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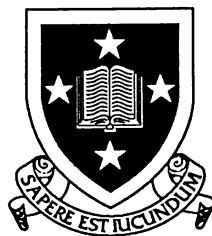
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**The influence of subsoiling
on
soil physical properties
and
pasture production**

A thesis
submitted in fulfilment
of the requirements for the Degree
of
Doctor of Philosophy in Earth Sciences
at the
University of Waikato

by

Richard Chapman



University of Waikato

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ABSTRACT

INFLUENCE OF SUBSOILING ON SOIL PHYSICAL PROPERTIES AND PASTURE PRODUCTION

by
Richard Chapman

In many areas of New Zealand, soils under pasture have become compacted by a combination of livestock trampling, use of heavy machinery and natural processes, or in the case of sports fields, heavy use at high moisture levels. These processes create soil horizons that have a high resistance to a penetrometer, often a high bulk density and hence a lowered porosity. These horizons reduce hydraulic conductivity, change soil moisture characteristics and restrict root elongation and consequent pasture yield.

An arable type subsoiler was re-designed for pasture use and its effects on five soils in the Hamilton Basin were investigated. Soil disturbance was assessed for differing operational depths, tip sizes, operating modes and soil moistures. Soil physical characteristics such as bulk density, soil strength, pore space, water tension and infiltration were measured at intervals after subsoiling. Root growth and yield response of pasture were quantified.

Subsoiling in the vibrating mode under relatively dry soil conditions increased soil disturbance by 30% in comparison with non-vibrating; wide tips in comparison with narrow tips increased disturbance by up to 100%. Results indicated that the effectiveness of subsoiling at a standard speed, is a function of operational depth, tip size, pitch angle, soil type and soil moisture. Generally subsoiling below 45 cm depth resulted in a reduction in soil disturbance and was less effective under wet soil conditions at deeper than 35cm

Increased water stress in and around the subsoiled slot resulted from summer subsoiling. The addition of press rollers reduced evaporation and reduced ground heave by 25%.

Measurements of ground heave following subsoiling using a purpose built heaveometer enabled comparisons between different soils to be made. The more clayey Hamilton and Whatawhata soils showed greatest heave.

Subsoiling reduced bulk density by up to 30% within 10 cm distance of the subsoil slot; significantly reduced levels were sustained at this distance in the more clayey soils for up to two years.

The effect on bulk density decreased with distance from the subsoil slot. Bulk density estimations *in situ* showed greater changes in response to subsoiling than laboratory measurements.

Penetrometer measurements provided additional crucial information on the extent of soil disturbance and its sustainability with time. Repeated measurements defined “envelopes” of soil disturbance emanating from the subsoiled shank and tip. The lowest soil penetration resistance was found down the slot, where strengths were commonly reduced from 4 MPa to 1 MPa.

The depth of influence was shallower further from the slot following a 45 - 50° angle up from the subsoiler tip to the surface. In the more clayey soils a discrete zone of higher strength soil was occasionally identified contiguous to the lateral extremities of disturbance. Subsoiling shattered large aggregates thus creating a larger volume of soil. Soil mixing was limited to a relatively small area around the subsoiler shank and tip where 17 - 19% of A and B horizon aggregates interchanged. Consequently a redistribution of soil texture and organic matter occurred within soil profiles.

Pores >9.76 µm increased from 20 to 35% in A horizons and from 3 to 35% in B horizons. Increased porosity to the full depth of soil disturbance resulted in rapid movement of excess summer rain, and in the case of the poorly drained Whatawhata soil drier soil conditions prevailed in winter. Measurements of root elongation, together with SEM analysis showed that grass roots had difficulty penetrating high bulk density (1.35 - 1.50 Mg m⁻³), high strength (>5.00 MPa) soil layers. In these cases subsoiling facilitated increases of up to 20% in root length and a consequent increase in pasture yield of up to 17.7%.

The more clayey soils derived greater benefits from subsoiling than sandy soils, both in the extent of soil disturbance and duration of reduced bulk density and soil strength.

In the case of an artificially constructed soil, near surface compaction was ameliorated with a consequent improvement in turf.

Provided that subsoiling was carried out under optimum conditions, a positive response in pasture yield could be expected, even where soil physical properties were not limiting.

Re-compaction rates following subsoiling are a function of pasture management and soil physical properties, but provided subsoiling is carried out with optimal soil disturbance, then a subsoiling frequency of two years for sandy soils and three years for more silty and clayey soils is recommended.

DEDICATION

Dedicated to the memory of George Bernard Chapman, who endured the hardships of the depression, fought with distinction for his country and with the unfailing support of his wife Joan succeeded through extremely hard work, in farming the poorly drained sticky clay soils of the Yorkshire Pennines.

ACKNOWLEDGEMENTS

I would very much like to take this opportunity to thank the many people who have contributed to this study.

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CHAPTER ONE

CHAPTER ONE

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CHAPTER 1: INTRODUCTION

1.1 REASONS FOR STUDY

An agricultural soil may be defined as being compacted, when the total pore volume is insufficient to sustain adequate root development and therefore optimal crop production. When soil is compacted the total porosity is markedly reduced, so that the movement of water and air are restricted, thus causing poor root growth. This situation will frequently result in water lying on the soil surface during periods of wet weather, even though, generally the soil is freely drained.

Compacted soil layers for example fragipans may result from natural soil forming processes. They may also result from human influence, such as livestock trampling under intensive grazing systems, use of heavy machinery, or in the case of sports fields, continuous use under wet conditions. Compaction affects nearly all properties and functions of the soil, physical as well as chemical and biological. It is therefore essential to provide a soil environment which encourages crops to root deeply and extensively, in order that they can utilize soil moisture, soil air and nutrient reserves, especially under conditions of stress.

Many Waikato pasture farmers including those questioned in a national survey (Chapter 3.6.11) expressed concern about what they perceived as an increasing soil compaction problem. The Waikato Rugby Union was concerned about the near surface compaction identified at Rugby Park, Hamilton. In response to the above a research programme, involving the construction, manufacture and use of a subsoiler was initiated in July 1986, between the University of Waikato and Gallagher Engineering Limited, Hamilton.

There are a number of subsoilers at present on the New Zealand market. The machines are readily available and are often demonstrated at agricultural shows and fielddays throughout the country. The manufacturers of these machines often quote in their promotional brochures much unsubstantiated information on the benefits of subsoiling. Greenwood (1989) has shown that subsoiling arable soils in Canterbury can result in a significant increase in crop yield, however very little information is available for showing the effects of subsoiling of pasture lands.

The major thrust of the present programme therefore, in addition to the development of the subsoiler is to investigate the effects of subsoiling on five soil

types under pasture, four of which are commonly found within the Hamilton Basin and the other is an artificially constructed soil at Rugby Park, Hamilton.

1.2 AIMS OF STUDY

The aims of this study are to design and test a subsoiler suitable for use under pasture, taking account of whether it is used in a vibrating or non-vibrating mode and the size of the tips used. When using such a machine the initial soil moisture conditions need to be known, for optimum operating depth and soil disturbance.

The effect this machine has on the soil with respect to soil physical parameters will be studied and also the effect on plant growth as indicated by root elongation and pasture dry matter production.

Recommendations on subsoiling operational procedures and the optimal conditions for subsoiling will also be addressed.

1.3 STUDY AREA

The locations of the five study sites are shown in a simplified soil map (Figure 1.3.1).

A schematic cross section showing the Hamilton Basin is shown in Figure 1.3.2, it comprises of an asymmetric oval-shaped graben approximately 80 km north to south and 45 km west to east, bounded by ranges up to 300 m high. The Hamilton Hills represent the dissected remains of the Walton-Sub-Group sediments. These sediments were deposited during the Late Pliocene and Early Pleistocene into a fault-bounded graben. Two main units are found within these sediments, the Puketoka Formation, consisting of weakly-welded ignimbrites and ignimbrite debris and the Karapiro Formation, which represents pumice-rich alluvium. During the Mid-Pleistocene changing sediment supplies and river base levels resulted in the incision of streams into these sediments, producing a dissected landscape with an overall summit-concordance. Overlying the Walton-Sub-Group sediments is a sequence of tephra deposits with associated paleosols. These include the Kauroa Ash Formation underlying the younger strongly weathered Hamilton Ash Formation, which is the parent material for **Hamilton clay loam** a well developed, reddish-brown, clay-rich soil.

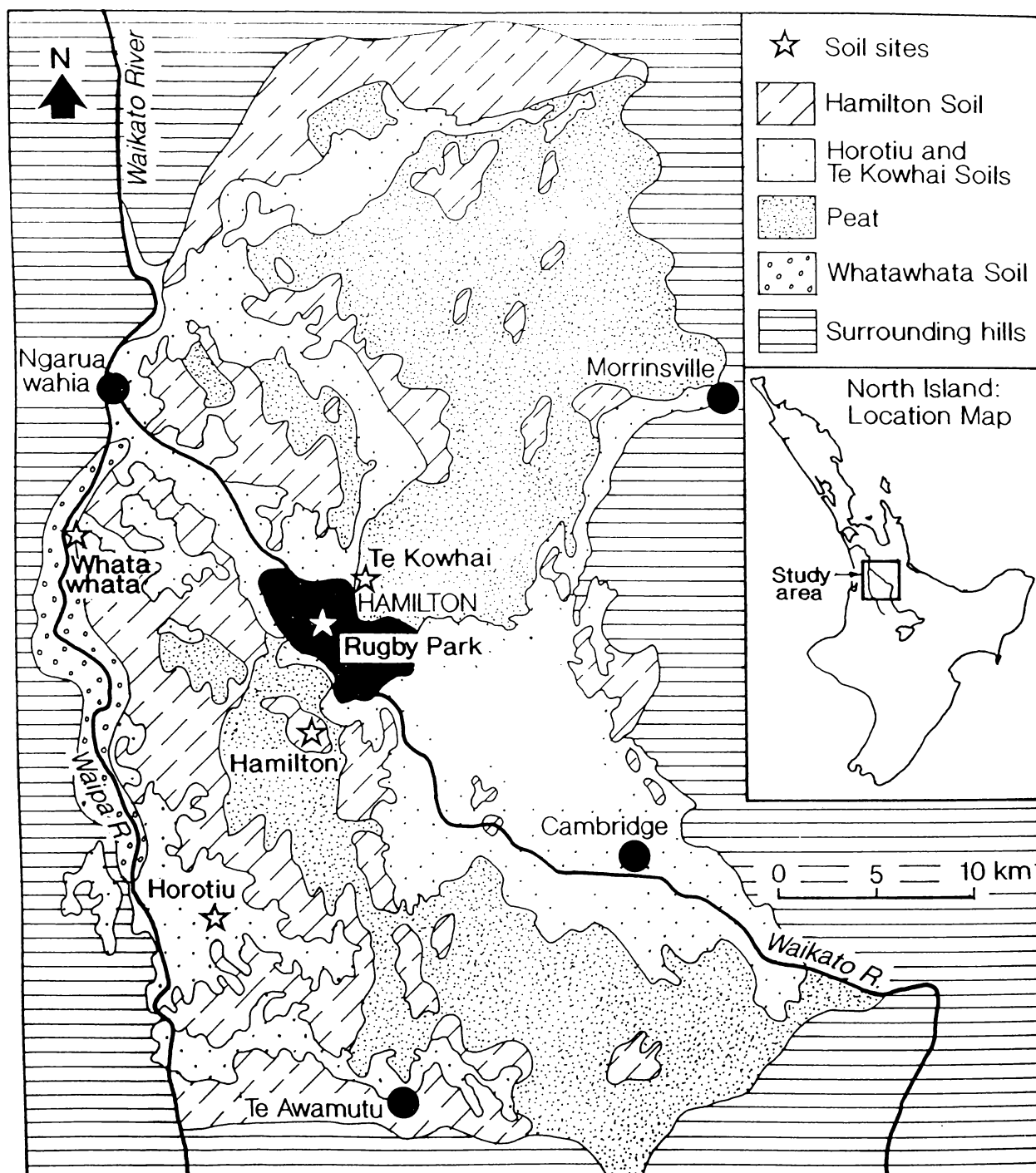


Figure 1.3.1 Map of Hamilton Basin showing soil sites and localities (adapted from McCraw 1967).

The Hinuera Gravels are mainly composed of a rhyolitic alluvial fan, deposited by the Waikato River in several episodes between 65,000 - 15,000 years ago. Closer to source in the south the gravels almost completely bury the old landscape, represented by the Hamilton Hills, but towards the north the thickness decreases and more of the hills are exposed.

The surface of the alluvial fan represents a complex mixture of soil parent materials, with the main units consisting of coarse levee sediments, fine river bed and overbank deposits and organic sediments associated with peat bogs. In addition the region has been regularly dusted with many Late Pleistocene and Holocene airfall tephra deposits, which mantle the alluvial fan surface and the Hamilton Hills to depths ranging from 0 - 50 cm. The major soils formed on the undulating Hinuera surface are **Horotiu sandy loam**, a free draining allophanic soil, derived mainly from tephra deposits overlying levee sediments and **Te Kowhai silt loam**, a gley soil developed on poorly drained, pumice-rich riverbed and overbank deposits. At Whatawhata, about 16,000 years ago a large temporary lake formed when the Waikato River blocked the course of the Waipa River. This lake resulted in the accumulation of a large quantity of fine grey silt which now forms the parent material for the local **Whatawhata clay loam**, a gley soil with poor internal drainage. (McCraw, 1967; Lowe, 1981).

1.4 CLIMATE

The climate of the Hamilton Basin with its relatively low relief, is mild with temperatures reaching a mean February maximum of 24°C and a mean July minimum of 13.3°C. Screen frosts have been recorded from April to September. Mean soil temperatures at 30 cm depth range from 20°C in February to 9.5°C in July. The mean annual distribution of rainfall varies from about 1000 - 1500 mm (Figure 1.4.1). Although a net annual moisture surplus exists in the Hamilton Basin, a relatively short but frequent seasonal soil moisture deficiency occurs (Figure 1.4.2). June and July mean monthly rain is approximately 150 mm, with January and February driest, recording approximately 70 mm. Fogs are most frequent between March and August, with a yearly average of about 40 fog days. Sunshine averages about 2100 hours annually and relative humidity averages about 80% for the year. The prevailing winds are from the southwest, west and northeast and average approximately 10.5 km hr⁻¹ (source: New Zealand Meteorological Service, 1983).

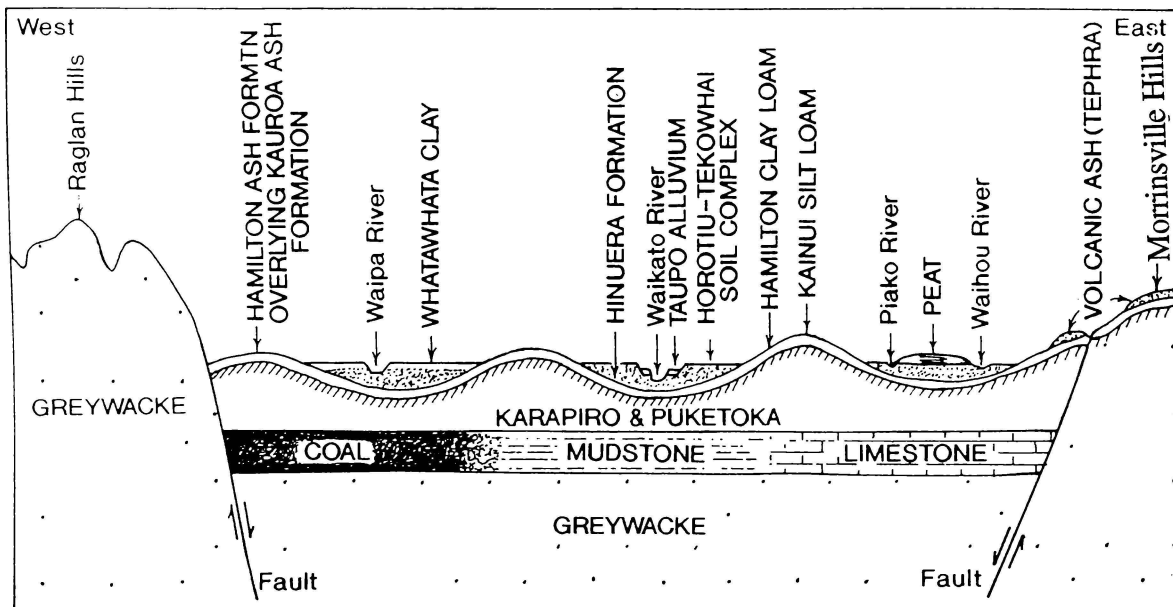


Figure 1.3.2 Schematic cross-section through the Hamilton Basin showing simplified stratigraphy in relation to topography (Adapted from Geological Society of NZ Annual Conference Field Excursion Guidebook, Hamilton, 1976)

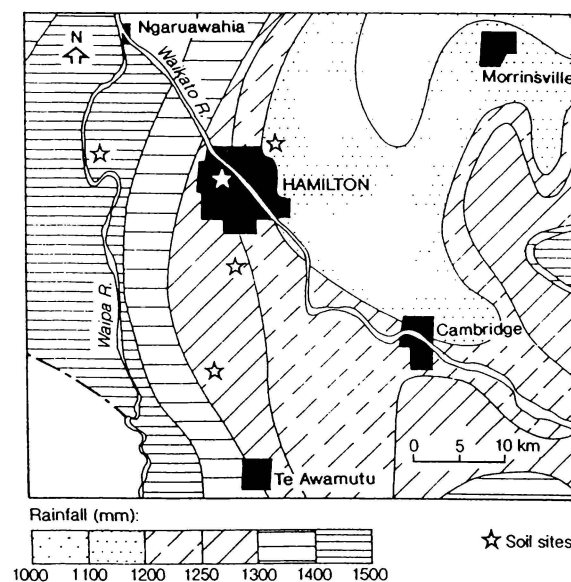


Figure 1.4.1 Mean annual rainfall distribution. Data from de Lisle (1967) and Maunder (1974) modified after NZ Meteorological Service (1983) and Lau (1978)

1.5 VEGETATION

The vegetation of the Hamilton Basin has been extensively changed by pre-European and European settlement. Most of the basin is now dominated by ryegrass - clover pasture, with a few isolated patches of native forest. Fodder crops, such as maize and horticultural crops, contribute significantly to the regions economy, but to a much lesser extent than the outputs of such primary products as dairy, beef and sheep.

According to Cranwell (1939), the ancestral alluvial fan deposits of the Waikato River (Hinuera Formation), at the time of European settlement supported manuka scrub and fern. The wetter depressions between the gravelly ridges were covered with kahikatea forest and tall manuka, with sedge, flax, moss and rushes associated with the peats. The drier parts and rolling Hamilton Hills were covered with a mixed broad leaf - podocarp forest dominated by rimu, tawa, matai and rewarewa.

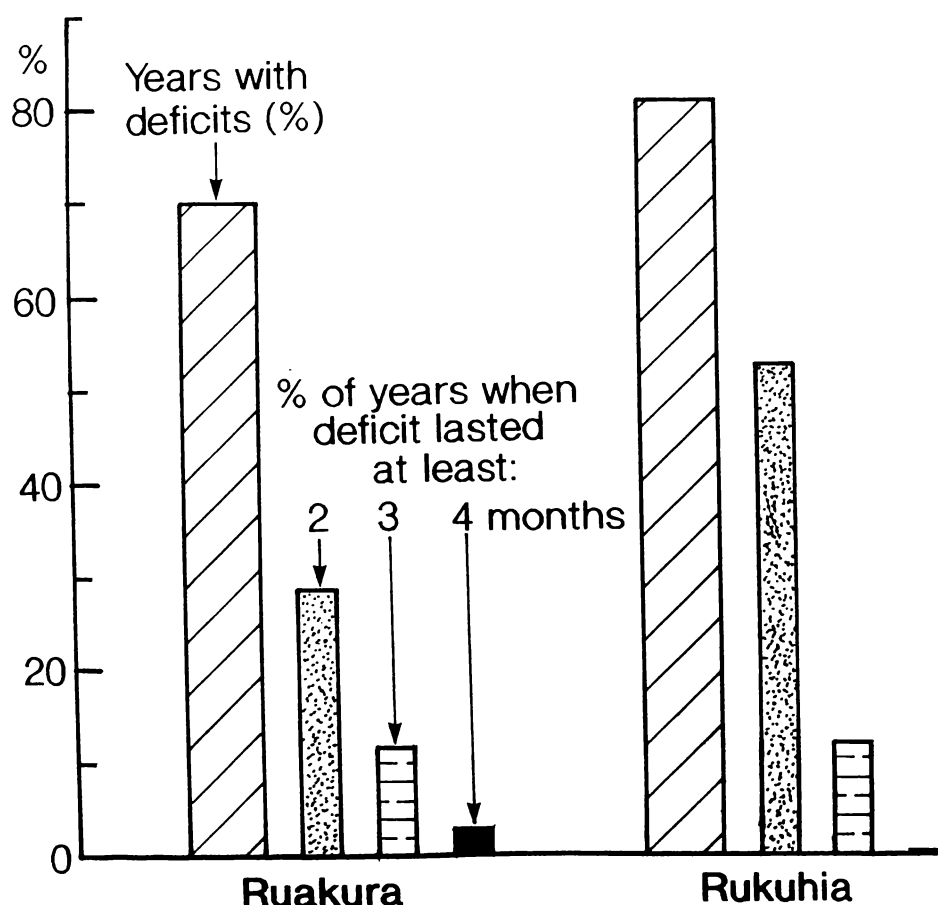


Figure 1.4.2 Soil moisture deficits at two stations in the Hamilton Basin (after deLisle, 1967).

CHAPTER TWO

CHAPTER 2: LITERATURE REVIEW

2.1 DEVELOPMENT OF SOIL PHYSICAL RESEARCH INTO COMPACTION

It was not until after World War II, that the effects of soil compaction on crop production were seriously investigated, although Froehlich (1934) had predicted subsoil compaction under heavy axle loads. The increased interest at this time can be attributed to the fact that, with the increase of fertilizer usage, shortage of nutrients is not a significant factor in depressing crop yields. It, however, became increasingly apparent (Eriksson *et al.*, 1974) that the use of heavier farm machinery had resulted in subsoil compaction and decreased crop yields. With the introduction of improved pasture species, stocking rates have also increased, resulting in increased near surface soil density as reported by Gradwell (1965). World-wide, much research has shown the effects of vehicles and wheels on soil compaction and crop responses to differing traffic regimes.

Reviews have covered various aspects of the compaction problem, Chancellor (1977) showed that soil exhibits strength both in resistance to volumetric compression and in resistance to linear deformation of soil structural bodies. In both these modes of resistance, strength of a given soil at a given moisture content generally increases together with increases in the compactness or density of the soil. Soil compaction and regeneration was the theme of the workshop on soil compaction, organised by the Commission of the European Communities (1987). The Commission recognised that since the establishment of the European Economic Community (EEC), changes in the technology of crop production in member countries have increased the risks and potential importance of soil compaction. The aim of the workshop was to discuss and compare the methods available for studying compaction and structural regeneration. Sessions were devoted to physical criteria for describing soil compaction, micro and macro-morphological approaches to the study of soil structure evolution during compaction, structural regeneration, influence of soil compaction on crop growth and the consequences of tillage in improving some compacted soils.

Håkansson *et al.*, (1988) reviewed the effects of machinery traffic on soils and crops, including stress distribution, soil response to applied stresses, influences of compaction on soil properties and processes, persistence of compaction and crop

response to compaction. Little attention, however has been given to soil physical research, in relation to soil compaction under pasture.

