateral extent of disruption was not as extensive as with PP (Figure 22). At the second penetrometry, shank lines with the surrounding zones of loosened soil were clearly visible (Figure 27) although few cone index values were in the 0–1 MPa range. There were no distinctive features in November (Figure 31).

The inability to operate the Paraplow® at its designed operating depth (450 mm) may explain the relatively shallow disruption pattern compared with SL in the February penetrometry. Clear patterns of low soil strength (0–1 MPa) were evident to a depth of about 250 mm (Figure 22). Shank lines were clearly visible at this time. On 30 June, shank lines with the surrounding zones of loosened soil were again visible (Figure 26). Shank lines remained evident in November although consolidation had occurred with cone index values exceeding 2 MPa present from about 250 mm and below (Figure 30).

On 20 February, mole ploughing resulted in a reduction of cone index values to a depth of 100 mm (Figure 24) compared with C. The passages of the mole plough were clearly visible with their surrounding pattern of lateral soil disturbance. On 30 June the shank lines of the mole plough were still visible (Figure 28), however not to the same extent as shank lines in PP and SL. On 11 November, the shank lines on M plots were not visible and the majority of cone index values were greater than 2 MPa (Figure 32).

Figure 22: Soil disruption patterns for penetrometry on 20 February 1997 for Paraplow® treatment on plot 3.

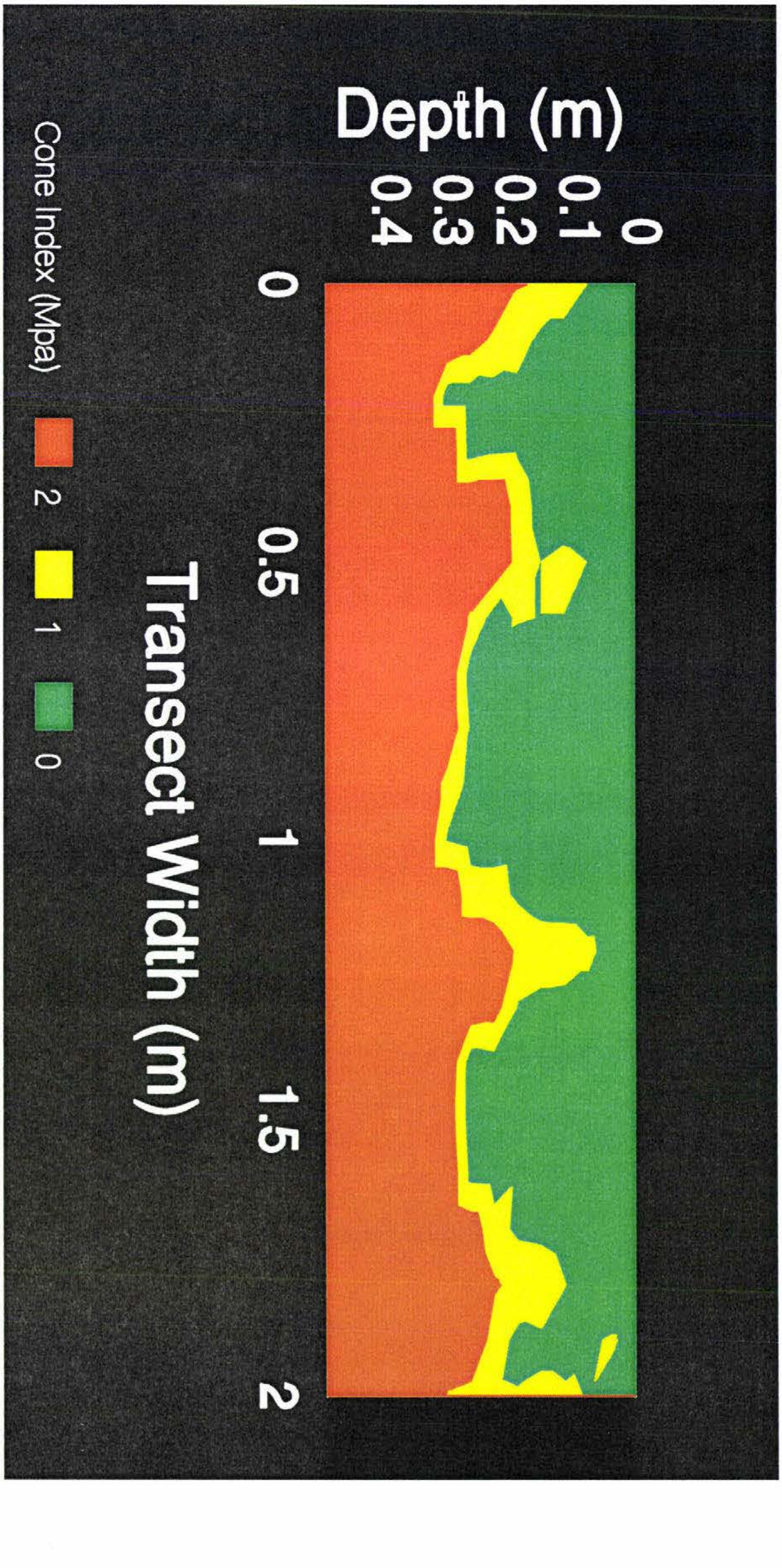


Figure 23: Soil disruption patterns for penetrometry on 20 February 1997 for Straight-legged subsoiler treatment on plot 2.

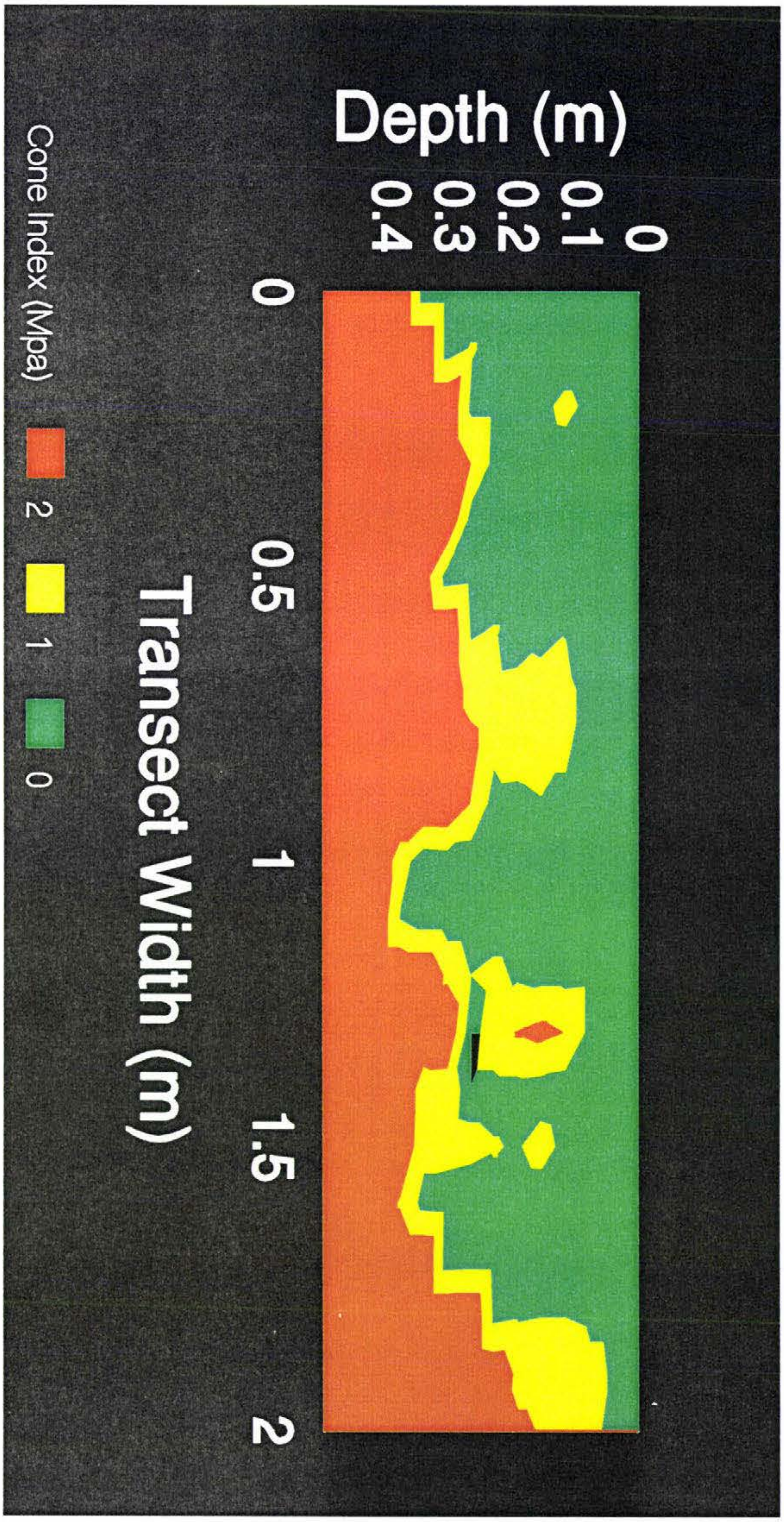


Figure 24: Soil disruption patterns for penetrometry on 20 February 1997 for mole plough treatment on plot 1.