Research in the 1950s was influenced to some extent by engineering concepts and soil mechanics. A common approach at this time, was to minimize soil compaction by restricting tillage operation on the basis of texture or moisture conditions, which involved interpreting the soil compaction test devised by Proctor in 1933. The test involves a moisture-density curve which is a function of the stress applied to the soil. The research was also heavily influenced by “engineering” theory that stated that “the pressure in the upper soil layer is determined by the specific pressure at the surface” (Soehne 1958). On the basis of this theory, as machine weight increased, the number and size of wheels increased to keep specific pressure on the soil surface relatively constant, thus minimizing soil compaction. Although manufacturers and farmers continued to compensate for heavier vehicles, by fitting more wheels and wider tyres, soil stresses continued to increase, as larger and heavier vehicles were used in response to agricultural mechanisation. Awareness of these increased stresses led to a need for research into stress prediction.

Most methods of predicting increases in stress within a soil arising from the application of surface load are derived from the solutions of Boussinesq (1885) and Griffiths (1929). Froehlich (1934) modified these solutions by introducing empirical concentration factors, which concentrate the stress distribution about the vertical point load axis, to account for plastic behaviour and for finite boundary conditions.

Soehne (1958) developed expressions for the tyre/soil interface for three soil classes, ranging from dry to moist to wet. Blackwell (1979) proposed a fourth class, very hard. Smith (1987) developed a simple numerical model to predict changes in soil dry bulk density resulting from the passage of wheels. The model uses Soehne’s (1958) expressions and empirical isotropic stress-strain data to predict soil volume changes. The predictive models reinforced the increasing volume of evidence suggesting that heavier vehicles were causing considerable subsoil compaction, resulting in decreased crop yields. (Eriksson *et al.*, 1974). Voorhees *et al.*, (1978) reported increased penetrometer resistance to depths >30 cm resulting from wheel traffic. It was becoming apparent that subsoil compaction from heavier vehicles could pose an important obstacle to sustained agricultural production in spite of efforts to maintain a constant, relatively low specific pressure on the soil surface.

In 1980, a working group of scientists and engineers from Europe and North America was organised to conduct field research, to determine the effects of high axle loads on the extent and persistence of subsoil compaction, over a range of soil and climatic conditions and to determine the effect of subsoil compaction on growth and yield of several crops (Voorhees *et al.*, 1986).

Much of the research into the effects of tillage on soil compaction before 1965 was primarily laboratory based. The Coulomb equation (Coulomb 1776) was the most used, to calculate forces imposed on soil by implements. From 1965 onwards scientists with the advantage of more sophisticated measuring equipment, began to concentrate on *in situ* investigations of soil compaction, where the effects of traffic in particular could be assessed using penetrometers (Anderson *et al.*, 1980) and gamma-ray probes (Van Bavel *et al.*, 1985).

Willatt and Pullar (1984) calculated individual hoof pressures for cows to be 19.2 MPa, which compared with a figure of 16.0 MPa, calculated earlier by Lull (1959). Pressures of 10.0 MPa exerted by sheep have been reported by Lagocki (1978) and 8.3 MPa by Willatt and Pullar (1984). Pressures were calculated on the basis of weight per unit area of contact. This probably under-estimates the pressure applied, because animals when walking may have only two or three hooves on the ground which could raise individual hoof pressure quite substantially. Another factor is that the hoof is not necessarily placed flat on the soil surface, this tends to increase the applied pressure at points of contact with the ground surface. Interestingly, the values obtained for tractors is, according to Soehne (1958), less than 10.0 MPa and ranged from 3.0 to 15.0 MPa for work carried out by Soane (1970).

Because of the fact that a number of soil physical characteristics are destroyed when recovering soil samples from the field, it was decided that in this study *in situ* measurements would provide the most reliable data.

The theme of the 11th conference of the International Soil Tillage Research Organization (ISTRO) held at the University of Edinburgh, Scotland in July 1988 was "Tillage and Traffic in Crop Production". Topics included characterisation of soil structure, vehicle and wheel factors influencing soil compaction, crop responses in different traffic regimes and weather and environmental factors influencing crop response to tillage.

In addition to the above Hettiaratchi (1988) showed how advanced theories of soil behaviour under complex applied stresses, can be applied to the task of designing tillage tools. These are tools which are more effective in soil loosening while requiring reduced energy inputs. The opportunity to use modern modelling techniques to quantify fundamental interactions between machines, soil and crop production is becoming increasingly important. (Hadas *et al.*, 1988).

2.2 THE EFFECTS OF COMPACTION ON SOIL PHYSICAL CHARACTERISTICS

Compaction is distinguished from consolidation which is characterised by the removal of water from soil pores over time.

When a soil is subjected to a stress or external force that is higher than its inherent strength, the soil volume decreases. According to Harris (1971) the change in volume is a result of four possible factors: compression of the solid particles, compression of the liquid and/or gas within the pore spaces, change in the liquid and/or gas contents in pore spaces, rearrangement of the soil particles. Since the solid and liquid phases of a soil are relatively incompressible, the change in state of compaction depends on the change in the gas phase.

According to Soane (1973) the most obvious effect of compaction is a change in packing state, which involves the inter-relationship of the above four factors. Packing state therefore describes the volumetric properties of the solid, gas and liquid phases and can often be expressed as a dimensionless ratio, by comparing the value of a given property to the same property of the same soil, in a defined reference state.

The condition or state of compaction of the soil at any one time can be defined in terms of certain characteristics, such as bulk density, porosity, void ratio, specific volume, bulk weight volume or soil strength. The compactibility of a soil depends on soil type, moisture content and initial compactness. When a soil is compacted the bulk density increases and the porosity decreases.

Compaction mainly reduces the volume of large pores ($>30\text{ }\mu\text{m}$), this has been reported by many workers (Rasmussen, 1976; Eriksson, 1982; Marti, 1983; Riley, 1983; Allbrook, 1986). Such pores, essential for gaseous exchange and water

movement, are occupied by air, plant roots and soil organisms, such as worms. The proportion of smaller pores ($<30\mu\text{m}$) inevitably increases as a result of compaction, because of the collapse of larger pores (Rasmussen, 1976, Voorhees *et al.*, 1978; Allbrook, 1986).

Infiltration rates for topsoils have been found to be severely reduced as a result of compaction (Gaheen and Njøs, 1977; Håkansson *et al.*, 1988; Lindstrom and Voorhees, 1980; Lal, 1986), resulting in a shortage of water in the root zone and increased risk of surface run off and erosion.

Eriksson (1986 a, b), found that drainage rates were reduced by soil compaction and Reicosky *et al.*, (1981) found that at low matrix water tension, the conductivity is higher in a loose soil, but when matrix tension increases the conductivity falls more rapidly in loose compared to compacted soil. Under dry soil conditions loose soil encourages crop wilting (Håkansson, 1966b; Voorhees, 1987), because of the slow movement of water and nutrients towards plant roots and also because of greater evaporation losses.

2.3 THE EFFECT OF COMPACTION ON PLANTS AND CROP PRODUCTION

According to many researchers (Scott and Eriksson, 1964; Taylor *et al.*, 1966, 1972; Greacen *et al.*, 1969; Russell and Goss, 1974; Gooderham, 1977a, b; Voorhees, 1977; Ehlers *et al.*, 1983; Dexter, 1986), restricted root growth caused by mechanical impedance is an outcome of soil compaction. Penetration resistance values lying between 2 and 5 MPa have been found to limit root growth. Since compaction reduces the number of large pores there are insufficient pores large enough for roots to enter readily. Although mechanical impedance can cause marked reductions in root growth, yield may not be reduced if the supply of nutrients and water in the rooting zone is adequate. However, a deep rooting system is advantageous, especially in dry conditions. The volume of roots in a specific soil volume, affects the extent to which plants can “use” the water in that volume, while the extent of root growth affects the total soil volume from which water can be withdrawn.

Dexter (1986) found that when elongating seminal roots of wheat encounter a layer of dense soil, they may be deflected horizontally and instead of penetrating the subsoil, they form a mat of roots at the interface between the less dense and the dense

subsoil. If this occurs, plants are unable to tap the reserves of water in the subsoil, during short periods of drought. Dexter's work investigated the behaviour of wheat roots, as they grew through artificial subsoil layers having a range of strengths and aggregate sizes. The strengths of the soil blocks were measured with a penetrometer and aggregates sieved into 1-2, 2-4 and 4-6.7 mm size ranges. The proportions of roots which penetrated into the subsoil were investigated as functions of subsoil strength and diameter of the aggregates in the seed-bed. The proportion penetrating was found to decrease exponentially with subsoil strength. The rate of decrease was similar for the 2-4 and 1-2 mm aggregates but was greater for the 4-6.7 mm aggregates. It was concluded that provided that the roots of different plant species behave similarly, the penetrometer strength of the untilled subsoil should not exceed 0.4 MPa for plants with a single seminal axis or 3 MPa for plants such as wheat with four seminal axes.

Bengough and Mullins (1990) concluded that except where direct measurements of root force are available, penetrometer resistance is currently the best method of estimating resistance to root growth in soil, although subject to many limitations such as the ability of roots to follow tortuous pathways through the soil, whereas a penetrometer is constrained to a linear path through the soil. They found that root elongation rate is progressively decreased by increasing mechanical resistance to growth, and ceases at root penetration resistance of about 1 MPa.

Jones (1983), Eavis (1972), showed that critical bulk density values for root growth varied in response to soil water content, soil texture and soil structural characteristics.

Compaction attributed to heavy wheeled harvesting traffic caused a 50% decrease in sorghum and pearl millet yields (Fribourg *et al.*, 1975) and a 92% loss in soya beans (Wilkins and Whigham, 1986). Grimes *et al.*, (1978) showed decreased yields of alfalfa under similar harvesting regimes.

Quantitative data for assessing the effects of soil compaction on pasture growth is limited. Federer *et al.*, (1961) reported a 20% reduction in pasture yields on a Wisconsin soil subjected to animal treading. However, they did not establish whether the primary cause was from damage to plants or to soil compaction.

According to Cannell (1977), to ensure optimum plant growth the soil must be well aerated, with the supply of oxygen in the soil being sufficient to meet not only the

respiratory requirements of the roots, but also those of the soil organisms. The transfer of gases between the soil and the atmosphere occurs via air-filled pores (Greenwood 1971, 1975) and anaerobiosis will occur in soil whenever the demand for oxygen exceeds the rate at which it can enter the soil. Russell (1977) calculated that if a soil was sealed at the surface, then the oxygen in the soil would only last for two days.

Compaction reduces air-filled pore space, which in turn, restricts gaseous diffusion. Asady and Smucker (1989) measured the response of bean roots to soil compaction and measured the changes in soil aeration attributed to the presence or absence of roots. They compacted a clay soil to bulk densities of 1.1, 1.4 and 1.7 Mg m⁻³, in which the beans were planted. Mechanical resistance, measured using a penetrometer, of the soil were 0.43, 2.14 and 5.50 MPa, respectively. Oxygen diffusion rates (ODR) were below the critical level for the 1.7 Mg m⁻³ treatment throughout the experiment. As root growth increased, ODR (from 10 - 25 cm depths) dropped below critical values for all bulk densities. Total root length after 30 days was significantly reduced by 46 and 19% respectively for the 1.4 and 1.7 Mg m⁻³ treatments compared with the 1.1 Mg m⁻³ soil. The ODR values for the 1.7 Mg m⁻³ treatments ranged from 17 to 46 $\mu\text{m O}_2 \text{ m}^{-2}\text{s}^{-1}$, significantly lower than the subcritical level of 67 $\mu\text{g O}_2 \text{ m}^{-2}\text{s}^{-1}$ set by Eriksson (1982). According to Cannell (1977) anaerobic conditions are most likely in clay soils, in which drainable pore space is low, or in soils containing large structural units, where surface flooding occurs, or where water tables are on or near the surface.

2.4 THE IMPORTANCE OF SOIL COMPACTION IN NEW ZEALAND

Compaction studies in New Zealand have involved arable cropping, forestry, land restoration, livestock treading, sports turf and improvements in subsoiling technology. A brief review of these studies will be given, but with major emphasis on livestock treading, as this cause of compaction affects a number of Waikato soils and therefore is more relevant to this study than the other causes of compaction.

2.4.1 Land restoration

Ross and Orbell (1986), in their overview of land restoration after mining, report on a field trial at Waimumu, near Gore. The trial was to determine the effect of compaction on pasture production and on the physical, biological and chemical

properties of restored soils. Three levels of compaction were examined, high, medium and low.

Various soil replacement treatments were then applied, incorporating differing proportions of A, B, C, horizons. One year after restoration soil bulk density values increased for all soil replacement methods, especially where B horizons were mixed. Bulk densities under earthmover wheel tracks (1.6 Mg m^{-3}) were similar to optimum densities of soil materials used for roading and dam building. Bulk densities for medium and low compaction treatments were less than the high compaction treatment. When compared with the control plots pasture yield increases of up to 56% were recorded for the first three years after restoration where subsoiling had been incorporated into the low compaction treatment. Ross and Orbell (1986) pointed out that land restoration is a general requirement of all mining operations in New Zealand. Therefore if land productivity is to be restored after mining, then careful consideration and appropriate management plans including the amelioration of compaction should be integral to all restoration design systems.

2.4.2 Forestry

Heavy machines such as bulldozers and skidders are used in forests to harvest mature trees and clear the land for planting. These operations disturb and compact the soil in which a new crop of tree seedlings are expected to grow. Crawler tractors are the most widely used machines in New Zealand for extracting cut logs and transporting them to landing sites, where the trees are loaded onto trucks. The tractors are capable of pulling loads of 20 tonnes, exerting ground pressures of 4 - 6 MPa (Vaughan 1984). According to Wendelken (1955) a compact layer of sand below the shallow Eyrewell Forest soil, Canterbury, prevented the downward penetration of tree roots and resulted in severe wind-throw problems. Van Ballekom (1980) working on a pumice soil in the Central North Island of New Zealand found penetrometer resistance values of up to 5.9 MPa in soils which had been heavily compacted beneath skid tracks and landings. Mason and Cullen (1986) also working on a pumice soil, found that when penetration resistance reached 3 MPa, the number of tree roots was significantly reduced.

Hughes (1987) measured the physical properties of pumice soils which had been subjected to five levels of disturbance, from undisturbed to heavily disturbed, to determine whether compaction had occurred and if this would affect seedling growth. The heavily disturbed soil exhibited large increases in bulk density and soil

strength, accompanied by decreases in infiltration, total pore space and permeability, all of which would be detrimental for optimal seedling growth so amelioration was recommended. Hughes (1987) working on a silty clay loam, in the Maramarua State Forest measured the physical properties of the soil before and after 21 passes of a skidder. In this case soil physical changes were relatively small and not considered to be significant therefore remedial treatment was not recommended.

2.4.3 Sports turf

New Zealand sports are well provided for in the availability of outdoor sporting facilities. The number of sports fields per head of population probably ranks very highly by international standards. The major winter field sports of rugby, soccer and hockey require flat, well drained, playing surfaces. However because the majority of these sports venues are managed on low maintenance budgets, playing surfaces often deteriorate considerably during the playing season. McAuliffe (1990) reported that 95% of New Zealand sportsfields have silt loam topsoils which are often shallow and overlie impermeable subsoils. Artificial surfaces can create “all weather surfaces”, but are very expensive to construct and therefore in the majority of cases they are not affordable. McAuliffe (1990), suggests that consideration should be given to low cost renovation programmes, such as routine subsoiling or vibramoling (a form of vibrating mole plough) which improve subsurface drainage by increasing porosity, encourage deeper root penetration and hence promotes a denser vegetation cover.

2.4.4 Crop production

In New Zealand crop production is limited to a relatively small, but none the less significant area, when compared with pasture and forest lands. The deterioration of soil structure as a result of intensive cropping in South Canterbury was recognised and measured by Packard and Raeside (1952).

Gradwell and Arlidge (1971) and Barratt (1971), recorded soil structural breakdown after long-term market gardening in a Patumahoe clay loam at Pukekohe. They concluded that improper cultivation practices caused the problem.

Cotching (1978) and Cotching *et al.*, (1979) examined soil physical characteristics of Horotiu silt loam and Puniu silty clay in the Waikato. Soils under pasture were

compared with continuous maize cropped soils. Both soils deteriorated structurally after maize cropping, the Puniu more so than the Horotiu.

Ross and Cox (1981) measured soil physical conditions of a Levin silt loam after five years of continuous cropping. Areas of normal cultivation, no tillage, and an uncropped heavily wheel-tracked area were compared. Soil strengths were lower in the cultivated soil in contrast to the wheel-induced compaction which recorded larger soil aggregates, higher bulk densities, greater mechanical strengths and a loss of macroporosity down to a depth of 15 cm.

Greenwood (1989) studied the effects of subsoiling intensively cropped yellow-grey earths in North Otago and Canterbury. He found that subsoiling increased the volume of pores larger than 30 μm by up to 30% of the total volume of soil. Air permeability was a sensitive indicator of the ability of subsoiling to create continuous macropores. Subsoiling at 17-30 cm depth increased air permeability and hydraulic conductivity by up to 3-4 orders of magnitude. The crop response to subsoiling in this trial is reported in Chapter 2.5.4.

2.4.5 Animal treading

Pasture growth in the Waikato continues through the winter months and is sufficient to support grazing of sheep and cattle. The introduction of better pasture species and the ready access of fertilizers has caused stock densities to increase significantly in the last 40 years. Topsoils are commonly at, or close to field capacity for much of the winter months and therefore are at this time very susceptible to compaction from stock treading. Stock treading in these conditions can cause pugging (puddling or poaching) resulting in much damage to soil structure and crops.

Gradwell (1968), in a trial on Te Kowhai silt loam, found that dry bulk density increased from 0.79 to 0.88 Mg m^{-3} in response to a stocking rate increase of 8.6 to 51.6 ewes ha^{-1} . Large pore content measured near the soil surface decreased progressively from 13% of soil volume to 7.1% as stocking rates increased. Gradwell (1960) had already shown that a month or two may elapse, before any improvement in soil structure is detectable after being damaged by heavy grazing. Furthermore he found that the density increased in puddled topsoil as it dried out in the early summer.

Gradwell (1965) showed that on both Te Kowhai sandy loam and Manawatu silt loam, increased topsoil density persisted for at least six months after puddling. He concluded that incautious winter grazing could result in a significant decrease in large pores, resulting in poor pasture growth in spring and summer due to water deficiency.

Edmond (1964), investigated the effects of stock treading on pasture: Four soils, Taupo sandy silt, Egmont brown loam, Manawatu fine sandy loam and Kairanga silt loam were compared as to their treading compactibility. The Manawatu and Kairanga soils compacted most. The mean resistance to penetration, for both these soils increased from 5.3 to 8.5 kPa and the bulk density mean for the 0-2.5 cm soil depth, increased from a control value of 1.03 to a trodden value of 1.13 Mg m⁻³.

Climo and Richardson (1984) selected three Manawatu soils for study during the winter of 1981. The purpose of the investigation, was to examine the three soils in relation to their susceptibility to treading damage. The Ramiha silt loam (bulk density 0.70 Mg m⁻³) a well drained yellow brown earth with a low susceptibility to treading had the highest macroporosity, which was not significantly altered by compaction. The Tokomaru silt loam, (bulk density 1.11 Mg m⁻³), a poorly drained yellow-grey earth with high susceptibility to treading had a 19% reduction in macroporosity after compaction. The Manawatu fine sandy loam (bulk density 1.20 Mg m⁻³), a well drained recent soil with a susceptibility to treading during heavy rainfall, showed a significant decrease of 39% in macroporosity following compaction. They concluded that during heavy rainfall, on soils which were approaching field capacity, treading damage occurs unless stock are removed from the pasture. The Ramiha soil would rarely, if ever, be saturated because of its high permeability and macroporosity. Stock could be returned almost immediately after heavy rainfall on the Manawatu soil, because of good draining, unless previous treading damage retarded drainage of the surface soil. The Tokomaru soil would probably remain susceptible to treading damage for some time following rainfall. This time could be decreased with the installation of a subsurface drainage system.

2.5 AMELIORATION OF SOIL COMPACTION

2.5.1 Natural recovery

Rates of natural amelioration of compacted soils are variable. Soil structure forming processes are the reverse of compactive processes, these are freeze and thaw, frost heave, wetting and drying and biological activity. For these processes to function, climatic conditions must produce the necessary temperature and moisture regimes.

Compacted soils are loosened by freeze and thaw cycles where winter freezing occurs (Brady 1974). Soil volume changes however, are not necessarily large, as water only expands 9% during freezing.

Frost heave, under optimum conditions produces larger volume changes in soil, than freezing and thawing. According to Dirksen and Miller (1966) for frost heave to occur 90% of the pore space should be filled with water, followed by severe freezing. They concluded that medium textured and compacted coarse textured soils are most likely to benefit from frost heave. Mace (1971), found that compacted surface layers of some soils recovered in two years due to frost heave. However in a milder climate Froehlich *et al.*, (1983) found that compaction caused by skid-trails persisted for at least 30 years.

Wetting and drying causes volume changes, primarily through shrinkage cracking of compacted soils. Properties that affect volume changes are the amount and type of clay minerals, aggregate arrangement, exchangeable cations, composition of the soil solution and organic and chemical bonding agents (Larson and Allmaras, 1971).

Soils dominated by smectite clays are the soils most likely to show significant volume changes. Blackwell *et al.*, (1985) working on a stagnogley clay soil in the United Kingdom, found that wetting and drying, not freezing and thawing, was the principal natural process which helped restore some soil structure.

The ability of some clay soils to regenerate a fine tilth through self-mulching after destruction by tillage operation under wet conditions has been described (Soil Survey Staff 1960). Grant and Blackmore (1991) have recently proposed a numerical index of self-mulching, which is a function of the slaking behaviour, wet stability, and total clay content of a soil.

It is evident from these studies that alleviation of compacted soils by natural processes usually occurs in near surface soil horizons and is in most cases a relatively slow process.

According to Håkansson *et al.*, (1988) the amelioration of subsoil compaction by natural processes is not likely, because the problem usually occurs below the zone of influence of such processes.

2.5.2 Conventional tillage

Conventional tillage operation such as mould board ploughing, disc harrowing and rotovating reduce the compactness of soil to the depth of operation. The use and effects of such implements have been reviewed by many (Russell, 1973; Unger *et al.*, 1981; Gupta and Larson, 1982; Unger and Stewart, 1983). These reports show that such implements have been extensively used to invert and mix soil in preparation for crop production.

Conventional tillage operations can however compact soil immediately below the depth of operation, creating soil pans of high density. If these pans are not broken up they may cause shallow rooting of plants as shown by Cooper (1971). Conventional tillage operations can only be used to ameliorate compacted soils under permanent pasture or under sports turf, when “complete” disturbance of topsoil and reseeding is contemplated. Dexter and Tanner (1974) showed that such disturbance may result in soils being more rapidly compressed than undisturbed soils at the same initial density and water content.

2.5.3 Subsoiling

Subsoiling is the most common form of deep tillage and has been used for many years to disrupt the subsoil (Soane *et al.*, 1986). Subsoiling loosens compacted soil but does not invert or mix the soil to any extent. It may also improve drainage, but the main purpose should be to cause the maximum disruption of the soil, rather than forming drainage channels.

Much of the subsoiling technology has developed from research carried out in Europe and the United States. The National Institute of Agricultural Engineering (NIAE) based at Silsoe in Bedfordshire in the United Kingdom has been responsible

for much technological innovation in subsoiler design and efficiency (Spoor and Godwin 1978). New Zealand manufacturers have essentially followed the technology and design emanating from NIAE.

Godwin *et al.*, (1984) showed that the extent of soil disturbance resulting from subsoiling is dependent on the design and operation of the machine. The volume of soil to be treated and the tractor power available determines to some extent the volume of soil to be treated and the spacing of the subsoiler shanks. Spoor and Godwin (1978) recommend that for complete soil disturbance, shank spacing should be set at 1 to 1.5 times the working depth for a conventional subsoiler. Increasing spacing to 1.5 to 2 times the working depth for winged machines and 2 to 2.5 times for winged plus shallow leading shank machines. The addition of sweeps or wings to the subsoiler shanks increased the extent of subsoil shatter.

Mason (1979) working in New Zealand forests reported that since the mid 1960's subsoiling has been routine practice before tree planting. He investigated the effects of attaching "wings" to the base of the subsoiler shank and concluded that wings made subsoiling more efficient since for a given power input a greater area of soil was shattered. While 60 cm is the most frequently prescribed subsoiling depth, some forest managers have subsoiled as deep as 150 cm and others as shallow as 45 cm. Contour and downhill subsoiling are limited to slopes of $<20^\circ$ and $<30^\circ$ respectively. In some areas, especially the pumice soils of Central North Island, New Zealand, down hill subsoiling leads to severe erosion.

Spoor (1982b) described two types of soil disturbance resulting from subsoiling:

- (a) disruption and re-orientation of soil fragments in the zone affected by the subsoiler, creating large pores between the fragments.
- (b) "opening up" of the soil along planes of weakness, creating large fissures, but without significant re-orientation of the soil fragments.

He also showed that soil movement always occurs in the direction of least resistance. Normally at shallow operating depths ($<35\text{cm}$), soil is moved forward, upwards and sideways by the subsoiler along rupture planes which radiate from just above the share tip (Spoor and Godwin, 1978; Koolen and Kuipers, 1983). As operating depth increases soil resistance to upward movement increases, until at a critical depth resistance to upward soil movement is greater than resistance to lateral movement. Soil moves forward and sideways which can in some cases create a compacted area around the tip.

Soil moisture content greatly influences the effectiveness of subsoiling. For best results subsoiling should be carried out when the soil is dry, so that brittle fracture can occur, or at least when the soil is drier than the plastic limit. (Swain, 1975; Spoor and Godwin, 1979; Spoor, 1982a; Pidgeon, 1982).

2.5.4 Benefits of subsoiling

According to Cannell (1973) subsoiling would be expected to improve root growth, where soil physical conditions are a limiting factor. The effects of subsoiling on root growth has largely been confined to arable and forestry crops, with little data on pasture response.

As shown by Bennie and Botha (1986), subsoiling provided rapid access to the subsoil by maize and wheat roots and resulted in greater maximum rooting depths. Earlier Balazs (1962) working in Hungary, found subsoiling encouraged deeper rooting of grass species.

Spectacular increases in cotton yield were reported by Taylor and Gardner (1963), where traffic pans which had previously proved impenetrable to cotton roots, were broken up by subsoiling.

Mason (1979) working in New Zealand showed that subsoiling improved soil structure, allowing young pines to root vertically deeper, thus developing a large straight grained taproot, crucial for tree stability. In other trials conducted by the Forest Research Institute of New Zealand subsoiling increased initial growth of pine seedlings in Northland, Canterbury and Otago (Mason, 1979).

Fortune and Burke (1985) set up a series of sugar beet yield experiments in 1980, in Ireland, to compare the effects of deep loosening with conventional tillage. Various types of subsoilers were used over a four year period, including rigid shanks, winged shanks and vibrating shanks. Subsoiling was carried out in dry soil conditions after harvest. Crop yields the following year varied from 20% increase on a sandy loam to nil increase on a number of other sites. They attributed the poor response to re-compaction caused by spring tillage on wet soils and a pattern of summer rainfall which was adequate to maintain growth even when rooting depth was restricted.

Vepraskas and Mines (1986) described relationships between mechanical impedance and tobacco root concentrations for both subsoiled and non-subsoiled treatments. Penetrometer readings were made in the tobacco rows and at 30 cm to the side of the rows; data was expressed as a mean cone index (CI). The compacted layers had CI values between 2.8 and 3.2 MPa. Subsoiling reduced the CI of the tillage pans to values between 1.2 and 1.6 MPa for up to 47 days from transplanting and thus facilitated significantly greater root penetration.

Vepraskas *et al.*, (1987) found soils where yields of tobacco could be increased by subsoiling had bulk densities $\geq 1.63 \text{ Mg m}^{-3}$ within or just below the plough layer horizon. Vepraskas (1988) estimated CI from bulk density and soil texture values from which he developed a compaction model. He found that minimum bulk density values associated with a subsoiling response when compared with ploughing/disc treatment were 1.66, 1.61, 1.60 and 1.58 Mg m^{-3} for a sand, loamy sand, sandy loam and sandy clay loam respectively. It was estimated that tobacco root concentrations would be zero at bulk densities of 1.85, 1.82, 1.81 and 1.80 Mg m^{-3} for the same textural classes.

Chapman and Allbrook (1987) showed that subsoiling under pasture reduced penetrometer readings, lowered bulk density and raised the porosity of the soil.

Busscher *et al.*, (1988) in the United States, evaluated soil and plant response to three subsoiling implements on a South-eastern coastal plain soil growing corn. Soil strength (CI) for the implements was evaluated with and without conventional surface tillage (disking). All three subsoilers effectively disrupted a compacted E horizon regardless of surface tillage. Soil strength results suggested that soils which had been subsoiled were less likely to restrict root development.

Ibrahim and Miller (1989) conducted studies to evaluate the influence of subsoiling and irrigation regime on growth of potatoes and field corn on two soils in Washington State, United States. They found that subsoiling a sandy soil was of little benefit when water stress between irrigations was minimized by daily irrigation. Where the irrigation interval was extended to 4 days, subsoiling prevented the degree of water stress that occurred without subsoiling, and yield and grade of potatoes and corn were increased compared to non-subsoiling. Subsoiling was less beneficial on a loamy soil than on a sandy soil.

Vepraskas (1988) also concluded that the less soil water a plant has access to during the growing season, the more likely it is for subsoiling to increase yield.

CHAPTER THREE

CHAPTER THREE

CHAPTER THREE

CHAPTER 3: FIELD WORK

3.1 SUBSOILER SHAKAERATOR DEVELOPMENT

Subsoiling is a form of deep tillage which has long been recognised as a routine operation on some arable farms. Arable type subsoilers come in many shapes and sizes, the majority of which consist of a tool bar on which shanks of various lengths and sizes are attached. One such machine, the Ripper, manufactured by Gallagher Engineering Limited, Hamilton, is shown in Figure 3.1.1. This machine is used for breaking up plough pans, soil aeration, irrigation schemes, root pruning and drainage improvement. However like many other machines, when used under pasture conditions, it caused much surface damage through scuffing and physical damage to pasture roots as shown in Figure 3.1.2. This damage is unacceptable to the majority of pasture farmers. In response to these faults it was decided in November 1986, to redesign the Gallagher Ripper in order to satisfy the requirements of the pasture farmer or sports turf user.

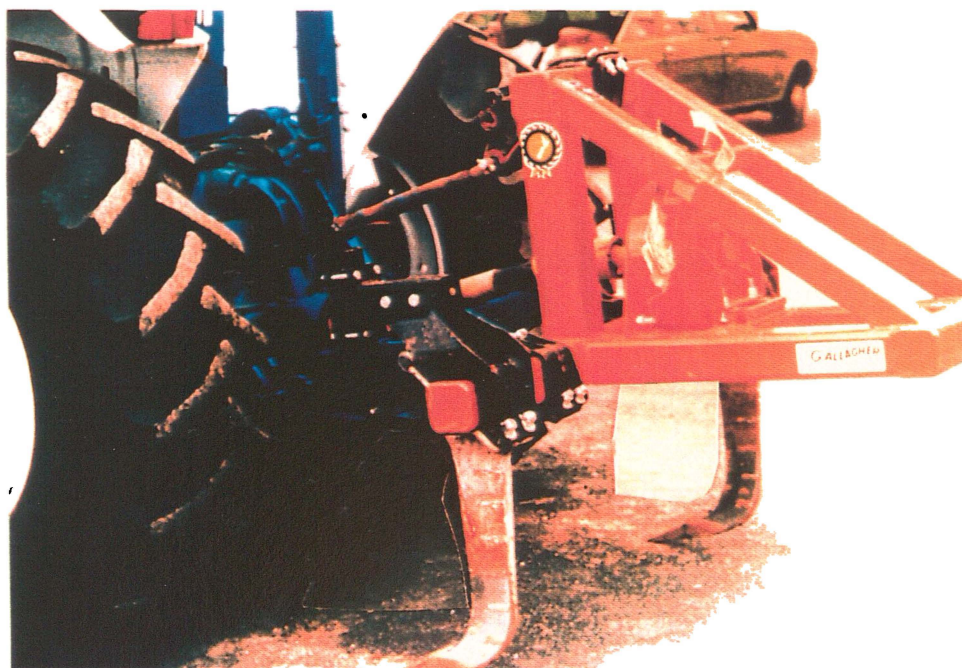


Figure 3.1.1 The Ripper subsoiler manufactured by Gallagher Engineering Ltd, Hamilton, New Zealand



Figure 3.1.2 Damage caused by Ripper to pasture

3.1.1 Objectives

The objectives were to produce a subsoiler which would:

- a) cause minimal damage to growing pasture
- b) minimise soil moisture loss, especially in the upper layers of soil, where most pasture roots grow
- c) create maximum subsurface soil loosening without compromising objectives a) and b)
- d) be strong, durable and economic to operate.

A team, comprising Richard Chapman, University of Waikato; Vaughan Jones, Gallagher Director; Peter Catel, Design Engineer; Kevin Marquand, Sales Manager, was set up to carry out the re-design of the Gallagher Ripper. A number of prototypes were built and tested under varying soil and pasture conditions.



Figure 3.1.3 Pasture subsoiler prototype I

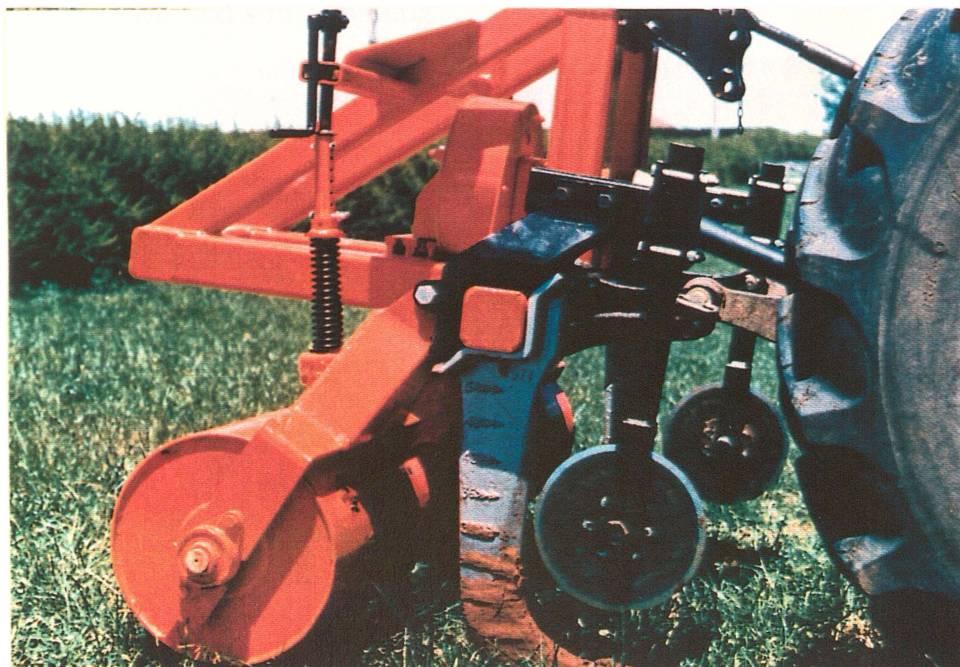


Figure 3.1.4 Pasture subsoiler prototype II

3.1.2 Reduction in surface damage

A series of disc coulters (locally known as skieths) and coultter attachments were attached to the frame and tested as shown in Figure 3.1.3. Costs had to be kept to a minimum and therefore some of the more sophisticated spring loaded models as shown in Figure 3.1.4 were discarded. Fully adjustable 35 cm diameter discs were tested. The discs were attached in front of each subsoiler shank and adjusted to cut cleanly through the turf to a depth of 10 cm. The subframe was altered to accomodate the discs. The shanks were attached at the back of the frame to improve weight transfer from machine to tractor, (Figure 3.1.5). This alteration produced a clean cut as shown in Figure 3.1.6 through which the subsoiler shank followed. Surface scuffing and extensive root disturbance and damage was virtually eliminated.

In order to reduce soil moisture loss, it was found necessary to construct rollers to press down the open slot created by the subsoiler shanks. Rollers of various design and dimension were tested. It was found that rollers fitted with water and weighing approximately 30 kg were effective in reducing moisture loss and were relatively cheap to produce. They were attached behind the subsoiler shanks shown in Figure 3.1.5 and were of sufficient weight to press down the heaved ground, reducing the height of the heave by approximately 25%. This reduced the width of the subsoiler slots and thus conserved soil moisture.



Figure 3.1.5 Pasture subsoiler prototype III

3.1.3 Operational efficiency

The shakaerator is driven via the tractor power take off (PTO), it incorporates a shaker box consisting of a number of eccentric weights which rotate and cause the machine to vibrate. Existing weights were found to cause excessive vibration at the recommended PTO speed of 540 revolutions per minute (rpm) and were reduced for optimum effect and compatibility with the new machine. Long (60 cm) and short (48 cm) shanks were made for pasture or orchard use. Wide (40 cm) and narrow (10 cm) tips shown in Figure 3.1.7 were also made. Preliminary tests showed that the vibrating treatment, caused more soil disturbance, and used less tractor power than non-vibrating. Various operating speeds, machine pitch angles and depths of subsoiling were tried, from which a standard operational speed was suggested.

Tests resulted in the following recommendations for general pasture use. Subsoiling should be carried out when soils are relatively dry, tractor forward speed 5 km h⁻¹, PTO speed 540 rpm, operating at 45 cm depth, disc coulters set at 10 cm depth shank spacing 1 m and, for optimal weight transfer, a pitch angle of 2° as shown in Figure 3.1.5. Unless otherwise stated, these recommendations were followed throughout the duration of the research project.



Figure 3.1.6 Pasture subsoiler prototype III, operating on Horotiu soil. Note reduced damage to pasture when compared with Figure 3.1.2

3.1.4 New machine, new name

The Gallagher* Shakaerator Subsoiler, suitable for pasture subsoiling, was launched in March 1987 and is shown in Figure 3.1.7. For arable subsoiling the machine was sold without discs and rollers. A glossy brochure was prepared and is seen in Appendix 1.

To date (December 1990) approximately 400 machines are operating in New Zealand. The majority of these are found on dairy farms, with lesser numbers associated with orchards and agricultural contractors.



Figure 3.1.7 The Gallagher Shakaerator subsoiler suitable for pasture subsoiling

** Mention of trade name does not imply endorsement by Waikato University to the exclusion of other products that may be suitable.*

3.2 FIELD SITES

Five sites were selected to represent five different soil types following checks on soil uniformity. Since four sites are on farmers property the land owners co-operation was essential in providing background data on land use, stocking rates, drainage and fertilisers. All plots were located away from gates, water troughs, races and fences.

3.3 EXPERIMENTAL DESIGN

The layout of the trial on the four dairy farms followed a simple block design incorporating eight plots (Figure 3.3.1). The dimensions of the plots varied from farm to farm, in order to fit the constraints of paddock size and drainage systems, but the majority were in the order of 10 m x 40 m. The A plots were subsoiled lengthways and the B plots were left untreated. At Rugby Park the entire playing surface was subsoiled, with the exception of the four corners, where 5 m x 20 m plots were left. At the Te Kowhai and Whatawhata sites, additional plots were used to assess the performance of vibrating versus non-vibrating subsoiling. All sites were situated on level ground except for the Hamilton site which sloped uniformly 10° to the west. The A plots on the imperfectly drained Te Kowhai and Whatawhata soils were “linked” to existing open drain systems, by subsoiling the ground between the A plots and the drains. To ensure access to the open drains, the subsoiler shanks and tips were lowered into the drain and pulled through at right angles to the direction of the drain, at 45 cm depth. Unless otherwise stated A plots were subsoiled in the direction of the long axis of the plot, at standard operational settings as laid down in Chapter 3.1.3. The Hamilton site was laid out with the long axis of the experimental block parallel to the 10° slope, thus ensuring that subsoiling was carried out along the contours of this hilly site.

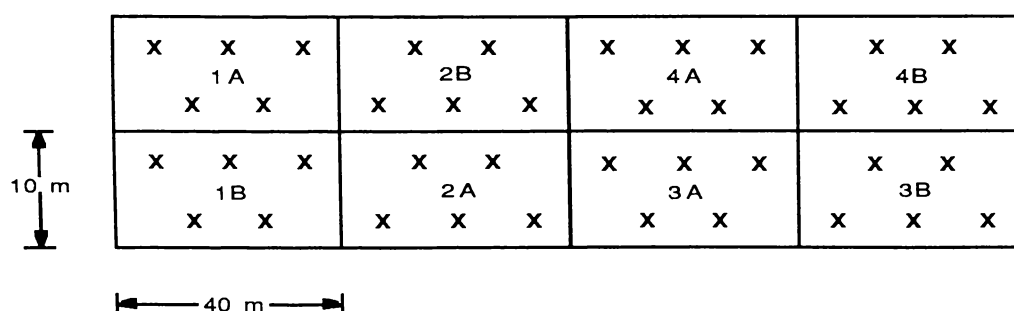


Figure 3.3.1 Experimental design used on the four farm sites. Plots marked A were subsoiled, B plots non-subsoiled. Sampling and soil physical measurements were taken from areas marked X.

3.4 SOIL SURVEY AND PROFILE SELECTION

Soil characteristics at each site were determined from auger samples and detailed pit descriptions.

3.4.1 Auger descriptions

In general five holes were made at each site using a Dutch clay auger. Soil properties of colour, texture, structure, mottles, evidence for compacted layers and horizon depths were determined. The most representative auger hole was used for full profile description and sampling.

3.4.2 Detailed soil profile description and soil classification

Detailed soil profile and site descriptions for each soil type were recorded according to procedures described in Taylor and Pohlen (1970). Soil horizon notation is based on Clayden and Hewitt, (1989).

Soil classifications were made according to Taylor and Pohlen (1968), Hewitt (1989) and soil survey staff (1975) for New Zealand Genetic classification, “New” New Zealand System and Soil Taxonomy respectively.



Figure 3.5.1 Hamilton clay loam

3.5 SOIL PROFILE DESCRIPTIONS

Soil Type **Hamilton clay loam** (Figure 3.5.1)
 Location: Leuthards property, roadside paddock opposite
 Raynes Road, Rukuhia, Hamilton
 Grid Reference: NZMS260 S15/132904
 Topography: Moderate slope of 10°
 Altitude: 65 m a.s.l.
 Aspect: West
 Drainage: Imperfect to moderately well drained
 Soil erosion: No erosion
 Current vegetation: Ryegrass, clover
 Past vegetation: Broadleaf-podocarp forest
 Land use: High quality pasture for intensive dairy farming

Profile	depth	Description
Ap1	0-15 cm	brownish black (10YR 2/2) clay loam; friable (when moist); slightly plastic; moderately developed granular structure; many roots; indistinct diffuse boundary,
Ap2	15-25 cm	dark brown (10YR 4/3) clay loam; firm; plastic; well developed nutty structure; many roots; distinct wavy boundary,
Bt	25-32 cm	yellowish brown (10YR 5/4) clay loam; firm; plastic strongly developed nut and coarse block structure; many fine roots; indistinct boundary,
2Bt1	32-49 cm	brown (7.5YR 5/4) clay; firm; strongly developed coarse block structure; peds with distinct clay skins; few manganese concretions; few fine roots; diffuse boundary,
2Bt2	49-74 cm	bright brown (7.5YR 4/6) clay; very firm; strongly developed coarse block and medium prismatic structure; few manganese concretions,
on		moderately argillised late Pleistocene tephra over strongly argillised Pleistocene tephra.

Classification:

New Zealand Genetic classification:

Moderately leached strongly clay illuvial central
brown granular loam.

“New” New Zealand system: Typic Orthic
Granular Soil

Soil Taxonomy: Typic Haplohumult

Hamilton clay loam occurs on rolling ridges, dissected high terraces and isolated
hills in the Hamilton Basin (Figure 3.5.2)



Figure 3.5.2 Hamilton clay loam landscape

Soil Type: **Horotiu sandy loam** (Figure 3.5.3)
 Location: Shaws property, Ohaupo to Paterangi Road,
 Ohaupo
 Grid Reference: NZMS260 S15/093608
 Topography: Flat
 Altitude: 35 m a.s.l.
 Drainage: Well drained
 Soil erosion: No erosion
 Current vegetation: Ryegrass and white clover
 Past vegetation: Dictyolous-podocarp forest with kahikatea
 Land use: Intensive dairy farming

Profile	Depth	Description
Ap	0-15 cm	brownish black (7.5YR 2/2) sandy loam; very friable; well developed granular to weak nutty structure; abundant roots and worms; distinct boundary,
Bw1	15-40 cm	bright brown (7.5YR 5/6) sandy loam; very friable; fine granular structure; few roots; indistinct boundary,
Bw2	40-70 cm	yellowish brown (10YR 5/6) sandy loam; very friable; fine granular structure; few pebble size pumice fragments,
on		rhyolitic gravel and sand.

Classification: New Zealand Genetic classification: Moderately leached central yellow-brown loam.
 “New” New Zealand System: Typic Orthic Allophanic Soil
 Soil Taxonomy: Dystrandept

Horotiu sandy loam and associated Horotiu silt loam occur on the Hinuera surface (Figure 3.5.4) which represents the surface of an alluvial fan deposited by the Waikato River in several episodes between 65,000 - 15,000 years ago. The fan is composed of rhyolitic sands and gravels, which buries the old landscape represented by the Hamilton Hills (Figure 1.2). A thin mantle of recent tephra is incorporated into the soil. The amount of allophane varies considerably.



Figure 3.5.3 Horotiu sandy loam



Figure 3.5.4 Hinuera surface landscape. Horotiu soils occupy the humps, Te Kowhai soils occupy the swales

Soil type: **Rugby Park soil**; artificially constructed soil (Figure 3.5.5)
 Location: Rugby Park, Hamilton
 Grid Refernece: NZMS260 S14/100777
 Topography: Slightly crowned pitch
 Altitude: 30 m a.s.l.
 Drainage: Moderately well drained
 Soil erosion: No erosion
 Current vegetation: Ryegrass turf mixture
 Past vegetation: Broadleaf - podocarp forest
 Land use: Club, provincial and international rugby.

Profile	Depth	Description
Ap	0-21 cm	brown (10YR 4/4)sandy loam; firm; medium crumb to granular structure; few stone size clinkers and pebble size pumice fragments; dense roots in top 10 cm of profile; diffuse boundary;
2Bg	21-40 cm	dull yellow orange (10YR 6/4) silt loam; many dull orange (7.5YR 7/4) medium sized mottles slightly plastic when wet; massive in place breaking to blocky structure; few roots; diffuse boundary,
2Bg	40-65 cm	light brownish grey (7.5YR 7/2) silt loam; massive; diffuse boundary,
on		pumiceous alluvium.
Classification		New Zealand System: Typic Truncated Anthropic Soil. Artificially constructed soil.

Rugby Park top soil (0-15 cm) has been artificially constructed by annual top dressings of sand. The initial construction in the 1930's resulted in a domed central area sloping (1 - 2°) to the touch lines to encourage run-off and hence better drainage. The soil profile below 21 cm depth resembles the Te Kowhai soil and thus has formed from pumice clays and silts of the Hinuera formation.



Figure 3.5.5 Rugby Park soil. The photograph was taken one year following subsoiling and shows a much improved turf when compared with Figure 3.5.6



Figure 3.5.6 Rugby Park, October 1986. Subsoiled with prototype I (Figure 3.1.3). Note ground heave and slot opening.