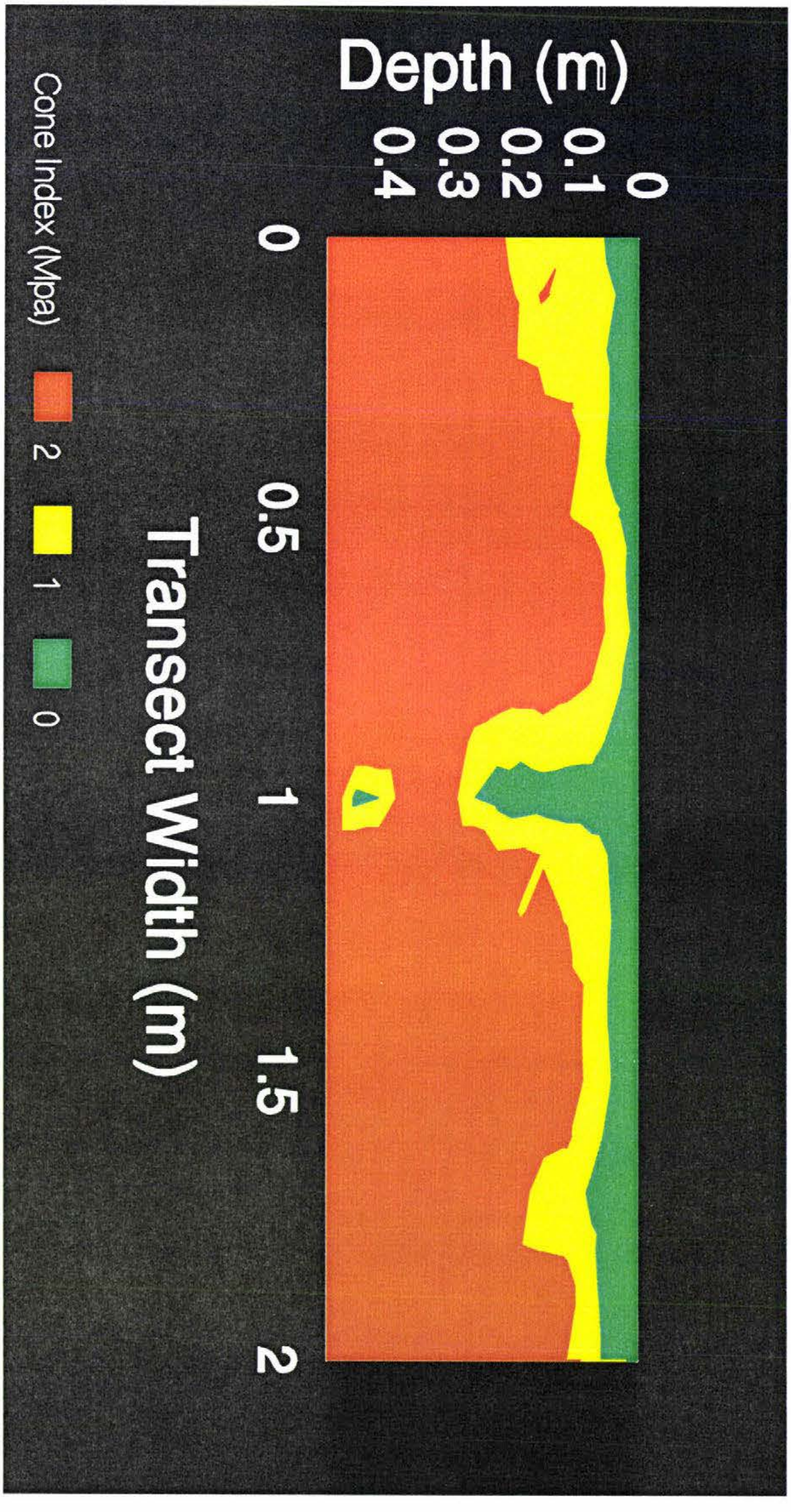


Figure 25: Soil disruption patterns for penetrometry on 20 February 1997 for control treatment on plot 4.

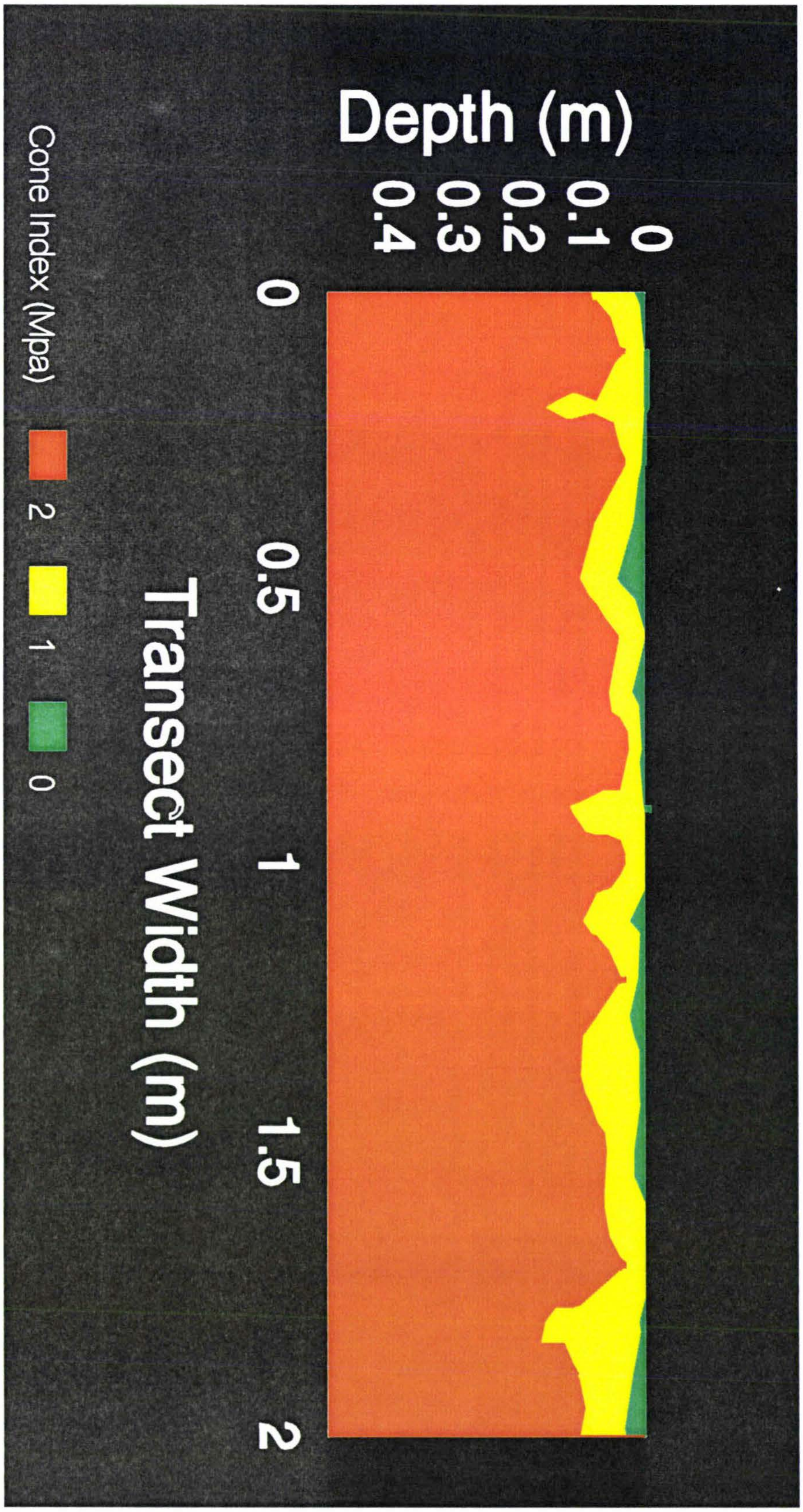


Figure 26: Soil disruption patterns for penetrometry on 30 June 1997 for Paraplow® treatment on plot 3.