Soil type: **Te Kowhai silt loam** (Figure 3.5.7)
 Location: Jones property, Greenhill Road, Hamilton
 Grid Reference: NZMS260 S14/145818
 Topography: Shallow depression, flat
 Altitude: 30 m a.s.l.
 Drainage: Poorly drained
 Soil erosion: No erosion
 Current vegetation: Ryegrass, clover, flat weeds
 Past vegetation: Kahikatea-dominant semi-swamp forest
 Land use: Intensive dry stock farming

Profile	Depth	Description
Ap	0-20 cm	brownish black (10YR 2/2) silt loam; very friable; medium to fine nutty structure breaking into medium granular structure; many roots; distinct boundary,
Bg	20-60 cm	yellowish brown (2.5Y 5/3) silt loam with many orange (5YR 6/8) medium sized mottles; firm non-sticky; plastic when wet; massive in place breaks to weakly developed blocky to prismatic structure; a few light grey (5Y 8/2) weathered pumice fragments (2 cm diameter); few vertical root channels; outlined by brown mottles; distinct boundary,
Cr	60-90 cm	light grey (5GY 8/1) silt loam; a few stone sized pumice fragments; lenses of bluish black (10BG2/1) heavy minerals; massive structure no roots; diffuse boundary,
on		pumicious alluvium.

Classification: New Zealand Genetic classification: gleyed yellow-brown pumice soil.
 “New” New Zealand System:
 Acidic Orthic Gley Soil
 Soil Taxonomy: Haplaquept

Te Kowhai silt loam occurs in the hollows (swales) of the undulating Hinuera surface (Figure 3.5.8). It is common to find Horotiu soils in close proximity on the slightly elevated (1 m) humps, which provide free draining. Te Kowhai soils are particularly prone to livestock pugging in the winter months. They do not however, drought which commonly occurs on Horotiu soils during February.



Figure 3.5.7 Te Kowhai silt loam. Note the distinct boundary and colour change between the A and Bg horizons and also the ground water surface evident at 1.0 m depth.



Figure 3.5.8 Looking down from the Hamilton Hills on to the undulating Hinuera surface. Note the presence of surface water occupying the swale in the middle right view.

Soil Type: **Whatawhata clay loam** (Figure 3.5.9)
 Location: McBrides property, Blacketts Road,
 Whatawhata
 Grid Reference: NZMS260 S14/981812
 Topography: Flat
 Altitude: 30 m a.s.l.
 Drainage: Poorly drained
 Soil erosion: No erosion
 Current vegetation: Prairie grass
 Past vegetation: Kahikatea-dominant semi swamp forest
 Land use: High quality pasture for intensive dairy farming

Profile	Depth	Description
Ap	0-16 cm	greyish yellow brown (10YR 4/2) clay loam; firm; moderately developed nut and granular structure; many roots; diffuse boundary;
Bt	16-26 cm	dull yellowish brown (10YR 5/3) clay; firm; well developed blocky structure; few roots; diffuse boundary,
Btgl	26-58 cm	dull yellow orange (10YR 6/4) clay; many orange (7.5YR 6/6) mottles; moderately developed prismatic structure; few roots diffuse boundary,
Btg2	58- 78 cm	dull yellow orange (10YR 7/3) clay; many prominent orange (7.5YR 6/6) mottles; firm; compact; moderately developed prismatic structure; no roots; distinct boundary,
on		alluvium of mixed origin.

Classification: New Zealand Genetic: gleyed central yellow-brown earth.
 “New” New Zealand System: Typic Firm Brown Soil
 Soil Taxonomy: Dystrochrept

Whatawhata clay loam occurs on terraces bordering the Waipa River (Figure 4.10). The soils are developed on a layer of alluvium deposited by the Waipa River over gravels of the Hinuera Formation. According to Grange *et al.*, (1939) a large temporary lake formed when the Waikato River blocked the course of the Waipa

River. The lake resulted in the accumulation of a large quantity of fine grey silt which now forms the parent material of the Whatawhata Soil. Whatawhata soils have poor internal drainage and pug badly in the winter months, through livestock treading (Bruce, 1978).



Figure 3.5.9 Whatawhata clay loam. The photograph was taken in September and shows a gleyed B horizon and severe livestock pugging in the paddock behind the hedge.

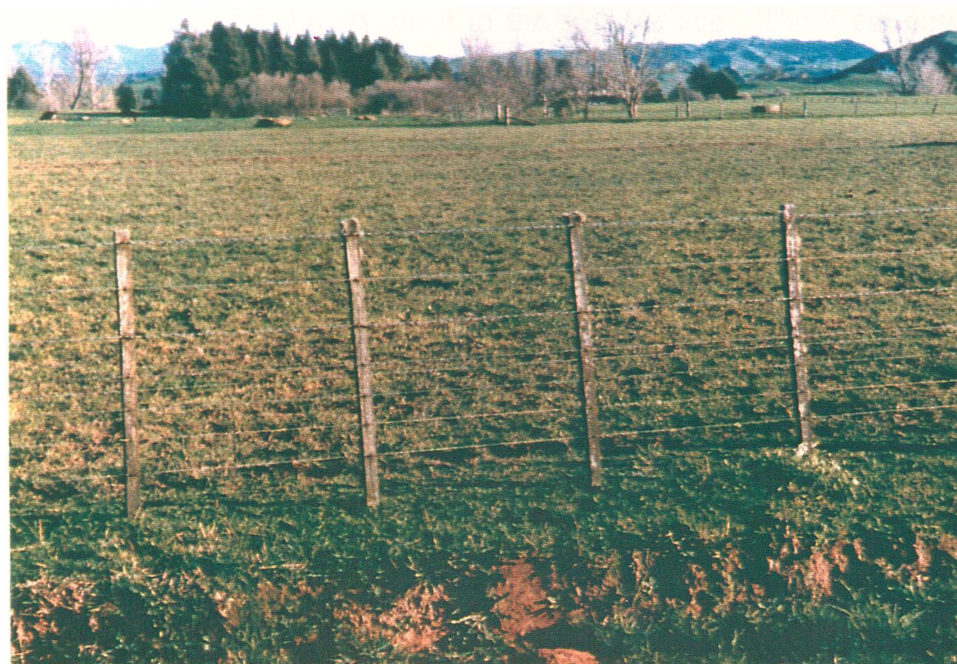


Figure 3.5.10 Whatawhata clay loam. Note the uneven surface of the paddock caused by livestock pugging.

3.6 FIELD MEASUREMENTS

3.6.1 Bulk density

The dry bulk density of a volume of soil is a measure of the solid phase plus pore space. In this study, bulk density is used as a measure to quantify the effects of subsoiling on differing textured soils. The variation of soil density with distance from the subsoiled slots was measured. A subsurface density gauge (Ronly model SDG-39) was used to measure soil bulk density *in situ*, for both subsoiled and non-subsoiled plots. Van Bavel *et al.*, (1985) concluded that two-probe gamma-ray densimeters give consistent and accurate results.

3.6.1.1 The Instrument

The Ronly model SDG-39 transmission subsurface density gauge (SDG) consists of two permanently connected probes (Figure 3.6.1). One probe contains a $3.7 \times 10^7 \text{Bq } \text{Cs}^{137}$ source, with a half life of 30 years and an expected operational life of 15 years. The other probe contains a Geiger-Muller detector. The detector records counts of received radiation and is designed to facilitate the taking of a large number of density measurements in the upper 45 cm of the soil. In addition to measuring soil density *in situ*, the main advantage of using this instrument is the possibility of measuring distinct thin soil layers close to the soil surface. The 3 cm active length of the Geiger detector gives an average minimum detection thickness of 1.5 cm. (Ronly manual, 1983).

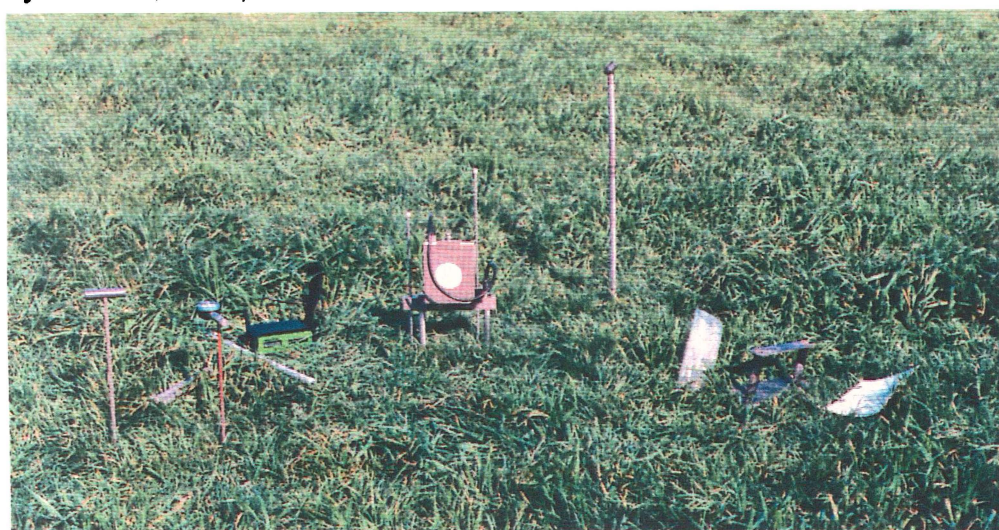


Figure 3.6.1 Some of the field equipment on site at Whatawhata. From the left, a hand held tensiometer, a pasture probe and in the centre the Ronly subsurface density gauge (SDG)

3.6.1.2 Gamma-ray absorption

According to the Beer-Lambert law, the absorption of gamma rays by soil follows from:

$$I = I_0 e^{-(\mu_s \cdot \rho_b + \mu_w \cdot \rho_w \cdot \theta_v)d}$$

where I = the radiation intensity after passage through d cm of the soil/water system

I_0 = the radiation intensity of the source

μ_s = the absorption coefficient of soil ($\text{cm}^2 \text{g}^{-1}$)

ρ_b = the soil bulk density (Mg m^{-3})

μ_w = the absorption coefficient of water ($\text{cm}^2 \text{g}^{-1}$)

ρ_w = the density of water (Mg m^{-3})

θ_v = the volumetric soil water content ($\text{V}_w \text{v}^{-1}$)

d = 21 cm, the distance between the source and the detector

e = The base of natural logarithms

The Ronly SDG* emits radiation at an energy level of 0.66 MeV. According to the Ronly instruction manual (1983) the absorption coefficient of water for Cs^{137} , at this energy level is $0.0857 \text{ cm}^2 \text{g}^{-1}$ and soil values ranging from 0.071 to $0.087 \text{ cm}^2 \text{g}^{-1}$ have been measured.

The absorption coefficients of soil and water are therefore negligible; thus the Beer-Lambert equation can be simplified to :

$$\log \frac{I'}{I_0'} = A \rho_{bw}$$

Where: I' = The count ratio in a soil/water system

I_0' = The standard count rate in air

A = A constant based on the absorption coefficient of water and soil, the counting efficiency and the fixed distanced.

ρ_{bw} = The wet bulk density

** Mention of trade name does not imply endorsement by Waikato University to the exclusion of other products that may be suitable*

3.6.1.3 Instrument Calibration

Instrument calibration is achieved by measuring I' and Io' for known wet bulk density values. To measure Io' a large number of 90 second count readings as suggested by the manufacturer were done with the probe standing in free air. A standard count was established from the average of these readings.

To measure I' an open ended particle board box was used to measure known wet bulk density values of oven dry sand, plus measured additions of water. Varying levels of compaction were used to obtain wet bulk densities ranging from 0.60 to 1.8 $Mg\ m^{-3}$. A correction factor was needed to allow for the effects of the bulk density of particle board.

3.6.1.4 Calibration curve

The count ratios (Io'/I') versus wet bulk densities were plotted, resulting in a calibration curve (Appendix 2) which tended to flatten out at the low density and steepen at the higher density. Each time the gamma probe was used in the field a standard air count was determined to enable calculation of the count ratios. The wet bulk density of soil could then be calculated directly from the measured count ratio.

3.6.1.5 Field measurement

A jig and auger are used to bore two holes 21 cm apart into which the probes were inserted. Measurements were made at 5 cm increments to a depth of 45 cm and wet bulk density calculated as discussed. The soil removed from the auger holes was retained, in order to determine soil moisture contents, so that bulk density on a dry basis could be calculated.

3.6.2 Soil Strength (penetration resistance)

Soil strength estimation was carried out using a Bush* recording cone penetrometer (Anderson *et al.* 1980). This instrument measures the resistance of soil to penetration by a 30° cone to a depth of 52.5 cm. A cone, 12 mm diameter was used. Readings in kg are automatically taken at increments of 3.5 cm as the cone is pushed down and stored in the memory. The force applied per unit area expressed as a cone index (MPa) was calculated using the cross sectional area of the cone where the recorded force is multiplied by the gravitational force and divided by the basal area of the cone used.

Penetrometer readings were taken at regular intervals within each plot (Figure 3.3.1). The maximum penetrometer reading attainable, before ^{instrument} overload (OL) was 75 kg or 5.625 MPa. The variation in cone index readings for a specific depth was less than 15% of the mean value; significance was calculated accordingly. In many cases where overload (OL) was registered, a pit was dug to investigate penetrometer resistance at depths below that at which OL was recorded. In these cases OL persisted down to depths of 50 cm. All five soils in this study are free from stones and therefore resistance to penetration is a function of the inherent strength of the soil at the time of measurement.

3.6.3 Soil Moisture Tension

The retention and movement of water in soils, its uptake and translocation in plants and its loss to the atmosphere are all energy related phenomena (Brady 1974). Differences in energy levels of soil water can be expressed in terms of suction or tension. The approximate equivalents of common means of expressing differences in energy levels of soil water are given in Table 3.6.1.

In this study soil water content at low tensions ranging from pF2 to pF3 was measured in the field using a Quickdraw Tensiometer. The moisture tensions for subsoiled and non-subsoiled plots were measured in both winter and summer.

** Mention of trade names does not imply endorsement by Waikato University to the exclusion of other products that may be suitable.*

Table 3.6.1 Approximate equivalents of common means of expressing differences in energy levels of soil water.

Height of unit column of water (cm)	logarithm of water height (pF)	Bars	kPa
10	1	0.01	0.98
100	2	0.10	9.8
346	2.53	0.33	32
1000	3	1	98
10000	4	10	980
15849	4.18	15	1470

3.6.3.1 The Instrument

The 2900 model Series E “Quick Draw”* soil moisture probe (a portable tensiometer) was used to measure soil suction *in situ*. The soil suction reading indicates whether there is water available for plant growth. (Figure 3.6.2)

3.6.3.2 Method

At each site five readings were taken from each plot at 10, 30, 45 cm depths. The first operation in taking a reading is to core a hole in the soil to the required depth with the tool provided. The tensiometer probe is then inserted into the hole and pushed in so that the sensing tip is in firm contact with the soil. Various adjustments are made until the probe reaches equilibrium; at this point a reading is taken. It was found that a reading could be taken on average every 3 - 4 minutes. Gauge readings were converted from centibars to soil moisture tension (pF) values. pF values have the advantage of being expressed in small numbers. For subsoiled plots, readings were taken from locations situated 10 cm away from the subsoiled slots because it was found that measurements taken down the slots were extremely variable. This was a consequence of the fact that intimate contact with soil was not always possible because of the variation in slot width and depth.

** Mention of trade names does not imply endorsement by Waikato University to the exclusion of other products that may be suitable.*

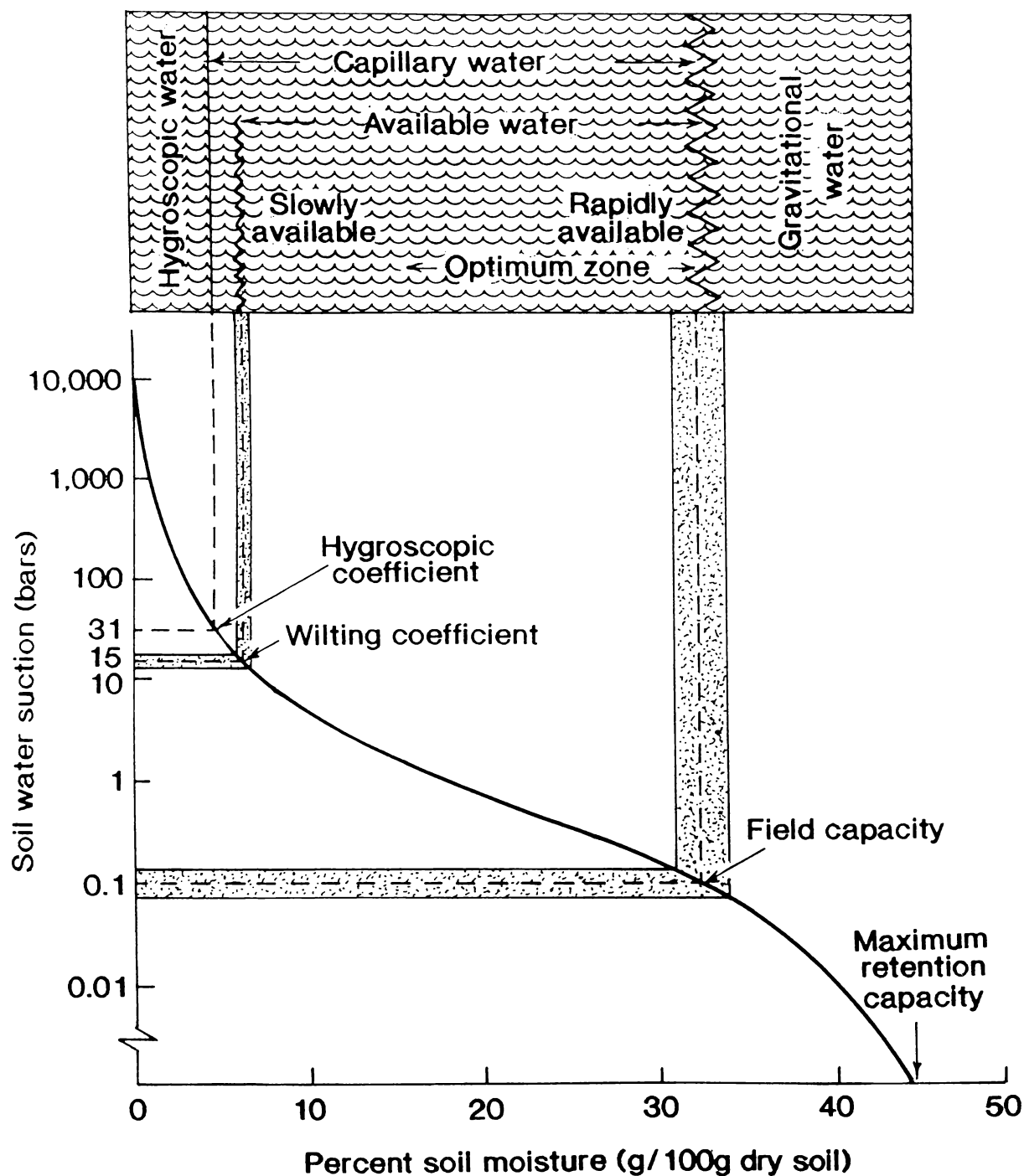


Figure 3.6.2 Suction-moisture curve of a loam soil as related to different terms used to describe water in soils (after Brady, 1974).

3.6.4 Infiltration

The objective of this part of the study was to establish infiltration rates for both subsoiled and non-subsoiled plots, when soil is relatively dry. In a dry soil any rainfall will increase soil moisture by the full amount of the rainfall, unless lost by the effect of run-off. The determination therefore, would mimic to some extent an intense summer rainstorm. Measurements were taken in mid December and repeated approximately one year later. Rugby Park was an exception to the above in that measurements were taken in September, as well as in December. These measurements were conditional on the weather being dry for the preceeding five days.

3.6.4.1 Methods

A metal infiltration ring 22 cm in diameter, 15 cm deep (5700 cm^3), and calibrated in one litre increments, was embedded firmly into the soil surface to avoid leakage around the base. One litre of water was next allowed to infiltrate, this was usually accompanied by many air bubbles as the surface soil de-gassed; a stop watch was then started and the time taken for one litre of water to infiltrate was recorded. The measurement was carried out centred on the subsoiled slot and then centred 22 cm and 44 cm away from the slot. Non-subsoiled plots were measured at the same time and dates as the subsoiled plots. Five sites per plot were measured. The infiltration time was then expressed as mm h^{-1} .

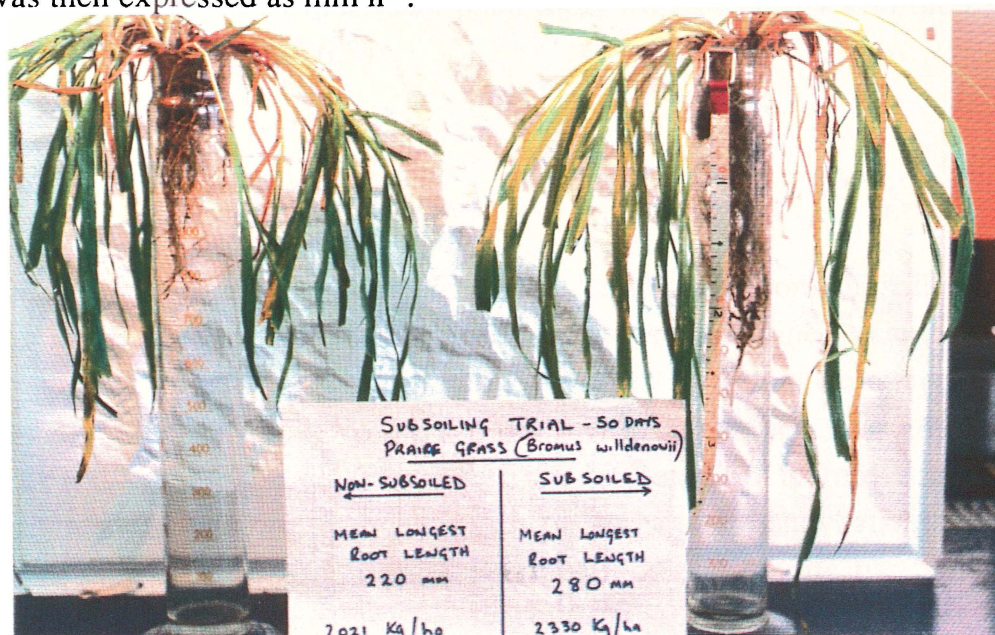


Figure 3.6.3 Matua Prairie grass representing plants from non-subsoiled and subsoiled plots.

3.6.5 Root Elongation

This measurement seeks to identify the relationship between root elongation and mechanical impedance in subsoiled and non-subsoiled plots at the Whatawhata site.

3.6.5.1 Method

The Whatawhata site was chosen for root elongation studies, because Matua Prairie grass was the predominant grass species growing on the site. It has been found that roots of this grass were particularly easy to measure *in situ* and single plants were easily recoverable and separated from soil monoliths, when compared to perennial ryegrass or clover have much finer and shallower root systems, and thus are more difficult to measure. Prairie grass develops a number of seminal root axes, which may grow vigorously, especially in free draining soil. Prairie grass had been established the previous season but it lacked vigour and leaf production. Ninety days after subsoiling, 40 observational pits (20 in subsoiled 20 in non-subsoiled) were dug 40 cm deep and 30 cm wide, to assess maximum root depth and to take monoliths 20 cm wide x 40 cm deep. Monoliths were taken within 10 cm of the subsoil slots and from random areas within the non-subsoiled plots. The monoliths were gently shaken on site to expose the root system and the length of the major roots was recorded.

A representative number of individual plant roots were taken back to the laboratory for photographing (Figure 3.6.3)

3.6.6 Pasture Production

A Pasture Probe was used to compare pasture production from subsoiled and non-subsoiled plots. The measurements at the sites were constrained to some extent by normal farming practices, which precluded direct seasonal comparisons. The Hamilton site however provided pasture dry matter production measurements for a period over summer, the Horotiu site from late autumn to mid-winter, the Te Kowhai site from late winter to early spring and the Whatawhata site from late autumn to mid-winter. Rugby Park was not included in this part of the study because the grass is kept short.