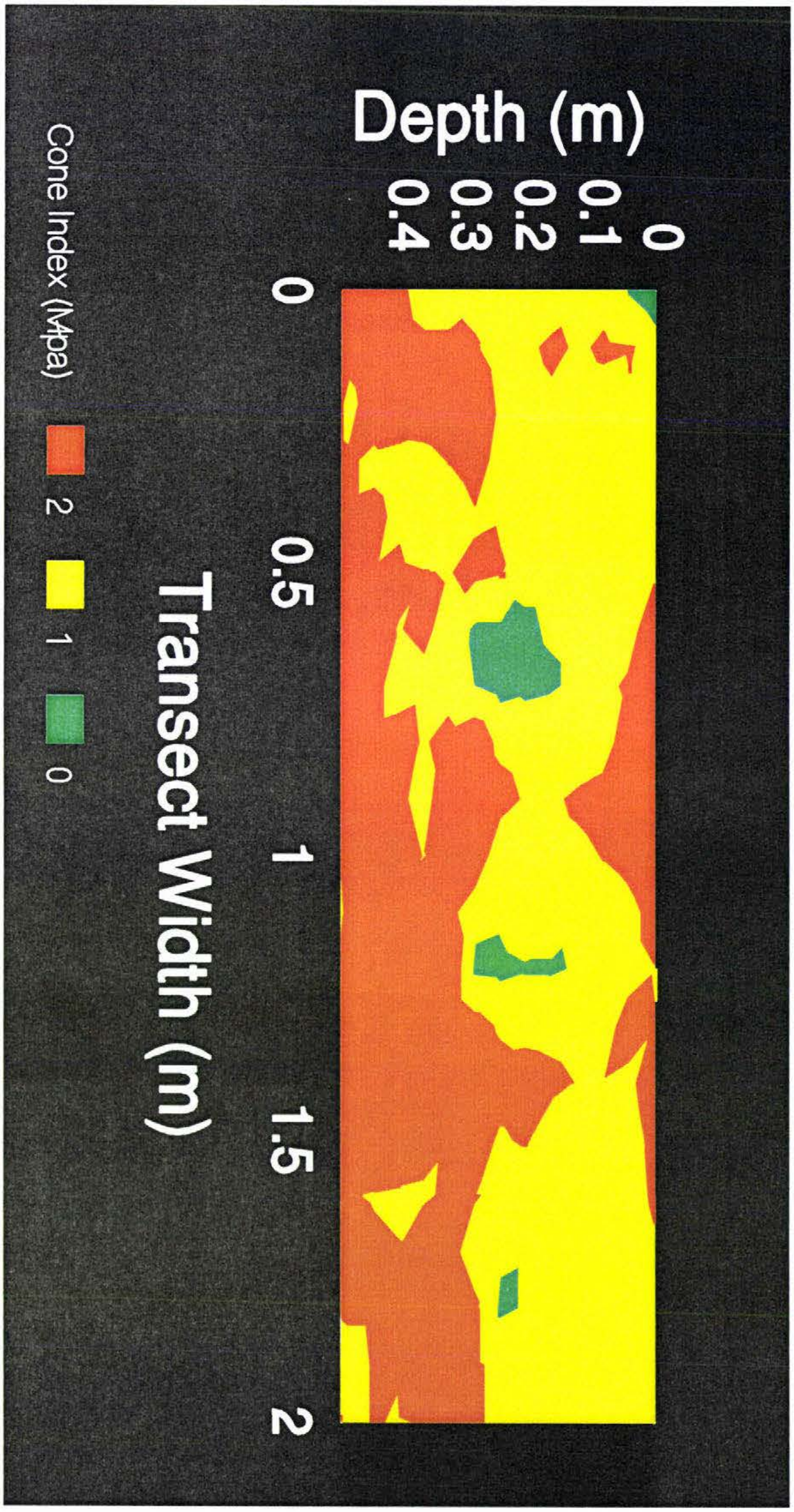


Figure 27: Soil disruption patterns for penetrometry on 30 June 1997 for Straight-legged subsoiler treatment on plot 2.

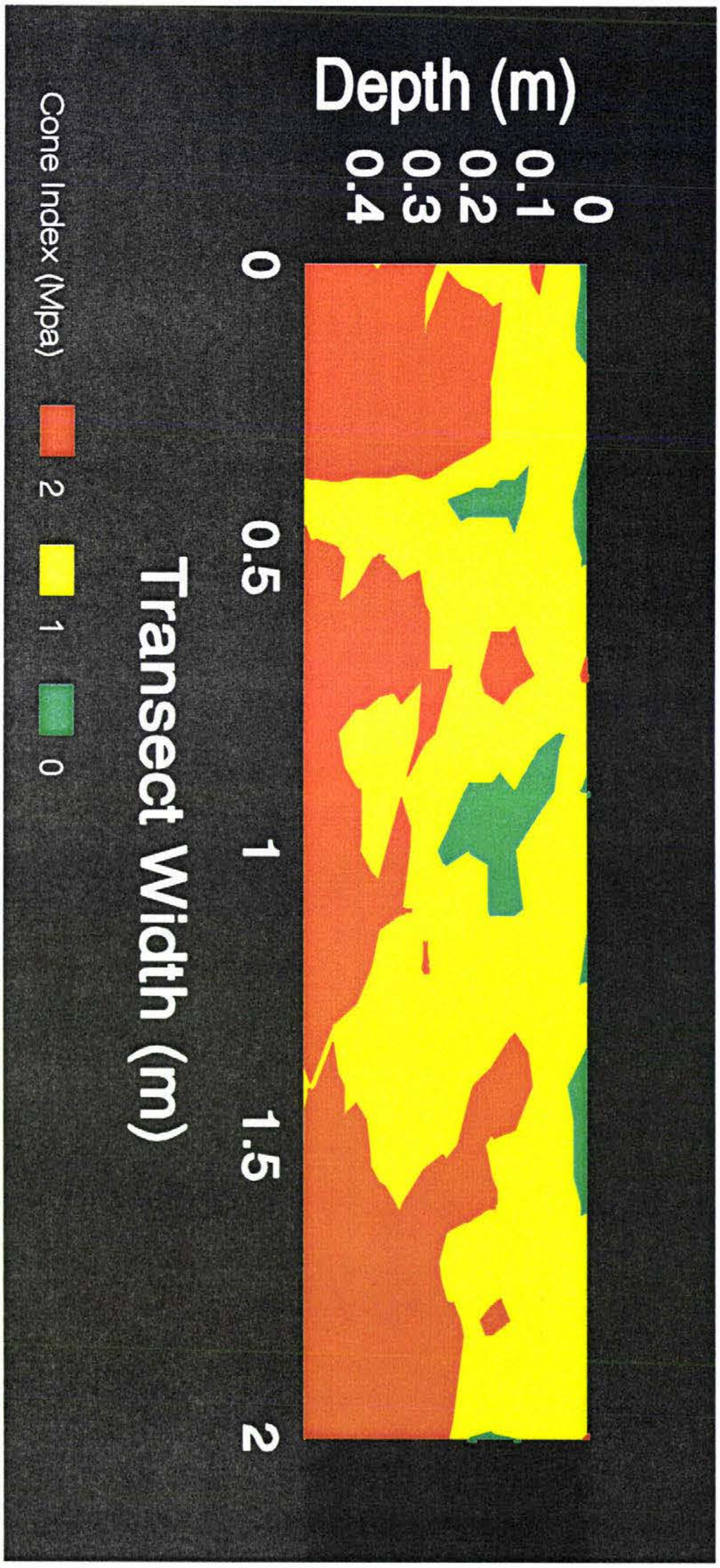


Figure 28: Soil disruption patterns for penetrometry on 30 June 1997 for mole plough treatment on plot 1.

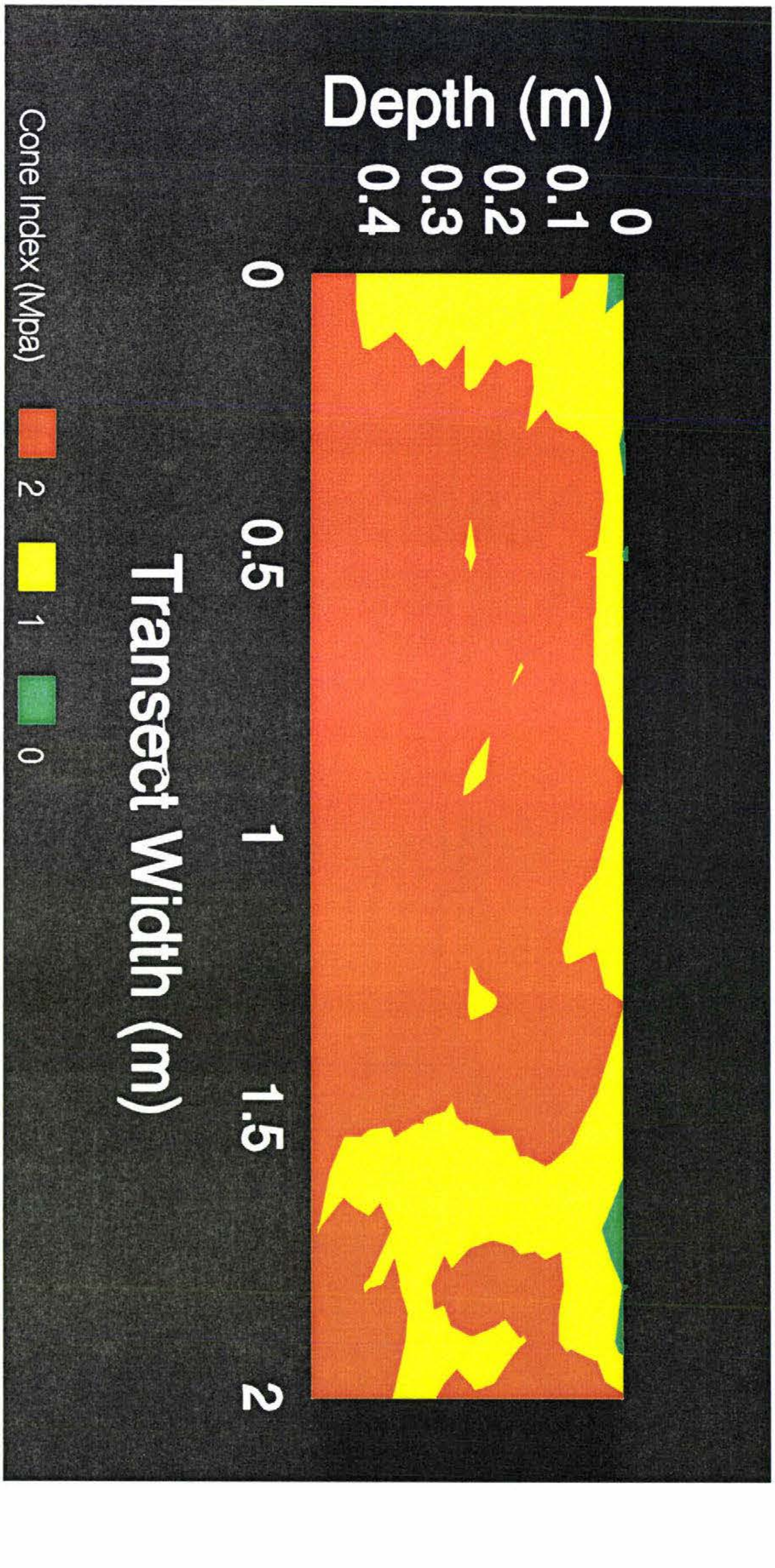


Figure 29: Soil disruption patterns for penetrometry on 30 June 1997 for control treatment on plot 4.

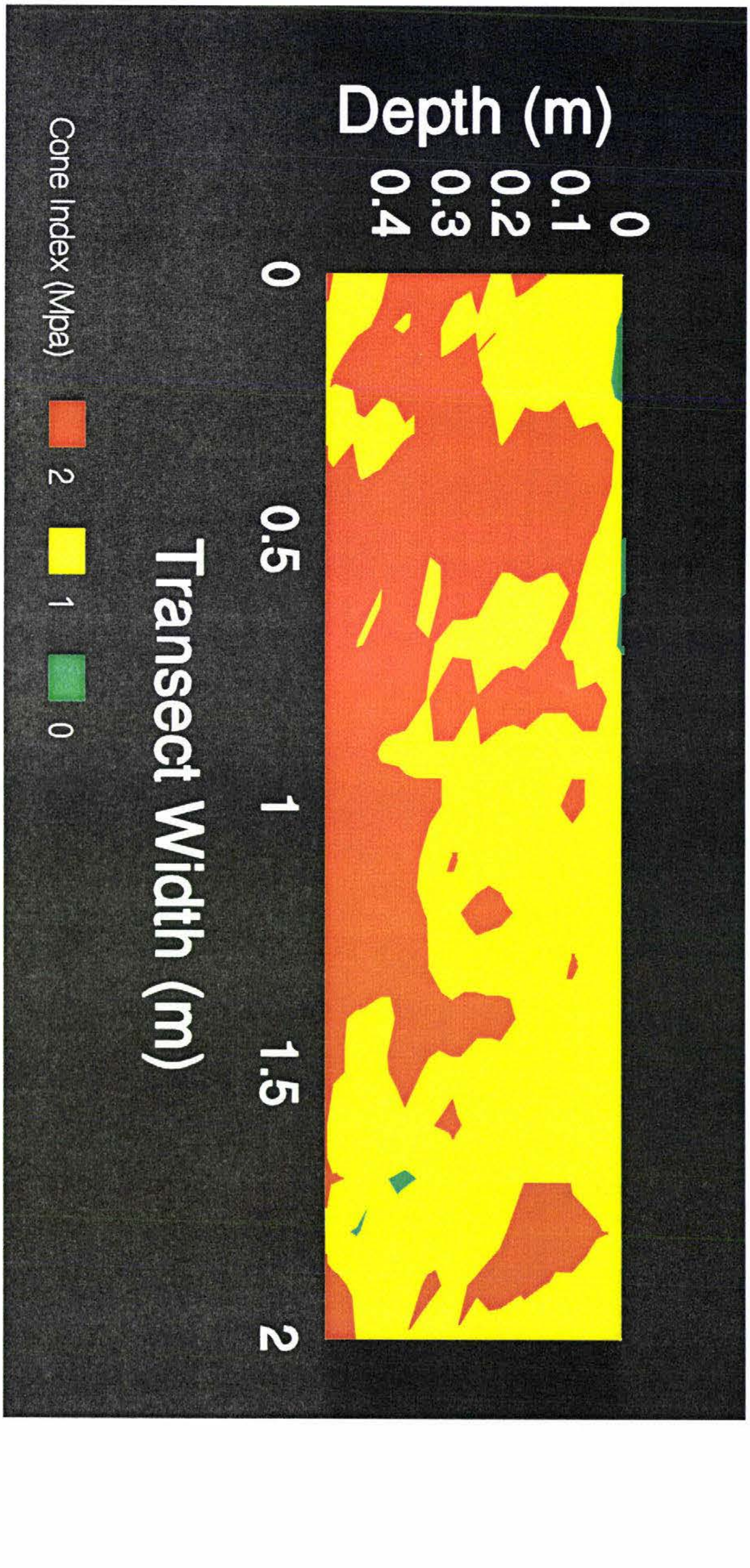


Figure 30: Soil disruption patterns for penetrometry on 11 November for Paraplow® treatment on plot 3.