3.6.6.1 The Instrument

Pasture production was measured using a pasture probe (Figure 3.6.4) supplied by Design Electronics,* Palmerston North. The instrument is a portable microprocessor controlled capacitance meter which measures, records and stores estimates of pasture mass, as (kg DM ha⁻¹). Ideally for accurate estimations, the probe should be calibrated using cut samples of pasture, however, in the case of this study, this was not required because the instrument was essentially being used to measure the differences between pasture production for subsoiled and non subsoiled plots on specific sites and comparison between sites was not required.

3.6.6.2 Methods

Before using the probe a coating of quality silicone wax must be applied to the lower 30 cm of the probe. This prevents a film of moisture adhering to the surface of the probe, which could affect the sensitivity of the instrument. Before measurements commence on each plot an air reading must be taken by holding the probe horizontally in the air, at shoulder level, ensuring that the operator is more than 30 cm away from any objects such as fences, buildings and underground power lines.

Immediately an air reading has been accepted the display reads “start of walk” and the probe is then ready to accept pasture readings.

Pasture readings are made by holding the probe stationary at right angles to the ground, with the probe resting firmly on, but not, in the ground (Figure 3.6.5). The probe should be placed at least 30 cm from all objects, including the operator’s foot. The probe takes 0.5 seconds to complete a reading. Fifty readings per plot were made, care was taken to avoid dung and urine patches. The dry matter (kg ha⁻¹) per plot is calculated by subtracting the air reading from the average of 50 pasture readings.

** Mention of trade names does not imply endorsement by Waikato University to the exclusion of other products that may be suitable.*

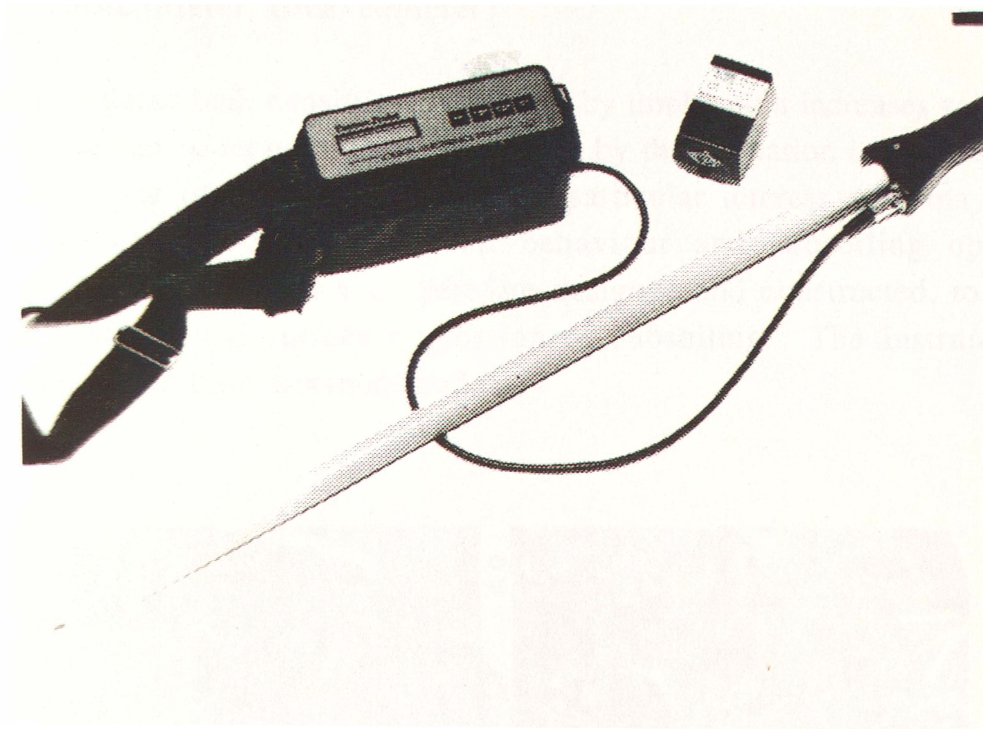


Figure 3.6.4 Pasture probe which measures and records pasture mass as kg DM ha⁻¹



Figure 3.6.5 Pasture readings are made holding the probe stationary for 0.5 seconds.

3.6.7 Profile Meter (heaveometer)

Subsoiling reduces bulk density and therefore by implication increases soil volume. This increase can be recognised at the surface by the formation of a hump (Figure 3.6.6). The size of the hump/heave is of particular interest as it may provide specific information relating to soil behaviour and subsoiling operational procedures. An instrument was therefore designed and constructed, to measure accurately the ground surface expression of subsoiling. The instrument was subsequently named the “heaveometer”.



Figure 3.6.6 Whatawhata soil pit showing surface heave centred on the subsoiled slot (tape measure denotes the slot).

3.6.7.1 Heaveometer design and construction.

A number of prototypes were constructed before a suitable instrument was produced. The instrument (figure 3.6.7) consists of a frame with two end members, 102 cm apart, with handles and reference points attached. The frame supports a mild steel bearer which is drilled with 1 cm diameter holes at 6 cm spacing. The

holes provide guide slots in which plastic rods 30 cm long can readily slide up and down.

3.6.7.2 Method of Operation

To measure surface heave the heaveometer is placed across subsoiled ground at right angles to the direction of subsoiler travel. The reference points (end members) are positioned on undisturbed ground at least 50 cm from the subsoiled slot. The plastic following rods are free to move up and down following the contour of the ground. The distance that the rods move is then measured with a ruler and recorded.

The heaveometer was used extensively to determine optimum shank spacing and critical working depth, in addition to its principle use of quantifying near surface increases in soil volume. Soil volume increase is determined by calculating volume of heave in relation to total treatment and is expressed as percent increase.

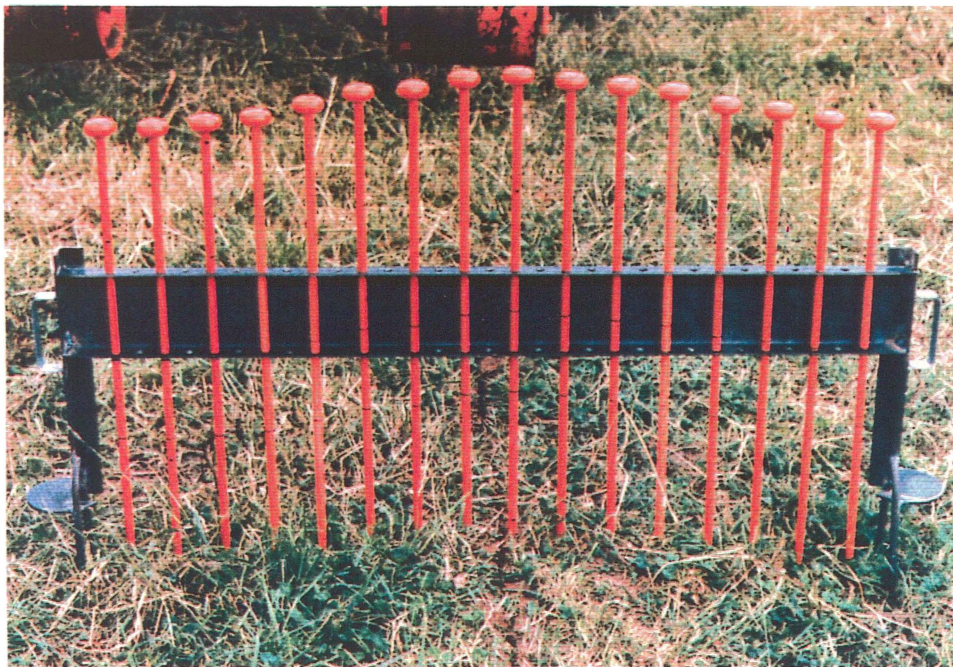


Figure 3.6.7 Heaveometer designed by the researcher to measure the height and extent of ground heave following subsoiling

3.6.8 Soil Profile, Pits and Soil Sampling

Approximately sixteen profile pits 1 m long, 0.5 m wide and 0.5 m deep were dug at each site before subsoiling commenced (Figure 3.6.8). They were specifically used for soil aggregate and textural re-distribution after vibrating and non-vibrating subsoiling. In many cases the pits were subsoiled through at right angles, thus providing a visual perspective of the changes to some soil physical characteristics as a result of subsoiling.

Soil samples for textural analysis and aggregate classification were taken from specified depths before and after subsoiling and carefully sealed into plastic bags and returned to the laboratory for analysis.



Figure 3.6.8 Te Kowhai site showing profile pits where detailed examination of soil physical changes were made following subsoiling

3.6.9 Subsoiling with and without press rollers

It became obvious as field trials progressed, that some form of roller or press mechanisms should be incorporated into the “new” Gallagher Shakaerator, to reduce soil moisture loss. Subsoiling in December and January caused pasture wilting along 30 cm strips centred on the subsoiled slots. This effect was also noticeable in late Spring and Autumn when there was no appreciable rain for ten days following subsoiling. To test the effectiveness of rollers in reducing soil moisture loss, two soils Hamilton and Horotiu were subsoiled in December 1987, with and without rollers and soil samples taken to determine moistures.

3.6.9.1 Methods

Two rollers were filled with 30 litres of water each and attached to the subsoiler immediately behind and central to the subsoiler shanks (Figure 3.1.6). The attachment allowed the rollers to “float” up and down, thus following the contours of the land. The standard tractor and PTO speed and depth of operation were set as described earlier (Chapter 3.1.3). The trial area on each soil comprised of a split plot design, incorporating four treatments. The total area for each soil in the trial was approximately 800 m². Five days after subsoiling, soil samples were taken at 4 - 10 cm depth from the trial plots. No rain occurred in the period after subsoiling and before sample collection. Soil samples were sealed in plastic to prevent moisture loss and then taken back to the laboratory for soil moisture analysis.

3.6.10 Subsoiling, its effect on soil disturbance

Subsoiling is an expensive field operation, because of the machinery involved, the tractor power required and the relatively small area covered per day. Users therefore must know the optimal conditions for effective subsoiling. It was therefore decided to subsoil under a range of soil moistures using wide and narrow tips, in vibrating and non-vibrating mode and at various depths. It was found previously that the above four factors influence the amount of soil disturbed. Therefore to measure subsoiling efficiency an attempt was made to quantify the amount of soil disturbance, resulting from operating under the various conditions.

3.6.10.1 Methods

At each site a small additional area of approximately 60 m² was used for this part of the study. All soils were subsoiled with wide and narrow tips and in vibrating and non-vibrating modes. The Hamilton soil was subsoiled in a “dry” condition at 30, 37 and 45 cm depths.

The Horotiu, Rugby Park and Whatawhata soils were subsoiled in relatively “dry” condition at 45 cm depth. The Te Kowhai soil was subsoiled in a dry condition at 45 cm depth and in a wet condition at 35 and 45 cm depth. The profile pits mentioned (Chapter 3.6.8) were used for this part of the study. Immediately after subsoiling “through” the pits, measurements were taken using the penetrometer and heaveometer to assess soil disturbance. A visual examination of the profiles was also carried out, to assess the extent of structural cracks. Subsoiled profiles were then photographed (Figure 3.6.9) and the information and data collected was processed and digitised for computer graphics as displayed (Chapter 4.7). Samples for soil moisture estimation were collected and sealed for laboratory analysis.

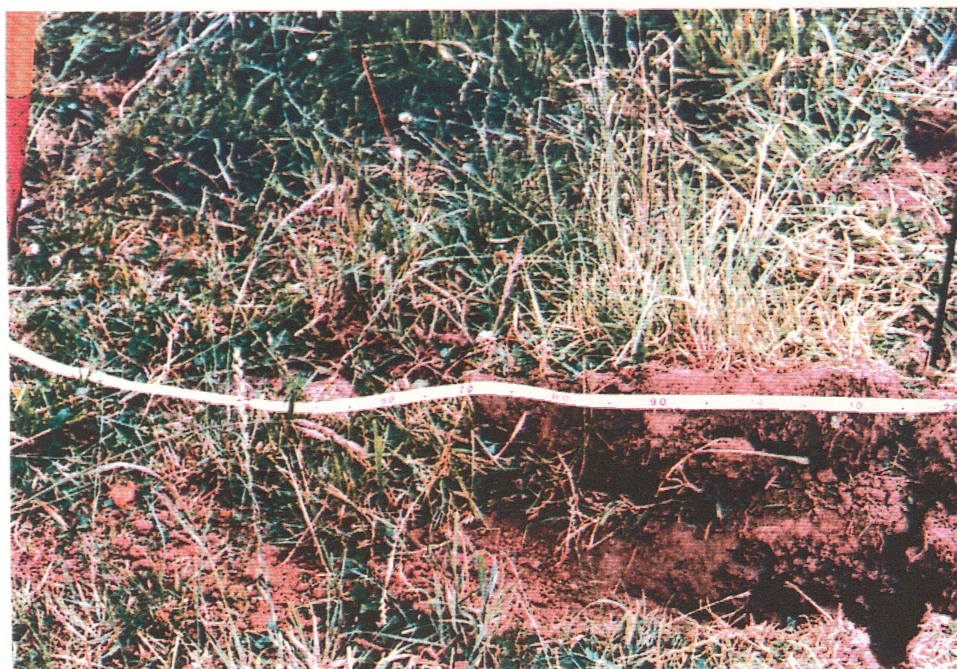


Figure 3.6.9 Whatawhata site showing part of subsoiled profile. The subsoiled slots are delineated by the spade and steel rod.

3.6.11 National subsoiling survey - August 1986

In order to find out why farmers purchased subsoilers, a letter and questionnaire, was mailed out to thirty farmers from Northland to Southland, who were in possession of a Gallagher subsoiler. Fifteen completed survey forms were returned and the results are summarised (Table 3.6.2). Eight respondents were pasture farming, five in horticulture and two in arable. Farm size ranged from 7 to 300 hectares. Soils derived from a wide range of parent materials were involved and these included; alluvium, glacial till, greywacke, peat, schist and tephra. Soil groups included Yellow brown loams, Brown granular loams, Brown granular clays, Yellow brown earths and Yellow grey earths. Soil textures included; sands, sandy loams, silts, silt loams, clays, clay loams and peat.

3.6.11.1 Discussion

The benefits of subsoiling according to the survey were better drainage, reduction in surface water ponding, subsoil mixing, break up of soil pans, improved soil aeration and soil structure and deeper rooting of plants.

Although the survey was biased towards machine owners and limited to only a few farmers and therefore not generally representative, it did however provide some useful background information. Farmers purchased subsoilers because they perceived they had “problem” soils, which inhibited crop production, through poor drainage, compacted soil layers, poor aeration and restricted root volume.

An important aspect, in relation to this study was the fact that pasture subsoiling was being carried out in order to improve drainage and soil structure. It was feedback of this type plus other stimulus such as the redesign of the shakaerator that initiated this research project. Simply, it was becoming increasingly important to substantiate generalisations, by implementing a controlled research programme.

Table 3.6.2 Response to subsoiler survey

Respondent Number	Farm Type	Size of Property (ha)	Soil Texture (most common on farm)	Problem Soil	Comments on the benefits of subsoiling
1	Sheep/orchard	98	Silt loam	Silt loam	Better drainage and aeration
2	Sheep and Beef	300	Sandy loam	Soil derived from Kaharoa tephra	Better growth and drainage
3	Dairy	87	Silt and Clay loams	Riponui soil	Better drainage
4	Dairy	101	Clay and Peats	Hamilton Clay loam and Te Rapa Peat	Aeration of peat and better structured subsoil
5	Arable	32	Silt loams	Loess derived	Break up of hard pan
6	Dairy	82	Silt loams	Waitoa and Te Puninga	Improved drainage
7	Horticulture	20	Clay	Compacted soil between rows of fruit trees	Improved drainage
8	Horticulture	9	Silt loam	Silt on sand	Break up of plough pan
9	Sheep and Beef	280	Silts	Pugged soil loam	Better drainage and soil structure
10	Horticulture	12	Silts	Compacted silt loam - traffic	Better drainage. Better root development
11	Dairy	100	Clay	Clay	Break up of hard pan and better drainage
12	Horticulture	7	Silts	Silts	Aeration, improved drainage and soil structure
13	Sheep and Beef	232	Sand	Shallow sandy soil	Better drainage and increased root volume
14	Horticulture	40	Silts and Clays	Clay pan	Better drainage and pan break up
15	Arable	170	Clay	Clay pan	Aeration, deeper rooting and improved drainage

CHAPTER FOUR

CHAPTER FOUR

CHAPTER 4: FIELD WORK RESULTS AND DISCUSSION

4.1 BULK DENSITY

The following data obtained with a gamma ray probe (SDG) are calculated from the mean measurements of five profiles per plot where the standard deviation (σ) never exceeded 8% of the mean. Soil moistures by weight were assessed for the 0 - 10 cm depth. SDG measurements were not taken for the subsoiled slot because of the presence of large cracks.

* Significantly different to non-subsoiled plots at corresponding depths ($P < 0.05$)

$\bar{x}$ = mean value

4.1.1 Hamilton Clay Loam

Table 4.1.1 Dry bulk density values (Mg m^{-3}) on a transect across subsoiled and non-subsoiled plots.

(a) 13/7/87, 33% moisture. A horizon = 0 - 25 cm depth

Depth (cm)	Distance from slot					$\bar{x}$
	10cm	20cm	30cm	40cm	Non subsoiled	
5	0.82*	1.13	1.21	1.18	1.19	1.11
10	0.85*	1.12	1.18	1.23	1.17	1.11
15	0.84*	1.02*	1.17	1.18	1.14	1.07
20	0.85*	1.02	1.11	1.14	1.09	1.04
25	0.88*	1.10	1.10	1.11	1.15	1.06
30	0.91*	1.09*	1.25	1.22	1.22	1.14
35	0.86*	1.11*	1.36	1.36	1.31	1.20
40	0.85*	1.22*	1.39	1.37	1.38	1.24
45	0.80*	1.31	1.41	1.43	1.42	1.27
$\bar{x}$	0.85	1.12	1.24	1.25	1.23	

(b) 9/12/87, 23% moisture

Depth (cm)	Distance from slot					$\bar{x}$
	10cm	20cm	30cm	40cm	Non subsoiled	
5	1.01*	1.14	1.15	1.20	1.16	1.13
10	1.04*	1.10	1.16	1.17	1.19	1.13
15	1.05*	1.08*	1.12	1.16	1.20	1.12
20	1.00*	1.09*	1.08*	1.12*	1.26	1.11
25	1.10*	1.13*	1.14*	1.31	1.29	1.19
30	1.11*	1.17*	1.27	1.39	1.36	1.26
35	1.12*	1.28	1.38	1.46	1.41	1.33
40	1.09*	1.38	1.41	1.50	1.44	1.36
45	1.12*	1.46	1.51	1.57	1.54	1.44
$\bar{x}$	1.07	1.20	1.24	1.32	1.31	

(c) 5/7/88, 36% moisture

Depth (cm)	Distance from slot					$\bar{x}$
	10cm	20cm	30cm	40cm	Non subsoiled	
5	1.10	1.14	1.15	1.15	1.17	1.14
10	1.04*	1.07*	1.12	1.17	1.21	1.12
15	1.01*	1.09	1.10	1.15	1.18	1.11
20	1.09	1.14	1.15	1.14	1.12	1.13
25	1.16	1.23	1.20	1.21	1.26	1.21
30	1.17*	1.31	1.29	1.30	1.31	1.28
35	1.15*	1.27	1.31	1.36	1.30	1.28
40	1.19*	1.36	1.32	1.37	1.36	1.32
45	1.21	1.39	1.41	1.39	1.35	1.35
$\bar{x}$	1.12	1.22	1.23	1.25	1.25	

(d) 13/12/88, 19% moisture

Depth (cm)	Distance from slot					$\bar{x}$
	10cm	20cm	30cm	40cm	Non subsoiled	
5	1.09	1.12	1.08	1.13	1.17	1.12
10	1.06*	1.10	1.10	1.12	1.18	1.11
15	1.07*	1.14	1.17	1.15	1.24	1.15
20	1.10	1.16	1.24	1.18	1.21	1.18
25	1.17*	1.21	1.28	1.27	1.29	1.18
30	1.20*	1.34	1.31	1.34	1.36	1.31
35	1.20*	1.33	1.36	1.30	1.35	1.31
40	1.19*	1.29	1.39	1.38	1.40	1.33
45	1.22*	1.31	1.38	1.41	1.40	1.34
$\bar{x}$	1.14	1.22	1.26	1.25	1.29	

4.1.1.1 Summary of results for Hamilton soil

Table (a) shows that subsoiled, compared to non-subsoiled^{treatment} reduced bulk density in the 10 cm distance profile, with a 31% reduction recorded at the 5 cm depth, increasing to 43% at the 45 cm depth. Bulk density was reduced significantly at the 15, 30, 35 and 40 cm depths in the 20 cm distance profile but was not significantly changed at other depths in this profile.

The mean values for the 30 and 40 cm distance from slot profiles were not significantly different from the non-subsoiled value, but at the 30 - 45 cm depth for the 30 cm distance from slot profile there was a relatively large (0.19 Mg m⁻³), increase when compared with corresponding depth in the 20 cm distance profile. Major increases in bulk density occur at 30 and 35 cm depth.

Table (b) shows a significant trend at the 20 cm depth where there is 20, 13, 14, 11% reduction at 10, 20, 30, 40 cm from the slot respectively. Reductions for the 10 cm profile were not as great as in Table (a) but significant reductions were recorded at 20 and 25 cm depth for the 30 cm and at the 20 cm depth for the 40 cm distance profiles. Interestingly mean bulk densities for the non-subsoiled plots increased from 1.23 for 13/7/87 to 1.32 Mg m⁻³ for 9/12/87. This may be due to

shrinkage as the soil dried from 33 to 23% moisture. Bulk density (>1.35) values regarded high for New Zealand soils were recorded in the 30 - 45 cm depth.

Table (c) shows one year after subsoiling that measurements taken at the 5 cm depth, for all profiles showed no significant differences. Greatest reductions occurred at the 10, 15, 30, 35, 40 cm depths for the 10 cm profile. Bulk density values for all other profiles and depths with the exception of 1.07 Mg m^{-3} recorded at 10 cm depth for the 20 cm profile, were not significantly different from the non-subsoiled values. When compared with Table (b) mean values for the 40 cm and non-subsoiled profile was less, perhaps reflecting increased moisture.

Table (d) shows that significant reductions in bulk densities only persisted in the 10 cm distance profile. Although densities were lower in the 20 cm profile, than in the non-subsoiled, they were not significantly different. The major increase at 30 cm when compared with 25 cm depth remains a distinctive feature of this soil.