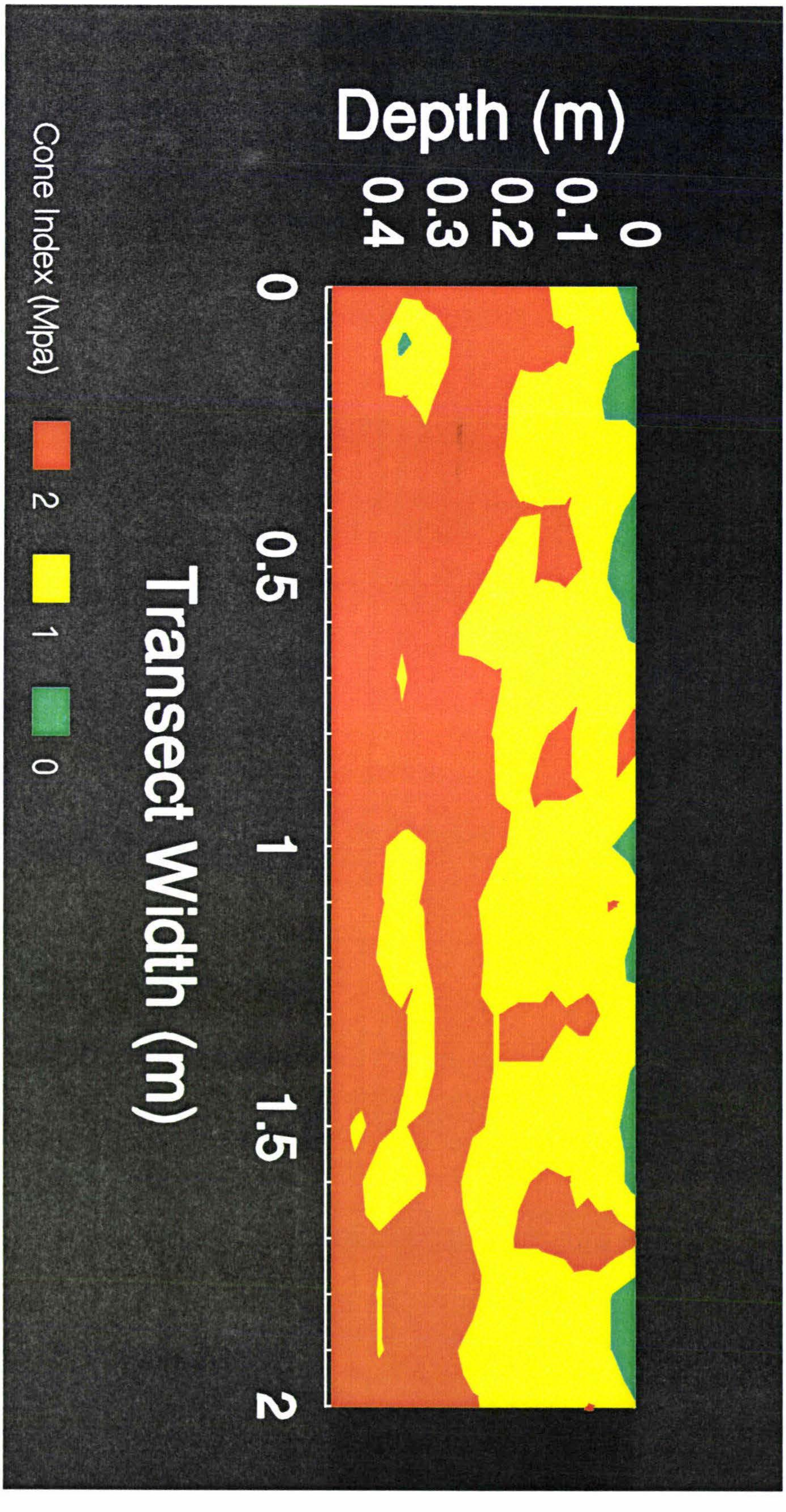


Figure 31: Soil disruption patterns for penetrometry on 11 November 1997 for Straight-legged subsoiler treatment on plot 2.

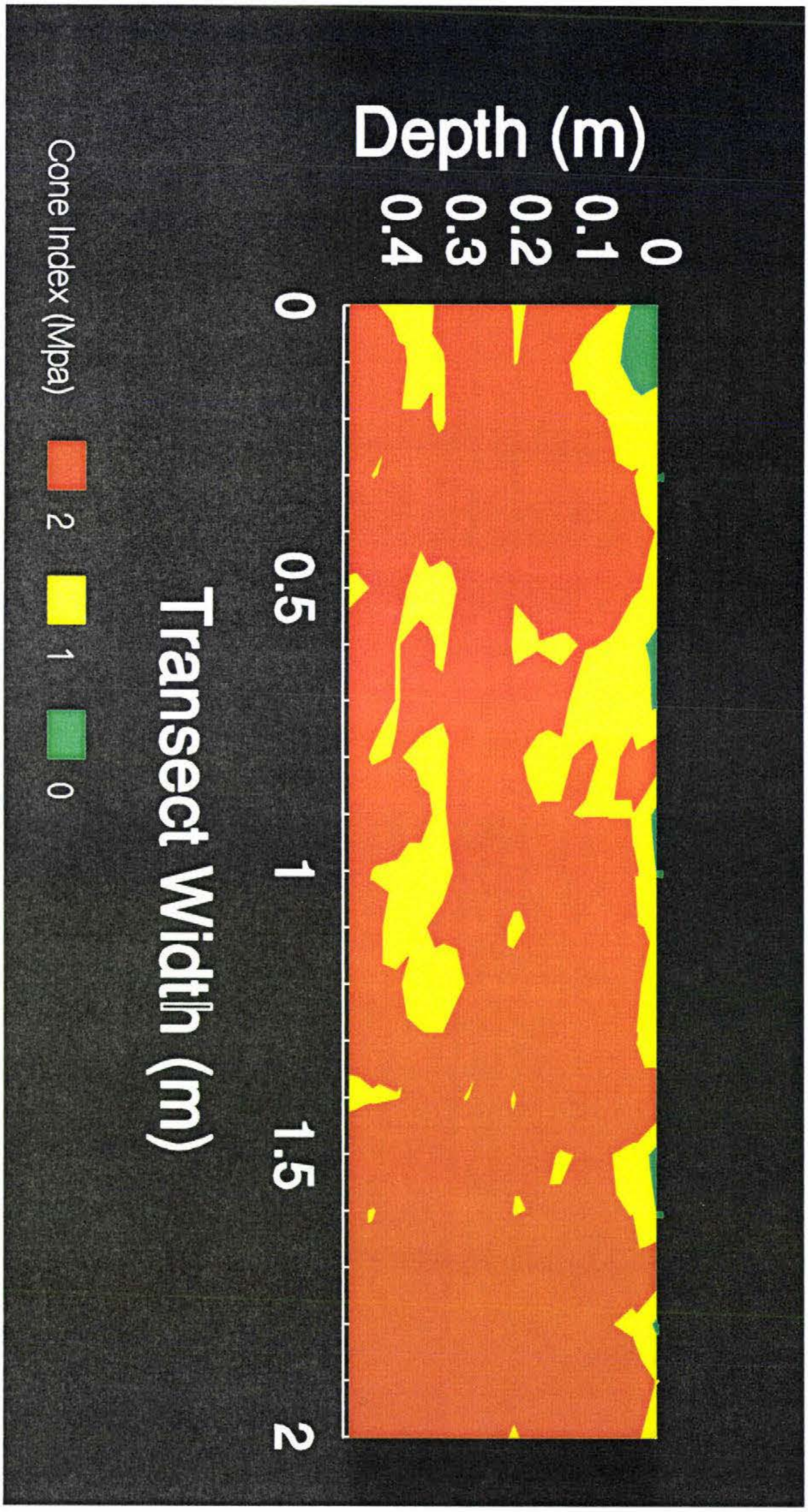


Figure 32: Soil disruption patterns for penetrometry on 11 November 1997 for mole plough treatment on plot 1.

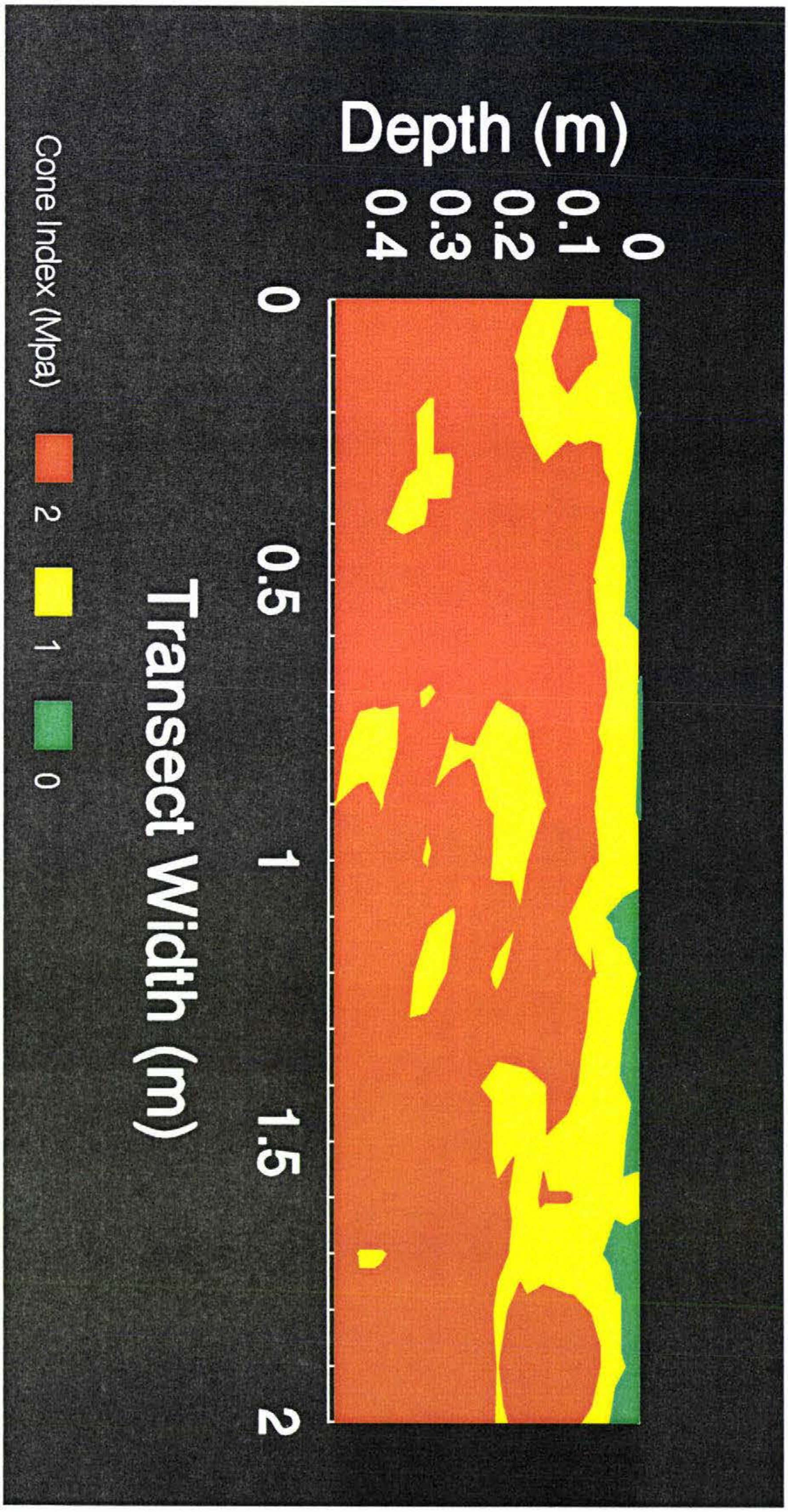
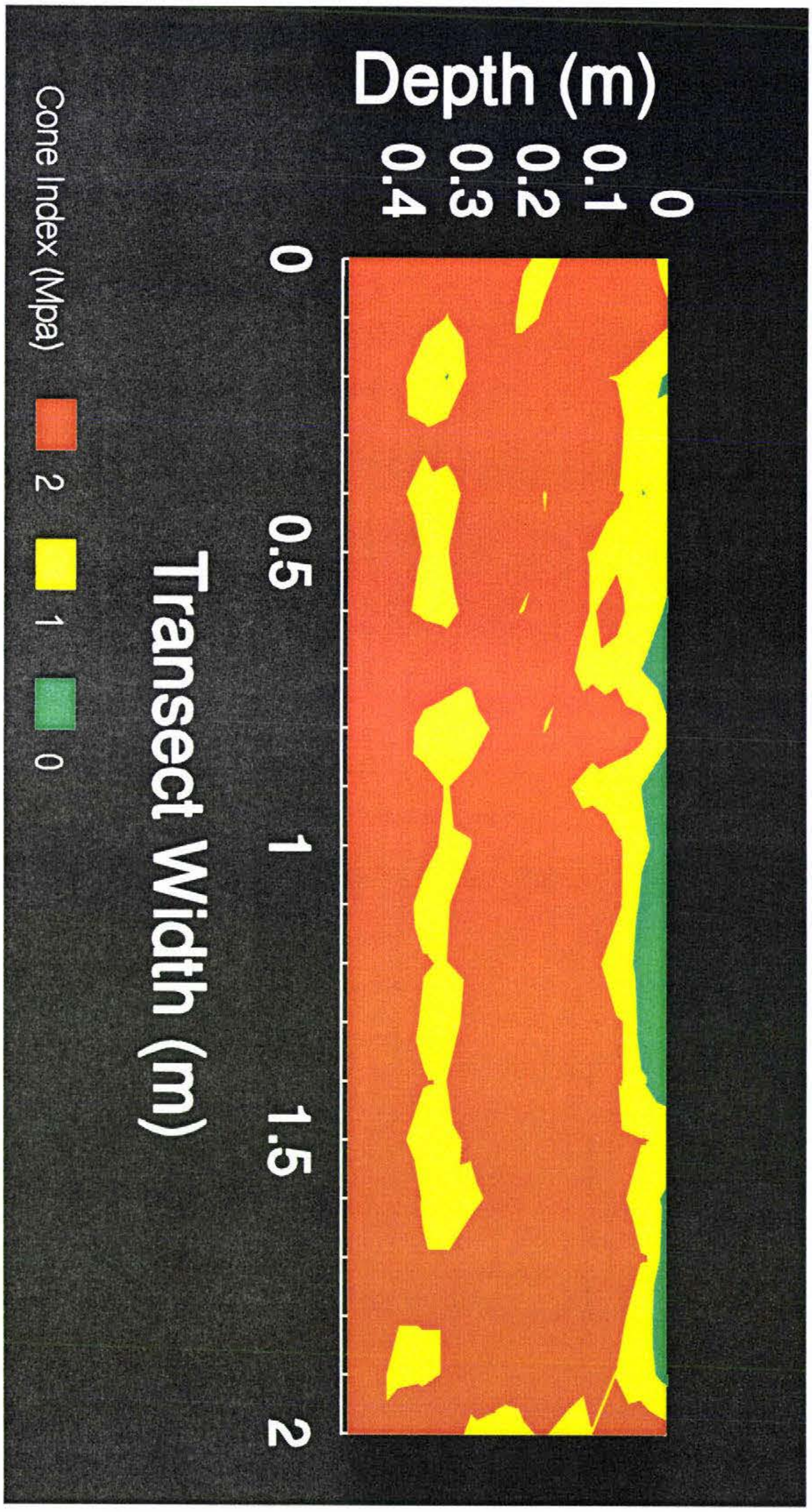


Figure 33: Soil disruption patterns for penetrometry on 11 November 1997 for control treatment on plot 4.

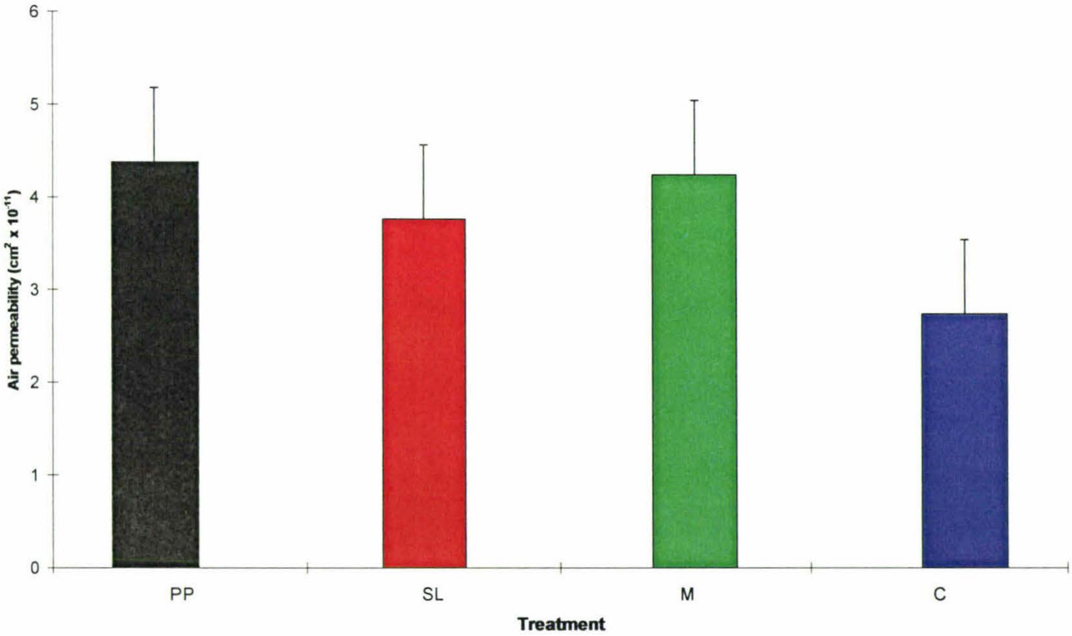


4.6 Air permeability

Air permeabilities in PP, SL and M plots (Figure 34) were significantly ($P \leq 0.05$) greater than those measured in C on 15 August. The average air permeability for the PP, SL and M treatments was 4.13 $cm^2 \times 10^{-11}$ compared with 2.74 $cm^2 \times 10^{-11}$ for C. The air permeability of soil depends on the air-filled porosity of the soil and on the sizes and continuity of the soil pores. Soil water content and bulk density have been reported as influencing air permeability (Hillel, 1980; McLaren and Cameron, 1996).

Although there were no significant differences in soil volumetric moisture content between treatments over any of the three depths monitored (*i.e.* 0–150, 150–300 and 300–450 mm) (Figure 19), no measurements for the moisture content of the 0–50 mm depth, where the air permeability was measured, were recorded and it is possible that differences in soil moisture between treatments may have been present at this depth.

Figure 34: Treatment air permeability, measured with falling-head permeameter (I = LSD at $P \leq 0.05$).



4.7 Forage brassica population and yield

Neither of the subsoiling or the mole drainage treatments significantly ($P \leq 0.05$) improved the brassica crop establishment compared with the control (Table 14). However, at $P \leq 0.1$, PP had a significantly lower mean plant population than C (LSD = 14.06). In addition, plant populations on PP plots were very variable as illustrated by the large standard deviation (as a proportion of the mean value).