4.1.2 Horotiu sandy loam

Table 4.1.2 Dry bulk density values (Mg m^{-3}) on a transect across subsoiled and non-subsoiled plots

(a) 15/12/86, 18% moisture, A horizon = 0 - 15 cm depth

Depth (cm)	Distance from slot					$\bar{x}$
	10cm	20cm	30cm	40cm	Non subsoiled	
5	0.51*	0.68*	0.74	0.76	0.78	0.69
10	0.60*	0.69*	0.75	0.72	0.80	0.71
15	0.62*	0.70*	0.76	0.78	0.85	0.74
20	0.72*	0.74*	0.80*	0.86	0.90	0.80
25	0.73*	0.75*	0.82	0.94	0.91	0.83
30	0.61*	0.70*	0.87	1.00	1.06	0.84
35	0.56*	0.64*	0.98	1.05	1.10	0.87
40	0.61*	0.81*	1.03	1.04	1.10	0.91
45	1.12	1.00	1.07	1.10	1.12	1.08
$\bar{x}$	0.67	0.74	0.86	0.88	0.95	

(b) 20/11/87, 20% moisture

Depth (cm)	Distance from slot				Non	$\bar{x}$
	10cm	20cm	30cm	40cm	subsoiled	
5	0.72	0.71	0.74	0.69	0.71	0.71
10	0.68	0.70	0.78	0.76	0.76	0.74
15	0.74*	0.72*	0.86	0.88	0.88	0.82
20	0.83*	0.81*	0.90*	0.98	1.06	0.92
25	0.87*	0.80*	0.91*	1.04	1.10	0.94
30	1.00*	0.95*	0.98*	1.03	1.12	1.02
35	0.94*	0.99*	1.05	1.10	1.14	1.04
40	0.96*	1.12	1.10	1.12	1.13	1.08
45	1.15	1.10	1.09	1.10	1.15	1.12
$\bar{x}$	0.87	0.88	0.93	0.97	1.00	

4.1.2.1 Summary of results for Horotiu soil

Table (a) shows that subsoiling significantly lowered bulk densities at 10 and 20 cm from the slot to a depth of 40 cm. Percentage decreases ranged from 35% at 5 cm depth (10 cm profile) to 49% at the 35 cm depth. Reductions down the 20 cm profile ranged from 13% at 5 cm depth to 42% at the 35 cm depth. The 30 cm profile showed reductions, but only significantly at the 20 cm depth. Bulk densities for the 40 cm profile were not significantly changed as a consequence of subsoiling but were nevertheless marginally lower with a mean value of 0.88 Mg m⁻³ in comparison with the non-subsoiled value of 0.95 Mg m⁻³.

Table (b) shows that near surface (0-10 cm depth) bulk densities were not significantly different to non-subsoiled and ranged from 0.68 to 0.76 Mg m⁻³. Significant reductions at 15 to 40 cm depths (10 cm profile) were recorded and ranged from 16 to 22%. The effect of subsoiling extended into the 30 cm distance profile but was limited to the 20 to 30 cm depth layer. In the 40 cm distance from the slot profile bulk density measurements, were not significantly different than non-subsoiled values. Mean bulk densities for the non-subsoiled plots for Tables (a) and (b) were not significantly different. Measurements taken two years after subsoiling showed no significant difference between non-subsoiled and subsoiled plots.

4.1.3 Rugby Park Soil

Table 4.1.3 Dry bulk density values (Mg m^{-3}) on a transect across subsoiled and non-subsoiled plots

(a) 7/10/86, 35% moisture. A horizon = 0 - 21 cm depth

Depth (cm)	Distance from slot				Non	$\bar{x}$
	10cm	20cm	30cm	40cm	subsoiled	
5	1.10*	1.09*	1.14*	1.26	1.35	1.19
10	1.10*	1.12*	1.12*	1.35	1.36	1.21
15	1.12*	1.12*	1.24	1.28	1.26	1.20
20	1.14	1.08*	1.14	1.19	1.20	1.15
25	1.14*	1.14*	1.15	1.19	1.22	1.17
30	1.10*	1.12	1.14	1.17	1.18	1.14
35	1.05*	1.06	1.10	1.18	1.17	1.11
40	1.00*	1.10	1.18	1.17	1.16	1.12
45	1.06	1.12	1.18	1.16	1.14	1.13
$\bar{x}$	1.09	1.10	1.15	1.22	1.22	

(b) 15/12/87, 18% moisture

Depth (cm)	Distance from slot				Non	$\bar{x}$
	10cm	20cm	30cm	40cm	subsoiled	
5	1.18*	1.20	1.24	1.26	1.28	1.23
10	1.20*	1.24	1.30	1.31	1.34	1.28
15	1.21*	1.26	1.29	1.36	1.35	1.29
20	1.15	1.16	1.18	1.20	1.21	1.18
25	1.14*	1.15	1.20	1.19	1.22	1.18
30	1.13	1.15	1.16	1.19	1.19	1.16
35	1.14	1.17	1.16	1.16	1.18	1.16
40	1.15	1.18	1.15	1.17	1.18	1.16
45	1.16	1.19	1.16	1.15	1.16	1.16
$\bar{x}$	1.16	1.19	1.20	1.22	1.23	

4.1.3.1 Summary of results for Rugby Park

Table (a) shows significant bulk density reductions in the top 5 cm for profiles situated 10, 20 and 30 cm from the slot, ranging from 16 to 19% . Bulk densities down the 10 cm profile were reduced for all measured depths, but only significantly at the 5, 10, 15, 25, 30, 35 and 40 cm depths. The 20 cm and 30 cm distance from slot profile recorded significant reductions in the top 25 cm and 10 cm respectively. Rugby Park soil shows decreasing rather than increasing bulk densities with increasing depth, reflecting compaction in the top 20 cm.

Table (b) shows bulk densities of similar values, for both subsoiled and non-subsoiled plots, with the exception of the top 15 cm of the 10 cm profile, where a significant mean reduction of 10% persisted. Compaction in the top 15 cm is still evident in both subsoiled and non-subsoiled areas.

4.1.4 Te Kowhai silt loam

Table 4.1.4 Dry bulk density values (Mg m^{-3}) on a transect across subsoiled and non-subsoiled plots

(a) 3/12/86, 20% moisture. A horizon = 0 - 20 cm depth.

Depth (cm)	Distance from slot					$\bar{x}$
	10cm	20cm	30cm	40cm	Non subsoiled	
5	0.61*	0.85	0.83	0.87	0.86	0.80
10	0.66*	0.74*	0.79*	0.88	0.94	0.80
15	0.65*	0.72*	0.82*	0.86	0.95	0.81
20	0.81*	0.80*	0.96*	1.10	1.18	0.97
25	0.83*	0.89*	1.15	1.19	1.28	1.07
30	0.84*	1.16*	1.29	1.31	1.35	1.19
35	0.76*	1.28	1.32	1.34	1.31	1.20
40	0.71*	1.29	1.27	1.30	1.36	1.19
45	0.74*	1.26	1.30	1.31	1.35	1.19
$\bar{x}$	0.73	0.99	1.08	1.13	1.17	

(b) 6/7/87, 39% moisture

Depth (cm)	Distance from slot					$\bar{x}$
	10cm	20cm	30cm	40cm	Non subsoiled	
5	0.70*	0.69*	0.74	0.75	0.78	0.73
10	0.71*	0.74*	0.82	0.81	0.86	0.79
15	0.80*	0.91	0.96	0.98	1.01	0.93
20	0.88*	0.99	0.96*	1.12	1.10	1.01
25	0.96*	1.15	1.19	1.16	1.25	1.14
30	1.05*	1.21	1.19	1.25	1.24	1.19
35	1.04*	1.27	1.26	1.31	1.29	1.23
40	0.95*	1.26	1.26	1.28	1.26	1.20
45	0.96*	1.21	1.23	1.27	1.28	1.19
$\bar{x}$	0.89	1.05	1.07	1.10	1.12	

(c) 11/12/87, 18% moisture

Depth (cm)	Distance from slot					$\bar{x}$
	10cm	20cm	30cm	40cm	Non subsoiled	
5	0.76*	0.78	0.80	0.79	0.86	0.80
10	0.78	0.80	0.83	0.80	0.84	0.81
15	0.84	0.89	0.88	0.86	0.91	0.87
20	0.86*	0.90*	0.98*	1.13	1.16	1.00
25	0.91*	0.93*	1.16*	1.21	1.26	1.09
30	0.89*	1.19	1.24	1.30	1.30	1.18
35	0.84*	1.28	1.30	1.31	1.34	1.21
40	0.88*	1.25	1.30	1.34	1.35	1.22
45	0.91*	1.23	1.31	1.29	1.31	1.21
$\bar{x}$	0.85	1.03	1.09	1.11	1.15	

(d) 15/12/88, 22% moisture

Depth (cm)	Distance from slot					$\bar{x}$
	10cm	20cm	30cm	40cm	Non subsoiled	
5	0.80	0.76	0.83	0.74	0.80	0.79
10	0.82	0.80	0.80	0.79	0.88	0.81
15	0.95	0.85	0.83	0.84	0.87	0.86
20	1.05	1.04	1.10	1.10	1.12	1.08
25	1.06*	1.08*	1.18	1.17	1.21	1.14
30	1.08*	1.14	1.20	1.20	1.24	1.17
35	1.14*	1.22	1.26	1.27	1.30	1.24
40	1.15*	1.26	1.29	1.27	1.28	1.25
45	1.17*	1.28	1.27	1.31	1.30	1.27
$\bar{x}$	1.02	1.05	1.10	1.08	1.14	

4.1.4.1 Summary of results for Te Kowhai soil

Table(a) shows bulk densities were lowered by 30 to 48% at 10 cm distance from slot profile. Significant reductions were also recorded in the 20 and 30 cm profiles but not in the 40 cm profile. A major increase in bulk density occurs at 20 and 30 cm depth.

Table (b) shows that reductions were restricted to the 10 cm profile and the top 10 cm in the 20 cm profile and the 20 cm depth in the 30 cm profile. The mean non-subsoiled value of 1.12 Mg m⁻³ compares with 1.17 Mg m⁻³ recorded under drier conditions (Table a).

Table (c) shows significant reductions for the 10 cm profile at all depths, with the exception of the 10 and 15 cm depth values. Significant reductions extended into the 20 and 30 cm profiles at depths of 20 and 25 cm. The increase in bulk density at 20 cm is a distinctive feature of this soil.

Table (d) shows that significant reductions in bulk density persisted in the 10 cm profile at the 25 to 45 cm sample depths and at 25 cm depth for the 20 cm distance

from slot profile. Mean values were significantly less for the 10 and 20 cm profiles when compared with non-subsoiled. Increase at 20 cm depth was still evident

4.1.5 Whatawhata clay loam

Table 4.1.5 Dry bulk density values (Mg m^{-3}) on a transect across subsoiled and non-subsoiled plots

(a) 15/12/86, 18% moisture. A horizon = 0 - 16 cm depth

Depth (cm)	Distance from slot				Non	$\bar{x}$
	10cm	20cm	30cm	40cm	subsoiled	
5	0.94*	0.85*	0.95*	1.12	1.15	1.00
10	0.96*	0.95*	1.10	1.17	1.18	1.07
15	0.97*	0.95*	1.16	1.22	1.25	1.11
20	1.00*	1.05*	1.21*	1.31	1.35	1.18
25	1.10*	1.06*	1.30*	1.39	1.45	1.26
30	1.12*	1.14*	1.30*	1.44	1.47	1.29
35	1.10*	1.05*	1.41	1.46	1.48	1.30
40	0.98*	1.25	1.30	1.36	1.32	1.24
45	0.96*	1.36	1.36	1.34	1.30	1.26
$\bar{x}$	1.01	1.07	1.23	1.29	1.32	

(b) 14/12/87, 19% moisture

Depth (cm)	Distance from slot				Non	$\bar{x}$
	10cm	20cm	30cm	40cm	subsoiled	
5	0.92*	0.96*	1.09	1.10	1.12	1.03
10	0.94*	0.96*	1.12	1.20	1.14	1.07
15	0.96*	1.00*	1.20	1.17	1.19	1.10
20	1.06*	1.10	1.20	1.20	1.26	1.16
25	1.12*	1.14*	1.34	1.38	1.40	1.27
30	1.10*	1.28*	1.39	1.45	1.44	1.33
35	1.12*	1.30	1.40	1.49	1.45	1.35
40	1.10*	1.28	1.38	1.40	1.36	1.30
45	1.12*	1.36	1.38	1.37	1.34	1.31
$\bar{x}$	1.04	1.15	1.32	1.31	1.36	

(c) 16/11/88, 22% moisture

Depth (cm)	Distance from slot					$\bar{x}$
	10cm	20cm	30cm	40cm	Non subsoiled	
5	1.11	1.12	1.18	1.15	1.18	1.15
10	1.12	1.12	1.17	1.19	1.20	1.16
15	1.10*	1.14*	1.17	1.26	1.28	1.19
20	1.10*	1.14*	1.27	1.34	1.39	1.25
25	1.15*	1.20*	1.38	1.48	1.46	1.33
30	1.18*	1.26*	1.38	1.47	1.50	1.36
35	1.20*	1.36	1.45	1.50	1.50	1.40
40	1.28	1.44	1.45	1.42	1.41	1.40
45	1.30	1.36	1.42	1.40	1.38	1.37
$\bar{x}$	1.17	1.24	1.32	1.36	1.36	

4.1.5.1 Summary of results for Whatawhata soil

Table (a) shows a mean 11% reduction in bulk density at the 5 cm depth for the 10, 20 and 30 cm profiles. A significant mean reduction for the 10 cm profile of 1.01 Mg m⁻³ compares with a mean value of 1.32 Mg m⁻³ for the non-subsoiled profile which represents a 24% decrease. The effects of subsoiling extended through to the 20 and 30 cm profile at depths ranging from 5 to 35 cm. The 1.36 Mg m⁻³ value recorded for the 45 cm depth in the 20 cm profile compares with 0.96 Mg m⁻³ for the 10 cm. Mean bulk density values reach a maximum at the 25 to 35 cm depth and then decline at the 40 to 45 cm depth.

Tables (b) and (c) show that significant reductions in bulk density, were evident, one and two years after subsoiling for the 10 and 20 cm distance profiles. However in these profiles it was at depths greater than 15 cm where this occurred. The 5 and 10 cm depths recorded lower bulk densities than non-subsoiled equivalents, but were non significant. The distinctive 25 to 35 cm depth layer of relatively high bulk density is shown for the 30 and 40 cm distance from slot profiles and also for the non-subsoiled profile.

4.1.6 Persistence of lowered bulk density for the 10 cm distance from slot profile.

Figure 4.1.1 shows that for the Hamilton soil immediately after subsoiling on 13/7/87, bulk density was lowered by approximately 31 to 43% at depths ranging from 5 to 45 cm. Re-compaction occurred relatively rapidly during the following five months, with bulk densities increasing by about 20%. Further increases of up to 10% occurred, between 9/12/87 and 5/7/88, with the exception of the 15 cm depth, where a relatively small reduction was recorded. On 13/12/88, seventeen months after subsoiling, reduced bulk densities of approximately 6 to 14% persisted when compared to non-subsoiled values.

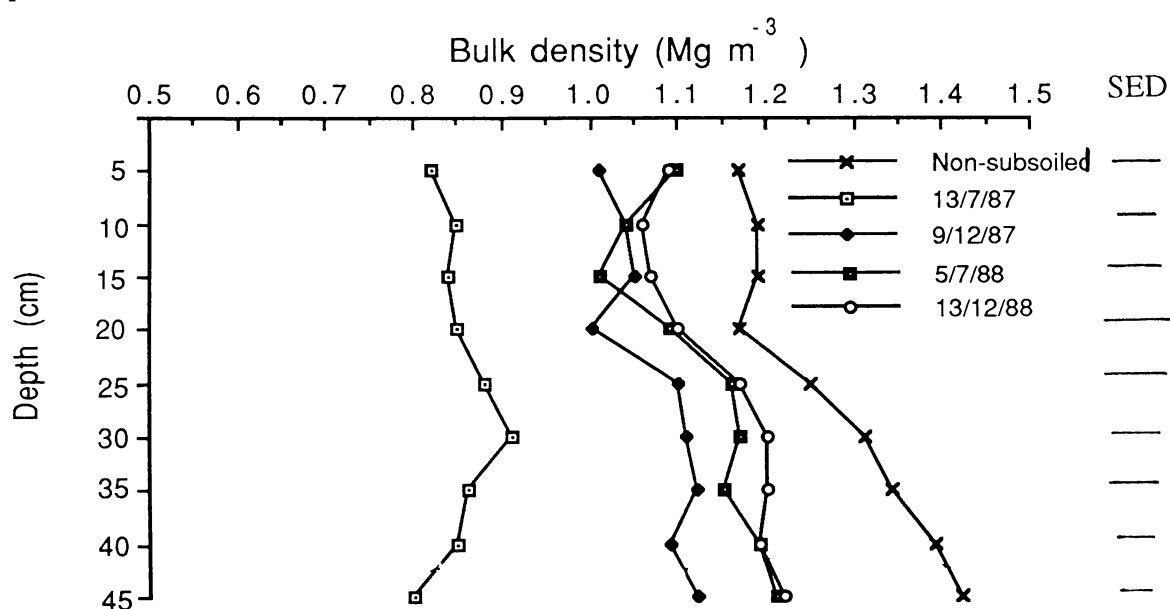


Figure 4.1.1 Hamilton soil variation in BD with time. Each data point is the mean of four replications per profile $P = 0.05$.

Figure 4.1.2 shows bulk density reduction for Horotiu soil on 15/12/86 before and after subsoiling. Reductions were 33 and 50% for the 5 and 35 cm depths respectively. The reductions at the 20 to 25 cm depth were not as great as those recorded for the 30 to 40 cm depth. Eleven months after subsoiling (20/11/87) rapid recompaction of the 5 cm depth had occurred, but for the 10 to 40 cm depths significant reductions of up to 13% persisted.

Figure 4.1.3 shows that for Rugby Park soil bulk density values immediately after subsoiling (7/10/86) were reduced by 15, 19, 6 and 16% for 5, 10, 25 and 40 cm depths respectively. Ten weeks after subsoiling (15/12/86) re-compaction had

occurred for the 30 to 45 cm depth, but significant reductions of about 9% persisted in the 5 to 15 cm depth layer.

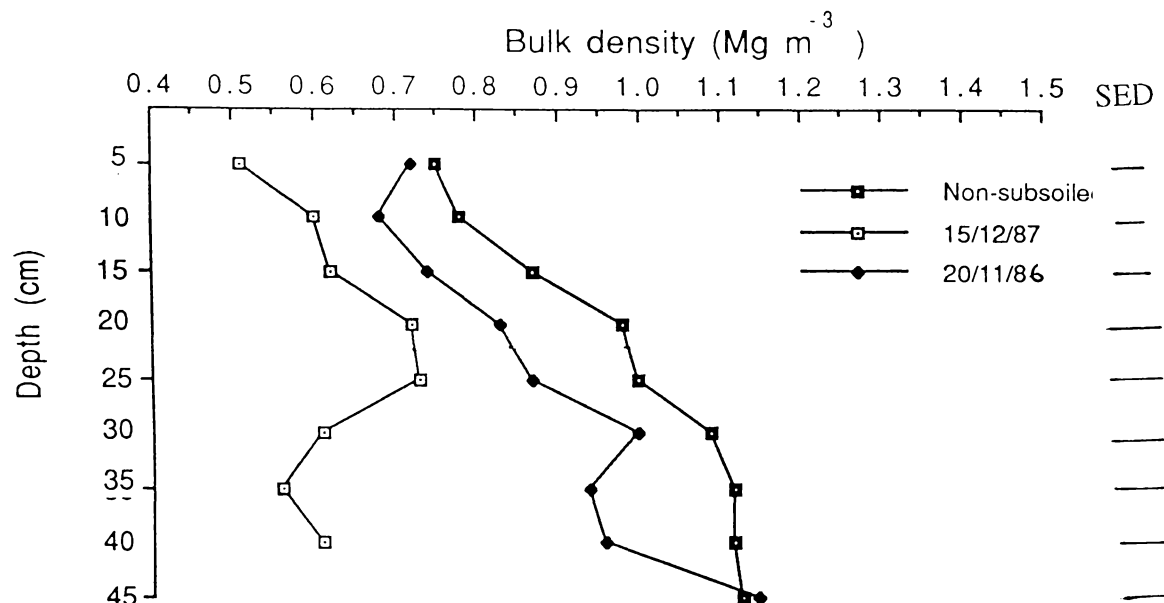


Figure 4.1.2 Horotiu soil, replications and error bars see Figure 4.1.1

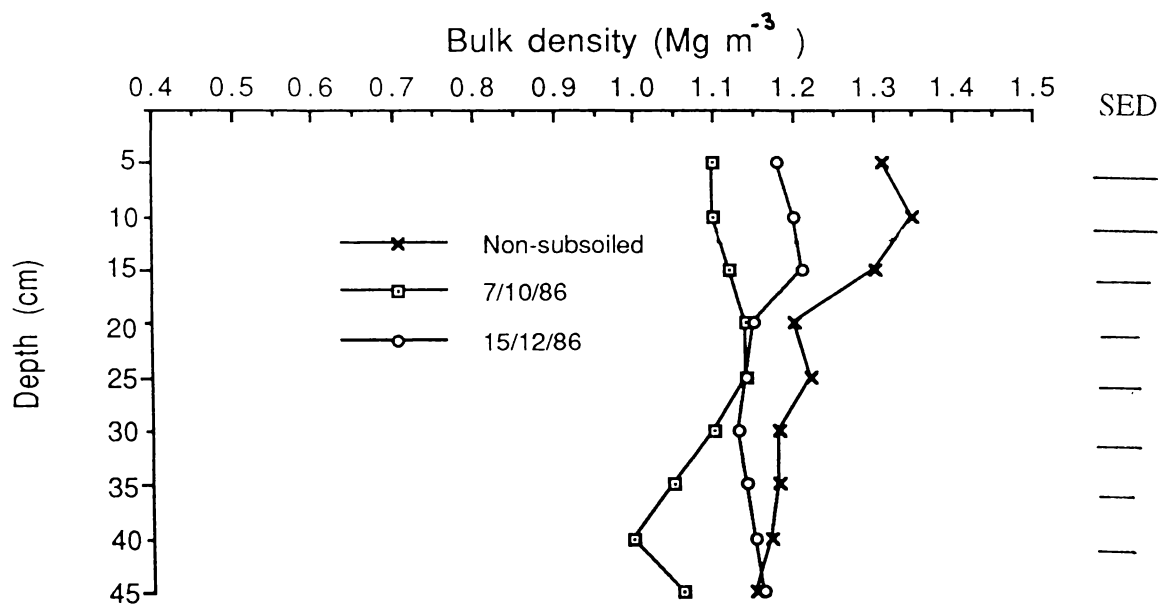


Figure 4.1.3 Rugby Park soil, replications and error bars see Figure 4.1.1.

Figure 4.1.4 shows that for Te Kowhai soil, a significant reduction in bulk density persisted for two years following subsoiling, for depths lying between 20 to 45 cm. Surface layers (0 - 15 cm), however had re-compacted. The initial reduction immediately after subsoiling for the 45 cm depth was 44%, decreasing to 25, 32 and 10% for values obtained on the 6/7/87, 11/12/87 and 15/12/88 respectively. The

significant decrease in bulk density for the 30 and 35 cm depth (11/12/87), when compared with (6/7/87) was not evident in other soils.