Table 14: Forage brassica plant populations at 27 days after sowing and yield harvest for 21 days regrowth after mowing on 1 July.

Treatment	**Plant population (plants m^{-2}) (mean ± standard deviation)**	**Crop yield (kg DM ha^{-1})**
Paraplow (PP)	68.3a ± 25.7	1925a
Straight-legged (SL)	80.4a ± 25.8	1886a
Mole (M)	78.3a ± 21.0	1807a
Control (C)	83.3a ± 23.7	1786a
LSD	16.8	222
Unlike letters within a column denote significant differences at ($P \leq 0.05$).		

Poor plant establishment on PP plots is best explained by reference to surface soil conditions at the time of sowing. Surface soil on the PP treatments was thoroughly loosened (see section 4.1) and there was no subsequent consolidation before drilling except for "wheeled" areas. Plant populations in PP plots were visibly greater where the tractor wheels had caused some consolidation of the loosened surface soil. The M and SL treatments did not have the same amount of surface soil lifting and heaving as PP. Adequate consolidation is essential in any seedbed to promote seed/soil contact, preserve moisture and optimise conditions for germination (Hamilton-Manns and Milne, 1997).

In a similar study, Sojka *et al*., (1997) also failed to measure a response in plant establishment to subsoiling in combination with no-tillage. In a no-tillage situation, germination and establishment are largely a function of the type of opener used (Baker *et al*., 1996). The opener used in this particular study, and that of Sojka *et al*., (*loc. cit*.), has proved effective at minimising the influence of unfavourable soil

(Choudhary and Baker, 1981a) and micro-climate factors (Choudhary and Baker, 1981b) which might otherwise reduce stand population. Irrespective of any treatment differences in bulk density (Section 4.4) and soil strength (Section 4.5), which have a greater influence on root growth than they do on seedling emergence (Langer, 1990), it is likely that the Cross-Slot™ opener eliminated such differences. However, the opener was not able to overcome problems associated with excessively loose soil on PP plots.

There was no significant difference in brassica yield ($P \leq 0.05$) between the control, subsoiling and mole plough treatments after 21 days regrowth (1 July to 21 July) (Table 14). The crop grew well at the trial site; the mean daily growth rate, 88 kg DM ha^{-1}, compares very favourably with the reported daily winter growth rates for this crop of up to 80 kg DM ha^{-1} (Anon, 1996). This is a reflection of the good growing conditions associated with the mild, dry winter. Regression analysis determined a strong negative relationship between plant population and crop yield (r^2= -0.83). This is a characteristic of this particular crop (J. Millner pers. comm. 1998).

A range of crop responses to subsoiling has been reported in the literature, however few authors have measured the interaction between no-tillage, subsoiling and winter forage crop performance. The notable exception is Sojka *et al.*, (1997) who found that winter forage oat yields (sown by no-tillage) from autumn Paraplow® treatments yielded 30% greater than the control. That soil had been continuously cropped for 15 years and its structure was extremely degraded. In comparison, the present site, although cropped intensively and compacted, had pasture in the rotation, and no-tillage, had been introduced two years prior to this study.

In explaining the lack of plant responses to subsoiling, two points should be reiterated. Firstly, the type of opener used meant germination and establishment in the compact C was as good as in the loosened treatments. Secondly, the exceptionally dry and mild winter gave good plant growth rates on the compact C plots.

4.8 Forage brassica maximum vertical rooting depth and root mass

The PP treatment had the greatest maximum rooting depth of any treatment ($P \leq 0.05$) (Table 15). Maximum vertical rooting depth in PP plots was, on average, 24% longer than both C and SL which together had the shortest root length of the four treatments. The M treatment had a significantly greater maximum vertical rooting depth than SL and C. The difference in vertical rooting depth experienced in PP may have reflected the deep (450 mm) soil loosening caused by the Paraplow®. There were no significant differences ($P \leq 0.05$) in root mass between PP, SL and C. No reported studies have measured the rooting characteristics of "Pasja" and thus direct comparisons between this and other work is not possible.

In most experiments involving the loosening of compacted subsoils, subsoiling has increased plant root growth: New Zealand examples include the work described by Greenwood and Cameron (1990), Harrison *et al.*, (1994) and Chapman and Allbrook (1987). Greenwood and Cameron (1990), for example, recorded an increase in the rooting depth of peas from 300–400 mm to 600–700 mm after subsoiling. Harrison *et al.*, (1994) determined that significant differences in root length of pasture had developed in the spring following autumn subsoiling. In these treatments, pasture roots in the 200–300 mm depth were significantly longer than control plots. Similarly, in the first summer following subsoiling, the differences in root depth were obvious further down the soil profile, this time in the 300–400 and 400–500 mm depths. Harrison *et al.,* (1994) concluded that increased root growth rates occur largely in depths previously inaccessible to root growth because of the high bulk density of the soil.

There are a number of factors likely to have contributed to the smaller percentage increase in root growth after subsoiling and moling measured in the present study compared with others in the literature. The main reason was crop related. The brassica used ("Pasja") is characterised by large amounts of leaf and little bulb (Anon, 1996). In comparison, the other experiments cited above have used crops which have a more extensive and deeper root system.

The significant increase in maximum vertical rooting depth in PP did not translate into increased crop yields in this study (Table 14). This is not surprising given that the crop grew through one of the mildest (driest) winters on record (section 4.2).

Table 15: Root length and root mass of forage brassica.

	Root length (mm)	**Root weight (g)**
Paraplow (PP)	157.7a	1.88ab
Straight-legged (SL)	130.7c	1.99a
Mole (M)	134.8b	1.75b
Control (C)	127.0c	1.96ab
LSD	3.8	0.23
Unlike letters within a column denote significant differences at ($P \leq 0.05$)		

4.9 Cereal plant population and yield

There were no significant differences ($P \leq 0.05$) in wheat plant populations between treatments (Table 16). Damage by slugs (*Deroceras reticulatum*) resulted in actual plant populations below those targeted at sowing (*i.e.* 30 plants m^{-2}). However, the slug damage was evenly spread across all treatments.

There were no significant differences ($P \leq 0.05$) in final wheat yield between treatments (Table 16). At an average of approximately 5 t ha^{-1}, the final yield was representative of wheat yields harvested in the Manawatu in 1998. The differences in soil penetration resistance (Table 12) did not translate into yield differences in this study. As the summer of 1998 was hot and dry, the lack of response to PP cannot be attributed to favourable climatic conditions. Evans *et al.*, (1996) concluded that a single subsoiling operation had very little effect on plant growth and no effect on grain yield over the following seasons, while Carter *et al.*, (1996) indicated that increases in crop productivity as a result of subsoiling were minor.

Table 16: Wheat plant populations and final grain yield.

Treatment	Plant population (plants m^{-2})	Crop yield (kg ha^{-1})
Paraplow (PP)	25a	5120a
Straight-legged (SL)	26a	5149a
Mole (M)	25a	4942a
Control (C)	24a	5110a
LSD	4	354
Unlike letters within a column denote significant differences at ($P \leq 0.05$)		

5. Summary and conclusions

5.1 Soil factors

The subsoiling implements thoroughly loosened the compacted soil. Compared with control plots, subsoiling significantly reduced soil strength as measured by a cone penetrometer. Shortly after subsoiling, cone indices showed disruption to a depth of 300 mm with PP, 350 mm with SL and 100 mm with M. At the same time, approximately 20% of profile cone indices from subsoiled treatments (PP and SL) were greater than 2 MPa, compared to approximately 52% for C and M. At 267 days after subsoiling, PP continued to have lower cone index values than C and M.

There were few differences in soil volumetric moisture content between the treatments. The relative effects of the subsoiling implements and mole plough on water movement through and from the profile could not be tested due to the very dry nature of the winter of 1997.

Bulk density sampled with the Troxler® density probe (75 days after subsoiling and moling) revealed that, in the 0–300 mm depth, SL and PP had significantly ($P \leq 0.05$) lower bulk densities than either M or C. At this depth, PP had a significantly ($P \leq 0.05$) lower bulk density than any other treatment. This is indicative of the large amount of soil loosening achieved with subsoiling particularly the Paraplow®. After the cereal was harvested, no differences in bulk density were measured however. Increased bulk density values post cereal harvest suggested that all plots had undergone reconsolidation. Both vehicular and livestock traffic are thought to be responsible for this.

The persistence of subsoil loosening observed in this study mirrored many reported experiments both overseas and in New Zealand. Although differences in soil strength were observed in the first spring following autumn subsoiling and moling, the effects did not persist beyond 12 months (as measured by bulk density).

Air permeabilities in PP, SL and M plots were significantly ($P \leq 0.05$) greater than that measured in C. The average air permeability for the PP, SL and M treatments was 4.13 $cm^2 \times 10^{-11}$ compared with 2.74 $cm^2 \times 10^{-11}$ for C.