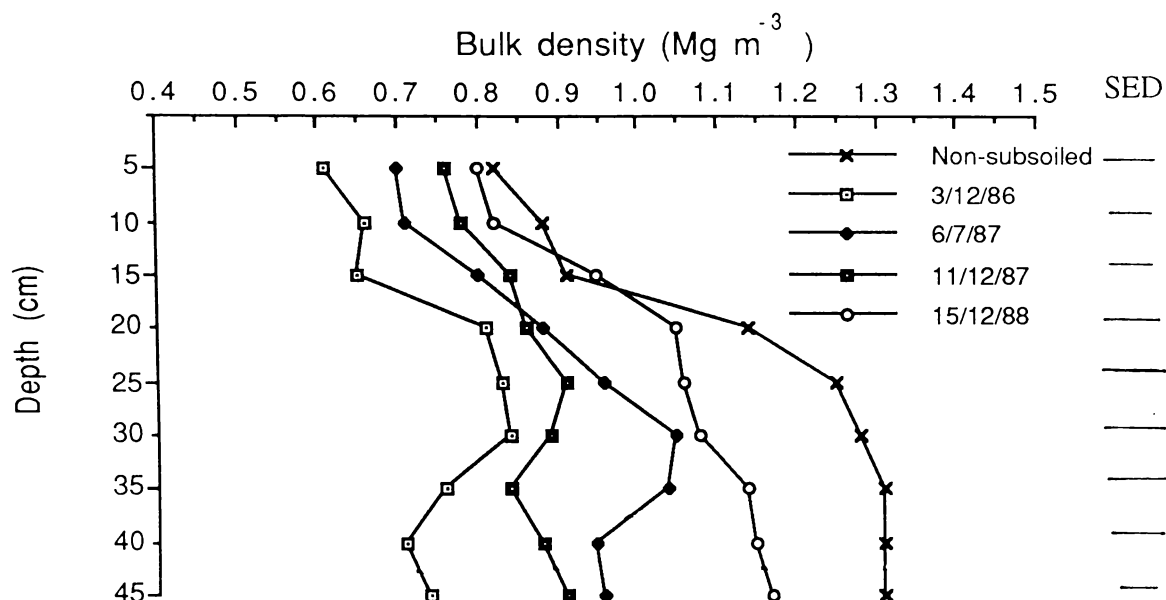


Figure 4.1.4 Te Kowhai soil, replications and error bars see Figure 4.6.1

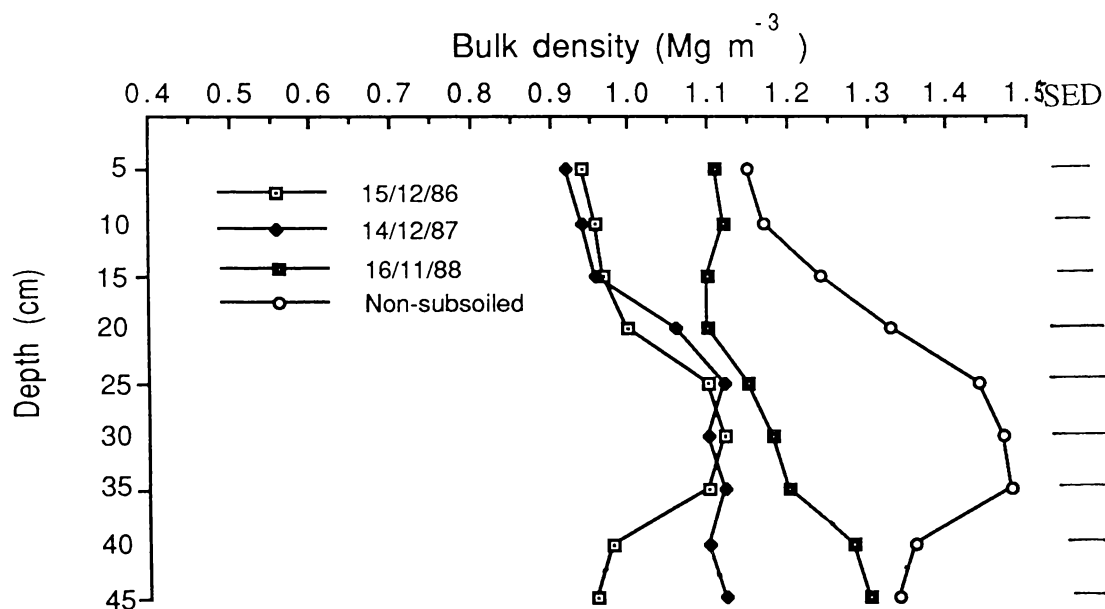


Figure 4.1.5 Whatawhata soil, replications and error bars see Figure 4.6.1

Figure 4.1.5 shows that for the Whatawhata soil reduction in bulk density persisted longer and was greater than for other soils in the study. For this soil there was no evidence of re-compaction in the top 35 cm, one year after subsoiling. Two years after subsoiling, the surface layer (0 - 10 cm), and a deeper layer at 40 - 45 cm had re-

compacted. Bulk densities for the 15 to 35 cm depth, however remained about 20% lower than for corresponding non-subsoiled values at this time.

4.1.6.1 Discussion

Subsoiling reduced bulk density values in all five soils. The extent and durability of this reduction both in magnitude and volume of soil affected was however variable. Re-compaction occurred at a faster rate in near-surface layers for the Hamilton, Horotiu and Te Kowhai soils and to a lesser extent for the Whatawhata soil when compared with deeper soil layers (15 - 40 cm). This is probably due in part to the effect of livestock treading. The ability of the Hamilton and Whatawhata soils to withstand re-compaction processes may be a reflection of the relatively high inherent bulk density of these soils. The more sandy textured, relatively low bulk density Horotiu soil re-compacted to pre-subsoiling values fastest. The artificially constructed Rugby Park soil behaved differently from the other soils. Re-compaction was faster in subsurface layers than in surface layers, perhaps reflecting weekly tractor mowing of the ground. The effect of subsoiling on bulk density for this soil was least effective, although surface compaction was initially reduced significantly. The Hamilton soil was subsoiled at a higher soil moisture than the other soils and this may explain why the extent of reduced bulk density was greater five months after subsoiling. Subsoiling, as discussed earlier, creates distinctive cracks which are more pronounced when the soil dries out in Summer. The more clayey Hamilton soil therefore did not show full benefit until the structural cracks opened and developed five months after subsoiling. This trend was not obvious in the Horotiu soil but was similar for the Te Kowhai and Whatawhata soils.

Before subsoiling a compacted layer exists in the Hamilton and Te Kowhai soils at 30 - 45 cm depth and at 20 - 45 cm depth for the Whatawhata soil. Such high bulk density values ranging from 1.2 to 1.4 Mg m⁻³ would be limiting to root elongation. A significant reduction in bulk density resulting from subsoiling, persisted at this depth for two years.

Subsoiling reduced bulk density most effectively in the 10 cm distance from slot profile, down to the operating depth (40 - 45 cm). It can also be assumed that this was the case for the slot profile. The effect was not as deep in the 20 cm distance from slot profile, rarely reaching 35 cm depth and for the 30 cm distance from slot profile a shallower effect to depths of 30 cm. Only in the Hamilton soil was there an effect for the 40 cm distance from slot profile at 20 cm depth. This "shallowing" effect creates an envelope of lowered bulk density, emanating from the operating depth in the slot and 10 cm distance from slot profile, which extends towards the surface at angle of approximately 45°. Generally the extent of the "envelope" diminishes over time, with the angle of influence steepening, until only the 0 - 10 cm distance from slot is affected. In the case of the Whatawhata soil, however, reductions persisted in the 20 cm distance from slot profile for at least two years, reflecting perhaps the establishment of a semi-permanent network of structural cracks in the relatively high clay content Bg horizon. These reductions in BD values from about 1.45 to 1.20 Mg m⁻³ may be sufficient to encourage deeper rooting of Matua Prairie grass growing at this site.

In the case of the Hamilton soil there is evidence to suggest that subsoiling caused a small increase in bulk density in the 30 - 40 cm layer for the 30 cm distance from slot profile. This could probably be attributed to lateral compaction caused by the shaking subsoiler shank under wetter soil conditions (33% moisture). This increase in bulk density was not evident for other soils in the study.

4.2 SOIL STRENGTH MEASUREMENTS

Soil strength estimates were carried out using a Bush recording cone penetrometer. Tables 4.2.1 - 5 show cone index, percentage difference from non-subsoiled values, calculated from Tables 1 - 5 (Appendix 3). Figures 4.2.1 - 5 show cone index against depth for different soils at different times of year also calculated from Tables 1 - 5 (Appendix 3). Values for tables and figures are calculated from the mean of five penetrations per plot taken at sample points marked X (Figure 3.3.1) .

The variation in cone index for all readings was <15% of the mean value; significance was calculated accordingly. Where resistance to penetration exceeded 5.625 MPa, the instrument registered overload (OL)

4.2.1 Hamilton Clay Loam

Table 4.2.1 Change in cone index of subsoiled expressed as percentage of non-subsoiled values

(a) 13/7/87, 33% moisture, A horizon = 0 - 25 cm depth

Depth (cm)	Slot	Distance from slot			
		10cm	20cm	30cm	40cm
7	34*	17*	23*	18CI	22
14	20*	40*	36*	14CI	0
21	57*	68*	32*	24CI	3*
28	76*	79*	40*	3	8
35	69*	59*	31*	3CI	10
42	70*	50*	32*	12	12
49	30*	14	5	5	20

* = significant % cone decrease

CI = % cone increase

Values $\geq 15\%$ significant ($P < 0.05$)

Figure 4.2.1a shows that subsoiling significantly reduced cone index values at most depths in the slot and at 10 and 20 cm distance from the slot. However at the 7 and 21 cm depth for the 30 cm distance from slot profile there was a significant increase in cone index.

Table (a) shows maximum decrease at the 28 cm depth in the 10 cm distance from slot profile. Percentage reductions generally decreased away from the slot. Cone index increased significantly for the 30 cm distance from slot profile in comparison with the 20 cm profile.

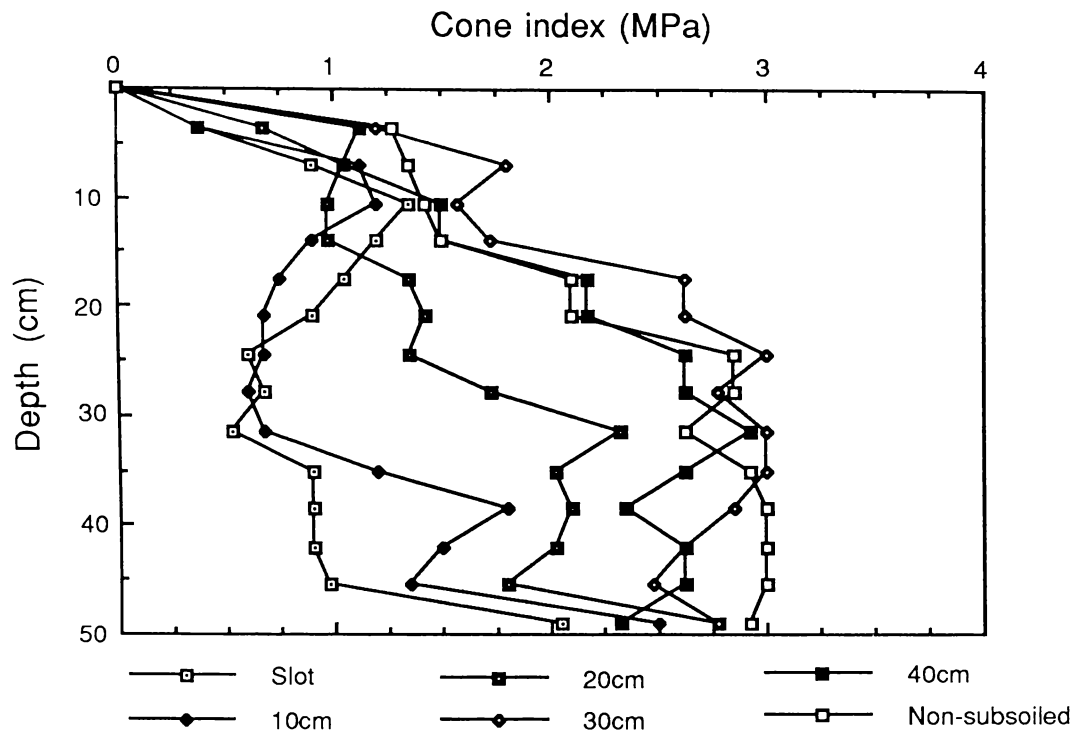


Figure 4.2.1a Hamilton soil, 13/7/87, 38% moisture

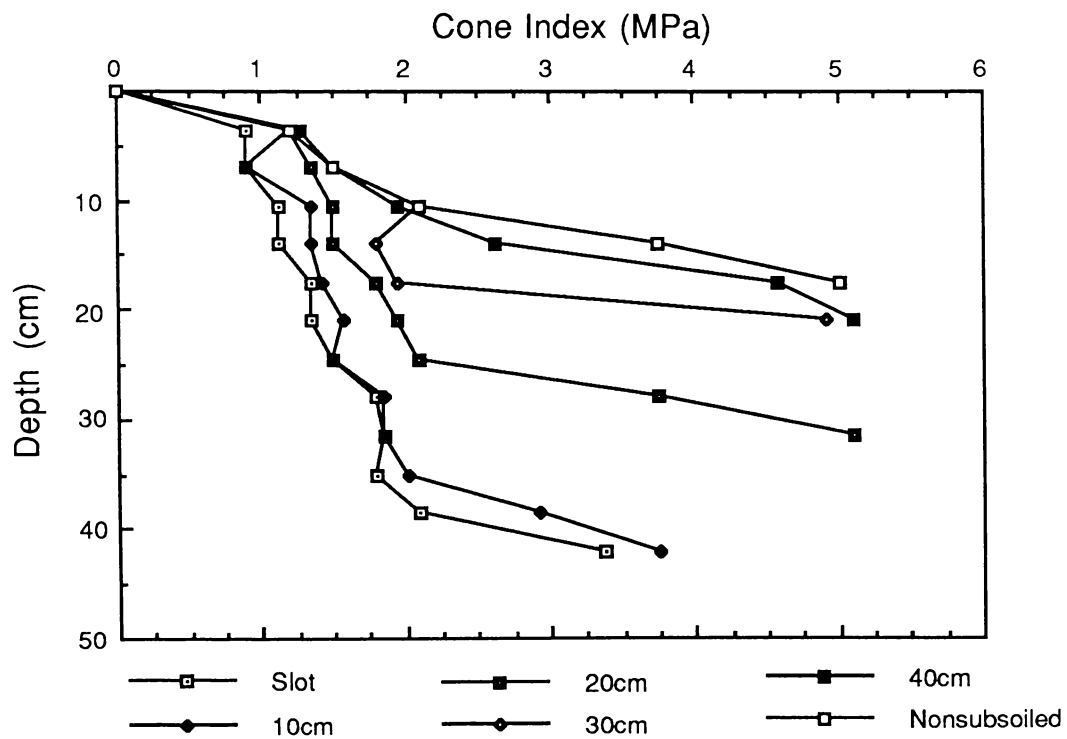


Figure 4.2.1b Hamilton soil, 9/12/87, 22% moisture

(b) 9/12/87, 22% moisture

Depth (cm)	Slot	Distance from slot			
		10cm	20cm	30cm	40cm
7	20*	40*	10	0	0
14	67*	64*	60*	52*	30*
21	76*	62*	65*	13	9
28	67*	66*	33*		
35	67*	64*			
42	41*	33*			
49					

* = significant % cone decrease

Values $\geq 15\%$ significant ($P < 0.05$)

Figure 4.2.1b shows that for the slot and 10 cm distance from slot profiles, subsoiling significantly lowered cone index values down to 42 cm. At depths greater than those recorded in the 20, 30 and 40 cm distance from slot profiles, the penetrometer registered overload. This compared with maximum values of 3 MPa in Figure 4.2.1a when soil moisture was higher.

Table (b) shows significant % reductions, greatest in the slot and 10 cm distance from slot profiles, reducing in magnitude and extent for measurements taken in the 20, 30 and 40 cm distance from slot profiles.

(c) 5/7/88, 36% moisture

Depth (cm)	Distance from slot				
	Slot	10cm	20cm	30cm	40cm
7	28*	33*	28*	17*	11
14	0	5	0	5	5
21	48*	58*	42*	28*	20*
28	50*	37*	28*	9CI	4CI
35	42*	31*	19*	6CI	8
42	31*	31*	4	9CI	4
49	13	8	0	0	5CI

* = significant % cone decrease

CI = % cone increase

values $\geq 15\%$ significant ($P < 0.05$)

Figure 4.2.1c shows that at depths less than 21 cm, cone index values for both subsoiled and non-subsoiled plots were similar. There were greater differences for depths ranging from 21 to 42 cm for the slot and the 10 and 20 cm distance from slot profiles. Cone index values were significantly lower than those recorded in Figure 4.2.1b reflecting wetter soil conditions.

Table (c) shows generally large percentage reductions in cone index, but also shows an area of increased soil strength in the 30 and 40 cm distance from slot profiles when compared with non-subsoiled plots.

(d) 13/12/88, 19% moisture

Depth (cm)	Distance from slot				
	Slot	10cm	20cm	30cm	40cm
7	25*	25*	0	20*	25*
14	34*	60*	45*	37*	22*
21	75*	64*	40*		
28	71*	67*			
35	53*	41*			

* = significant % cone decrease

Values $\geq 15\%$ significant ($P < 0.05$)

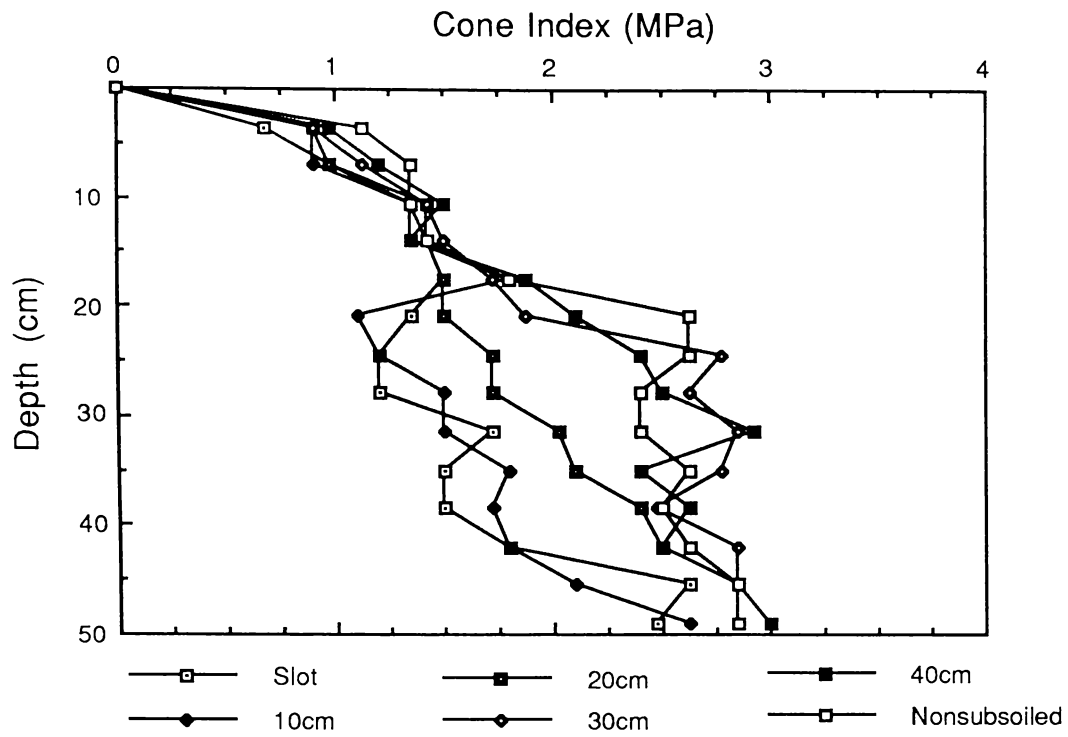


Figure 4.2.1c Hamilton soil, 5/7/88, 36% moisture

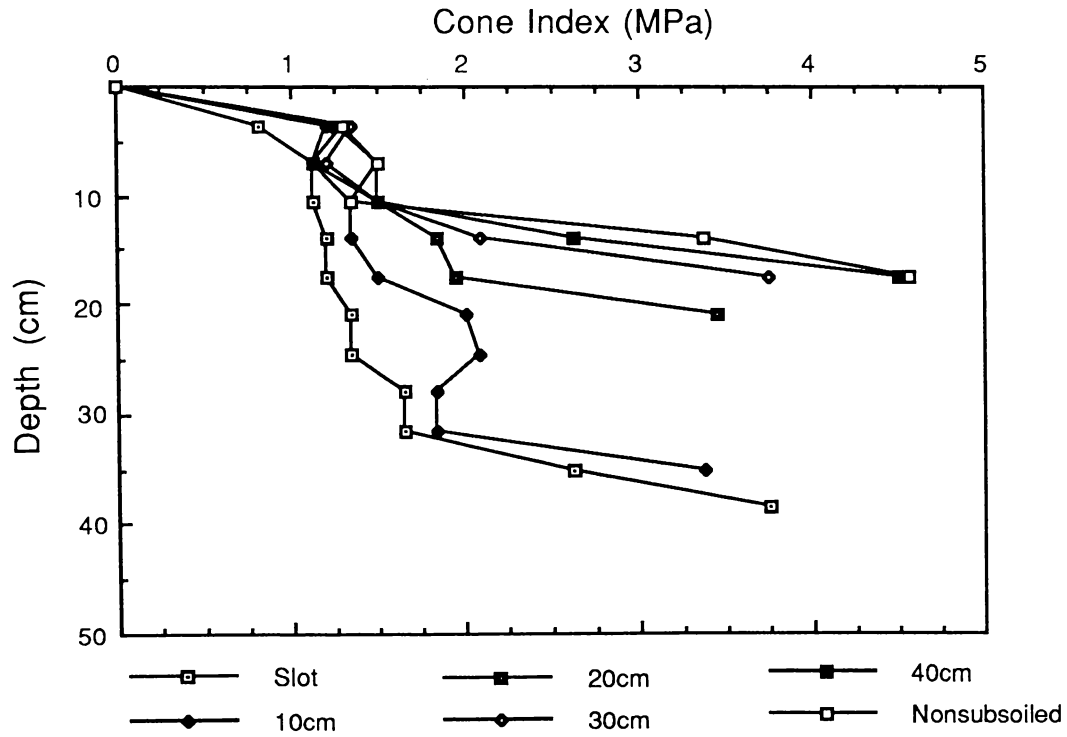


Figure 4.1.1d Hamilton soil, 13/12/88, 19% moisture

Figure 4.2.1d shows cone index values significantly lower for the slot and 10cm distance from slot profile at depths ranging from 14 to 35 cm. Overload was registered at relatively shallow depths for the 20,30 and 40 cm profiles, reflecting drier soil and increased soil strength.

Table (d) shows percentage cone index reduction was limited to shallower depths than previous measurements probably reflecting re-compaction and/or drier soil conditions.

(e) 6/7/89, 38% moisture

Depth (cm)	Slot
7	0
14	12CI
21	32*
28	38*
35	32*
42	0

* = significant % cone decrease

CI = % cone increase

values $\geq 15\%$ significant ($P < 0.05$)

(f) 10/12/89, 24% moisture

Depth cm	Slot
7	17*
14	46*
21	45*
28	49*
35	54*

* = significant % cone decrease

Values $\geq 15\%$ significant ($P < 0.05$).

Figures 4.2.1e and and Tables (e) and (f) show that cone index reductions and % reductions are confined only to the slot profile. Only slot and non-subsoiled data are given in (e) and (f), as other profiles did not give significant differences.