Table 17: Summary table of soil factors monitored.

	Paraplow	**Straight-legged**	**Mole**	**Control**
Soil volumetric moisture content (%)	No differences			
Bulk density (g cm^{-3}) (12 May)	1.27c	1.29b	1.34a	1.35a
Bulk density (g cm^{-3}) (28 February)	No differences			
Cone index (MPa) (20 February)	1.68c	1.62c	2.33b	2.54a
Cone index (MPa) (30 June)	1.46b	1.68ab	1.93a	1.86a
Cone index (MPa) (11 November)	1.68c	1.78bc	1.86ab	2.00a
Air permeability ($cm^2 \times 10^{-11}$)	4.38a	3.76a	4.23a	2.74b

5.2 Agronomic factors

Neither of the subsoiling or the mole drainage treatments significantly ($P \leq 0.05$) improved the establishment of the forage brassica compared with the control. It is suggested that the use of the Cross-Slot™ opener, with its inherent biological tolerance of variable soil conditions, resulted in successful plant establishment in C plots. At $P \leq 0.1$, however, PP had a significantly lower plant population than C. Excessive soil disturbance and poor soil: seed contact may be a risk with subsoiling in dry conditions.

There were no differences in forage brassica yield between treatments. In part this was probably due to the mild winter, which meant that growing conditions were favourable, and that excessive soil moisture did not restrict plant growth on any plots. In a wet winter, subsoiling and particularly moling may increase yield by improving drainage.

The PP treatment had the greatest maximum rooting depth of any treatment; on average, roots in PP plots were 24% longer than both C and SL which together had the least root length of any of the four treatments. There were no differences in root mass between PP, SL and C.

There were no significant differences ($P \leq 0.05$) between treatments in wheat plant populations and their subsequent final grain yield.

While subsoiling significantly loosened compacted soil (as measured by soil strength, bulk density and air permeability), these improvements did not translate into significant yield increases for either the winter brassica or the spring-sown wheat. In this trial, subsoiling contributed little to the no-tillage/subsoiling combination, which is to say no-tilled plots yielded as well as any of the other treatments.

Table 18: Summary table of agronomic factors monitored.

	Paraplow	**Straight-legged**	**Mole**	**Control**
Brassica population (plants m^{-2})	No differences			
Brassica yield (kg DM ha^{-1})	No differences			
Brassica vertical rooting depth (mm)	157.7a	130.7c	134.8b	127.0c
Brassica root mass (g)	1.88ab	1.99a	1.75b	1.96ab
Wheat population (plants m^{-2})	No differences			
Wheat grain yield (kg ha^{-1})	No differences			

6. Suggestions for further research

The most obvious suggestion would be to repeat the experiment discussed here in a wet winter. Irrigation could be used to artificially create wet conditions if necessary. Should a wet winter be experienced, measurements of oxygen diffusion rate should illustrate the effects of subsoiling and mole draining on the soil's oxygen status. The oxygen diffusion rate is a more direct measure of soil aeration than the measurement of air permeability and is more relevant to the oxygen status experienced by plant roots.

It could be argued that a different forage crop to the brassica used in the current study may have given different results. "Pasja" is characterised by large amounts of leaf and little bulb. Although significant differences in vertical rooting depth were observed in this study, selecting an alternative crop with a greater propensity to develop large root systems, such as forage oats (*Avena sativa*), may provide differences between treatments in terms of yield responses to more extensive root systems in loosened soil. Alternatively, establishing a winter cereal immediately after autumn subsoiling or moling may well provide a yield response in heavily compacted soils with poor drainage. By removing the intervening forage crop, the immediate effects (if any) of subsoiling and moling will be expressed in a "cash" crop. This type of experiment would have the added advantage of allowing an economic analysis of the benefits of deep tillage.

It was suggested that the Cross-Slot™ opener played a key role in eliminating, or at least masking, differences in plant establishment (and presumably final yield) between treatments. A study that compared no-tillage openers (including Cross-Slot™ openers) both with and without subsoiling (especially a Paraplow®) would answer these questions. Similarly, long-term studies of the effects of no-tillage (again using the Cross-Slot™ opener) in conjunction with mole ploughing may serve to determine the relationship between no-tillage and artificial drainage in poorly drained soils. In these soils this may prove to be the most useful combination for sustainable crop production.

7. References

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9. Appendices

1. Earthworm populations and biomass

As part of a separate study conducted by Landcare Research, the effects of a change from tillage were observed for two earthworm species, namely *Aporrectodea caliginosa* and *Lumbricus rubellus*. The populations (Table 19) and biomass (Table 20) of each of these two species were observed on two occasions spanning a 12 month period, with 1996 being the last time cultivation was performed on the site. The author gratefully acknowledges Drs Gregor Yeates and Craig Ross for supplying the data which, although unpublished, illustrate the significant increase in worm populations and mass.

Table 19: Changes in earthworm population of two species (*A. caliginosa* and *L. rubellus*) measured in 1996 and 1997 after the change to no-tillage.

	Earthworm population (number m^{-2})	
Year	***A. caliginosa***	***L. rubellus***
1996	275b	121b
1997	360a	466a
LSD	78	93
Unlike letters within a column denote significant differences at (P≤0.05)		

Table 20: Changes in earthworm biomass of two species (*A. caliginosa* and *L. rubellus*) measured in August 1996 and June 1997 after the change to no-tillage.

	Earthworm biomass (g m^{-2})	
Year	***A. caliginosa***	***L. rubellus***
1996	55b	65b
1997	97a	150a
LSD	23	51
Unlike letters within a column denote significant differences at (P≤0.05)		

The populations of both species were significantly greater (P≤0.05) under no-tillage (1997) with *A. caliginosa* populations increasing by 30% and *L. rubellus* increasing by a factor of over 3.8 (Table 19).

These results concur with those of other researchers who measured more earthworm channels in no-tilled soils when compared with ploughed soils. Bertsch (1982) reported earthworm populations that were 3.4 times greater under no-tillage compared with conventional cultivation.

These overseas results have been duplicated in local environments as Springett *et al.*, (1992) reported that earthworm population density and activity decreased with increasing intensity of cultivation, while in a more detailed eight year experiment comparing population densities of earthworms on areas with different cultivation histories, Springett *et al.*, (1992) concluded that earthworm populations are reduced by cultivation.

The same trend as that observed for lumbricid populations was recorded in earthworm biomass (g m^{-2}). After the cessation of tillage the biomass of *A. caliginosa* increased by 76% ($P \leq 0.05$), while *L. rubellus* biomass more than doubled (x 2.3). Carter *et al.*, (1988) reported that earthworm numbers and biomass were significantly increased by direct drilling compared with mouldboard ploughing, and in New Zealand, Janson (1984) compared the effects of no-tillage and conventional cultivation on earthworm density and mass and concluded that earthworm numbers more than doubled under no-tillage while their size increased in similar proportions.

2. Soil profile description

Soil Name: Milson silt loam

New Zealand Classification: Argillic Perch-Gley Pallic Soil
Yellow-grey Earth

Location: 0.8 km west on Reid Line East from the Nannestad Line junction. In paddock on the south side of Reid Line East.

Grid Ref.: NZMS 260 T23 347 035

Landform: Gently undulating, weakly dissected terrace

Elevation:	80 m
Slope:	1.5 SSW
Erosion:	Minor wind
Drainage:	Imperfectly drained
Land Use:	Arable agriculture
Vegetation:	Wheat, after winter brassica
Parent Material:	Loess

Horizon	**Depth (cm)**	**Horizon Description**
Ap	0 – 15	Dark grey to dark greyish brown (10YR 4/1-2) with few (5%) fine (1–2 mm) distinct strong brown (7.5YR 5/6) mottles silt loam; firm; strongly developed coarse (up to 15cm) blocky clod structure; many very fine roots; few medium (up to 5mm) black (N2/) iron-manganese concretions at the interface to Bg; distinct irregular boundary.
Bg	15 – 50	Light brownish grey (2.5Y 6/2) with many (50%) coarse (up to 10mm) prominent strong brown (7.5YR 5/8) mottles silty clay loam; firm; moderately developed coarse (up to 10cm) blocky clod structure; few fine roots; concretions as for Ap; indistinct irregular boundary.
Btg	50 – 90	Light olive grey (5Y6/2) with few (5%) coarse (up to 10mm) distinct olive yellow (2.5Y6/6) mottles silty

clay loam; slightly firm; weakly developed very coarse (up to 20cm) blocky clod structure; brown & dark brown (7.5YR 5/2 & 3/3) humus clay cutans down ped faces and old root channels; occasional very fine roots.

Concretion layer from 90 – 100+ cm from augering.