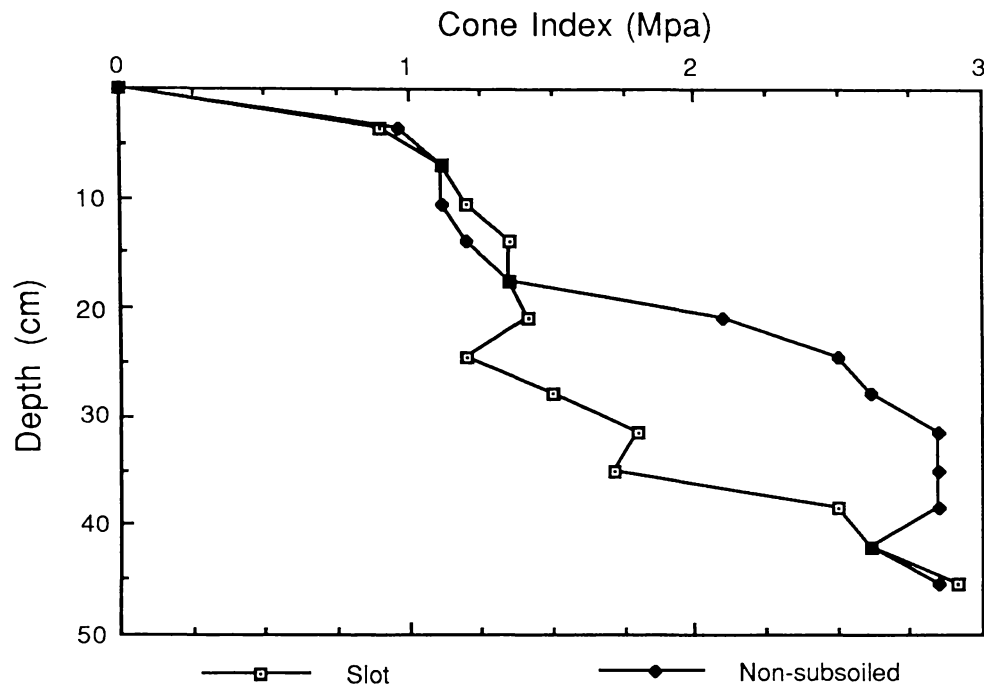


Figure 4.2.1e Hamilton soil, 6/7/89, 38% moisture

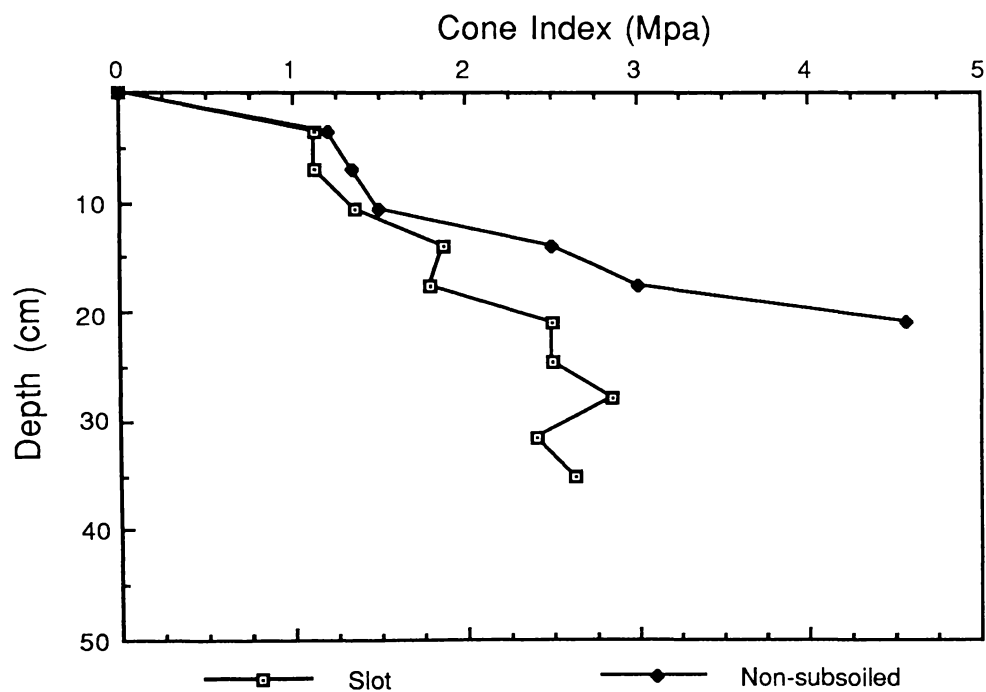


Figure 4.2.1f Hamilton soil, 10/11/89, 24% moisture

4.2.2 Horotiu Sandy loam

Table 4.2.2 Change in cone index of subsoiled expressed as percentage of non-subsoiled values

(a) 15/12/86, 18% moisture, A horizon = 0 - 15 cm depth

Depth (cm)	Slot	Distance from slot			
		10cm	20cm	30cm	40cm
7	87*	50*	0	25*CI	16CI
14	84*	73*	33*	15*	44C
21	91*	58*	41*	33*	8
28	87*	25*	5	12	12CI
35	68*	40*	8	10	17*
42	80*	40*	8	20*	3
49	3CI	14CI	14CI	11CI	10

* = % cone decrease

CI = % cone increase

Values ≥ 15 significant ($P < 0.05$)

(b) 20/11/87, 20% moisture

Depth (cm)	Slot	Distance from slot			
		10cm	20cm	30cm	40cm
7	65*	28*	28*	25*	8CI
14	62*	30*	16*	12	5CI
21	56*	13	8	9	8
28	66*	33*	18*	30*	7
35	44*	11	4CI	4CI	3
42	47*	20*	9	5CI	11CI
49	0	4CI	4CI	2CI	5

* % cone decrease

CI = % cone increase

* = values $\geq 15\%$ significant ($P < 0.05$)

Figure 4.2.2a shows large reductions in cone index for the slot and 10 cm from slot profile, down to 42 cm depth. A relatively small increase in cone index is evident at 49 cm depth for all subsoiled profiles with the exception of the 40 cm distance from slot profile.

Table (a) shows percentage decrease for Horotiu soil, is greatest in the slot profile. The effect of subsoiling diminishes away from the slot profile, both in magnitude and volume of soil affected.

Figure 4.2.2b shows for non-subsoiled profiles a large increase in soil strength, from 1.12 to 2.62 MPa, for 3.5 and 7 cm depths and a further increase at the 24.5 cm depth to 4.87 MPa. The effect of subsoiling remains highly significant for the slot profile, where cone index values are approximately 50% lower than for non-subsoiled profiles.

Table (b) shows varied cone index values in the 20, 30 cm distance from slot profiles, which generally trend towards non-subsoiled values. The 40 cm profile is not significantly different from non-subsoiled.

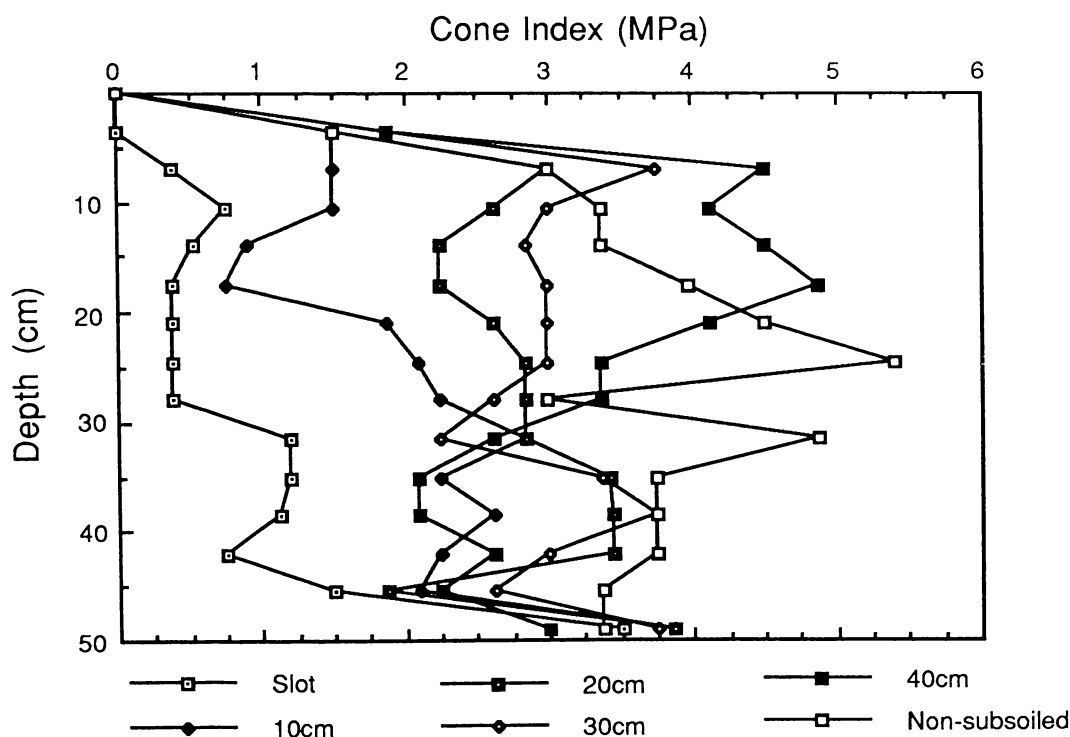


Figure 4.2.2a Horotiu soil, 15/12/86, 18% moisture

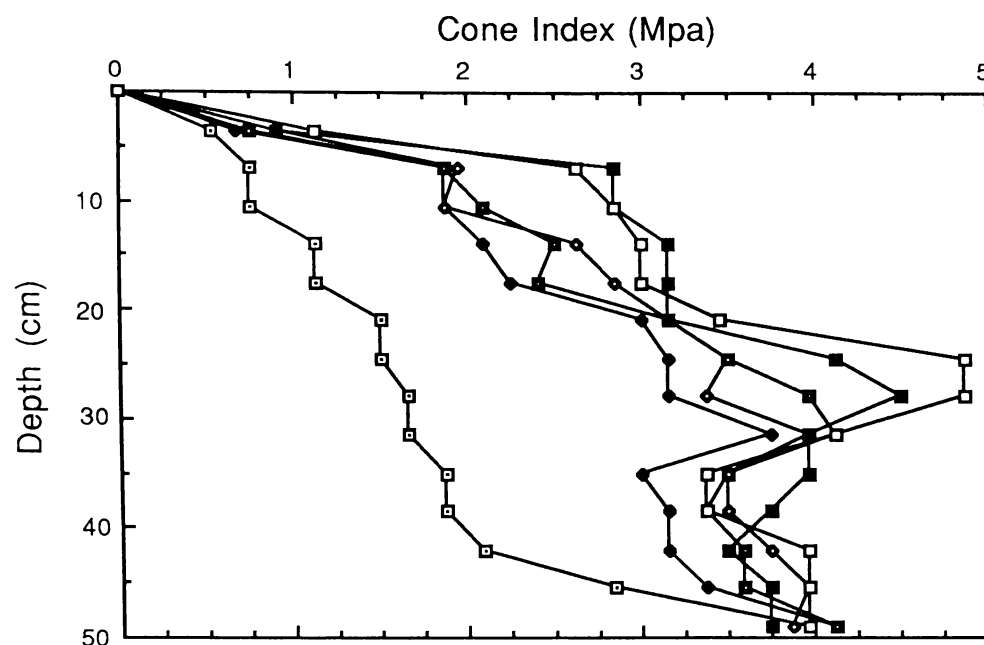


Figure 4.2.2b Horotiu soil, 20/11/87, 20% moisture

4.2.3 Rugby Park soil

Table 4.2.3 Change in cone index of subsoiled expressed as a percentage of non-subsoiled values

(a) 7/10/86, 26% moisture, A horizon = 0 - 21 cm depth

Depth (cm)	Distance from slot				
	Slot	10cm	20cm	30cm	40cm
7	100*	83*	83*	68*	8CI
14	88*	62*	66*	87*	4
21	83*	70*	62*	33*	
28	78*	55*	12*		
35	53*	33*			

* = % cone decrease

CI = % cone increase

values $\geq 15\%$ significant ($P < 0.05$)

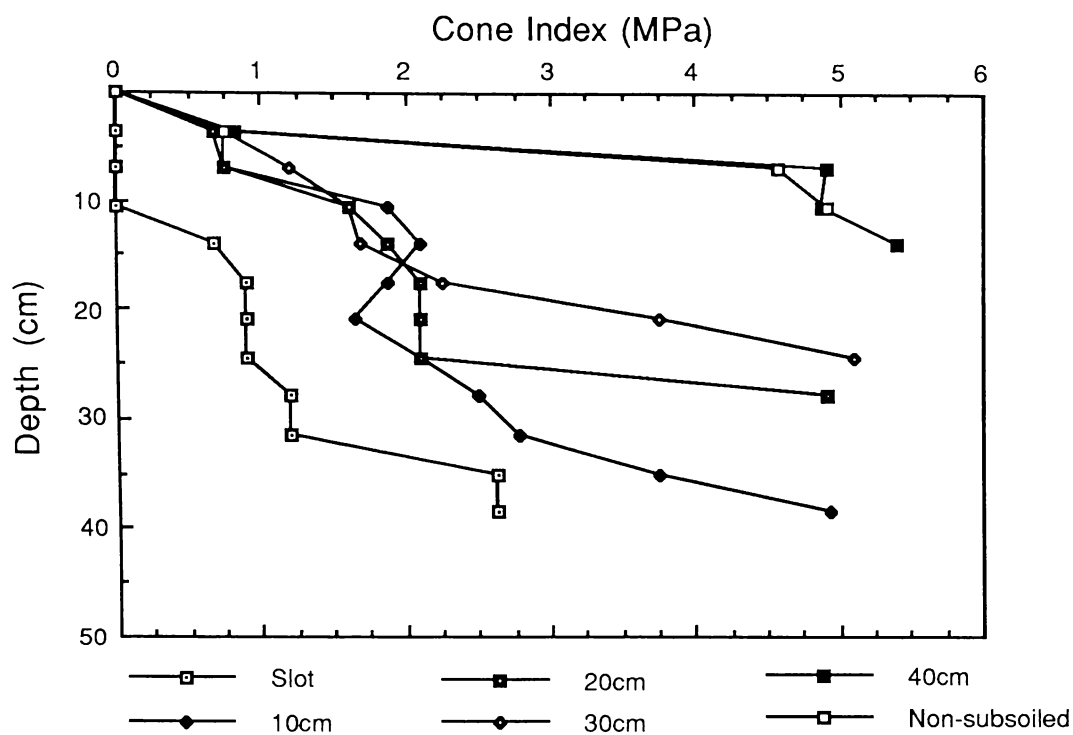


Figure 4.2.3a Rugby Park soil, 7/10/86, 26% moisture

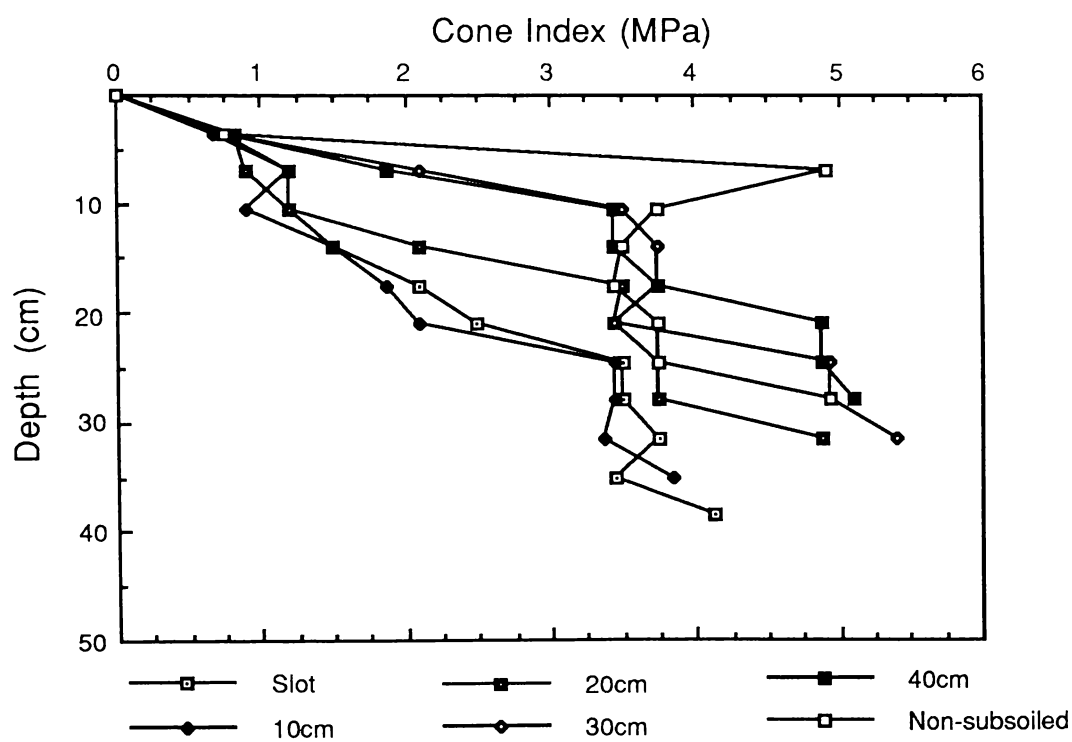


Figure 4.3.2b Rugby Park soil, 15/12/86, 18% moisture

Figure 4.2.3a shows 100% reductions in cone index down to 10 cm for the slot. In the 40 cm distance from slot profile there was non significance when compared with non-subsoiled. Overloading occurred at progressively shallower depths, for measurements taken at increasing distances from the slot profile. Table (a) shows a similar trend for % cone decrease values with significance extending into the 30 cm distance from slot profile limited to 0 - 21 cm depth.

(b) 15/12/86, 18% moisture

Depth (cm)	Slot	10cm	20cm	30cm	40cm
7	75*	75*	81*	57*	61*
14	73*	73*	40*	7CI	1
21	33*	45*	8	8	30CI
28	29*	30*	24*	0	3*
35	30*	22*			

* = % cone decrease CI = % cone increase * = values $\geq 15\%$ significant ($P < 0.05$)

Figure 4.2.3b shows considerable re-compaction for subsoiled profiles at depths ranging from 10.5 to 30 cm, when compared with Figure 4.2.3a. However near surface (0 - 7 cm) values remained significantly lower, as did also, the slot and 10 cm distance from slot values. Table (b) showed that largest decreases were recorded in the top 21 cm for the slot and 10 and 20 cm distance from slot profiles. Overloading occurred at 35 cm depth for the 20, 30 and 40 cm profiles.

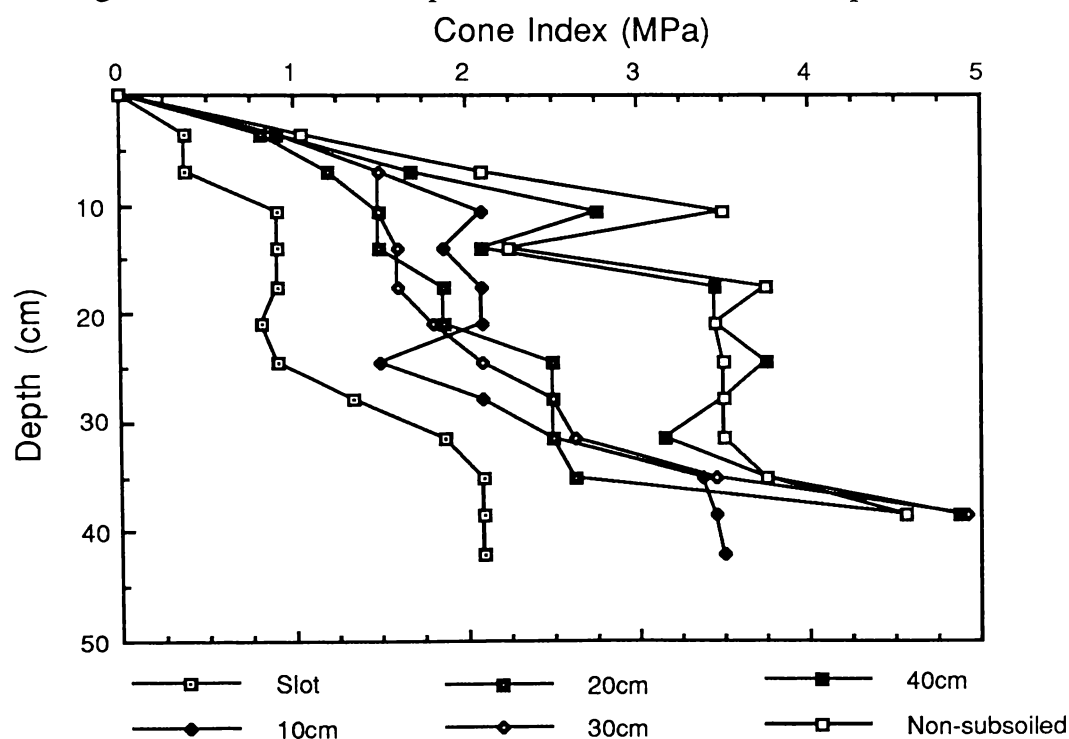


Figure 4.2.3c Rugby Park soil, 2/6/87, 35% moisture

(c) 2/6/87, 35% moisture

Depth (cm)	Slot	Distance from slot			
		10cm	20cm	30cm	40cm
7	82*	28*	42*	28*	20*
14	60*	16*	33*	28*	7
21	76*	39*	45*	46*	0
28	61*	40*	28*	28*	0
35	44*	10	30*	8	0
42	62*	37*			

* = % cone decrease

values $\geq 15\%$ significant ($P < 0.05$)

Figure 4.2.3c shows a general lowering in cone index for all profiles when compared with Figure 4.2.3b. A higher soil moisture level is certainly responsible for this effect. However high cone index values (>3.5 MPa) were recorded for the 40 cm subsoiled profile and non-subsoiled profiles at depths ranging from 17.5 to 38.5 cm.

Figure 4.2.3c showed that although mean cone index values were lower, the percentage reductions in cone index when compared with the non-subsoiled profiles remained highly significant, eight months after subsoiling.

4.2.4 Te Kowhai silt loam

Table 4.2.4 Change in cone index of subsoiled expressed as a percentage of non-subsoiled values.

(a) 3/12/86, 20% moisture, A horizon = 0 - 20 cm depth

Depth (cm)	Slot	Distance from slot			
		10cm	20cm	30cm	40cm
7	60*	20CI	11CI	11CI	7CI
14	86*	67*	30*	0	5
21	90*	81*	53*	63*	61*
28	75*	85*	64*	61*	7
35	75*	73*	64*		
42	82*	77*	64*		

* = % cone decrease CI = increase in cone index values $\geq 15\%$ significant ($P < 0.05$)

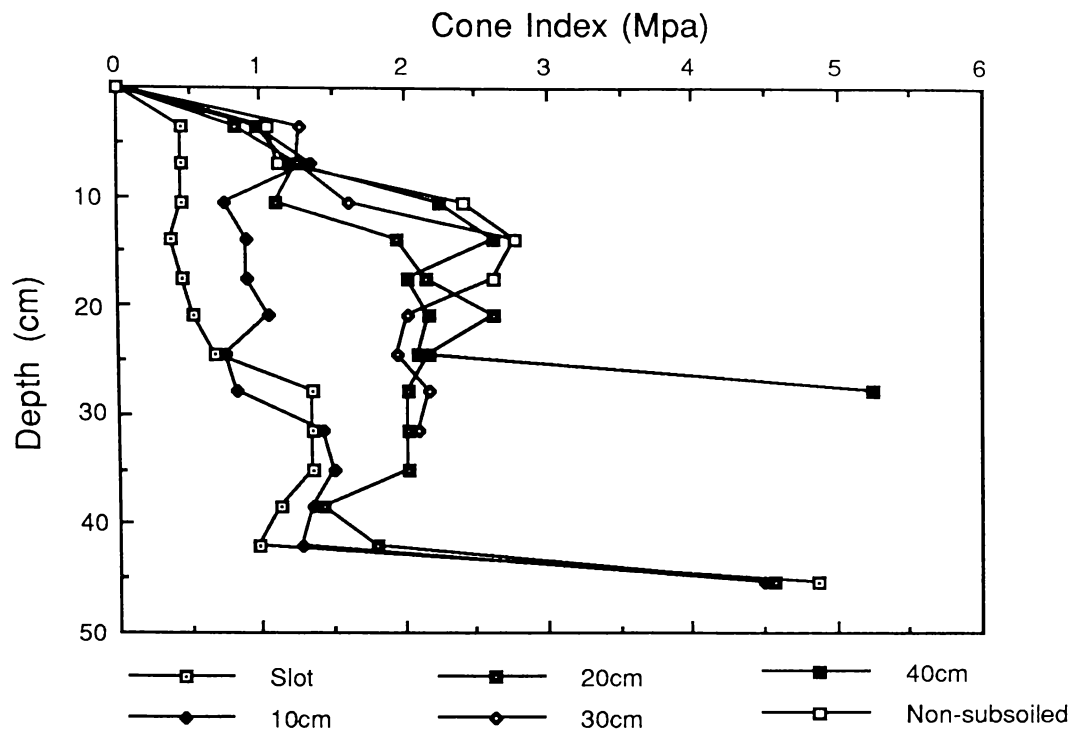


Figure 4.2.4a Te Kowhai soil, 3/12/86, 20% moisture

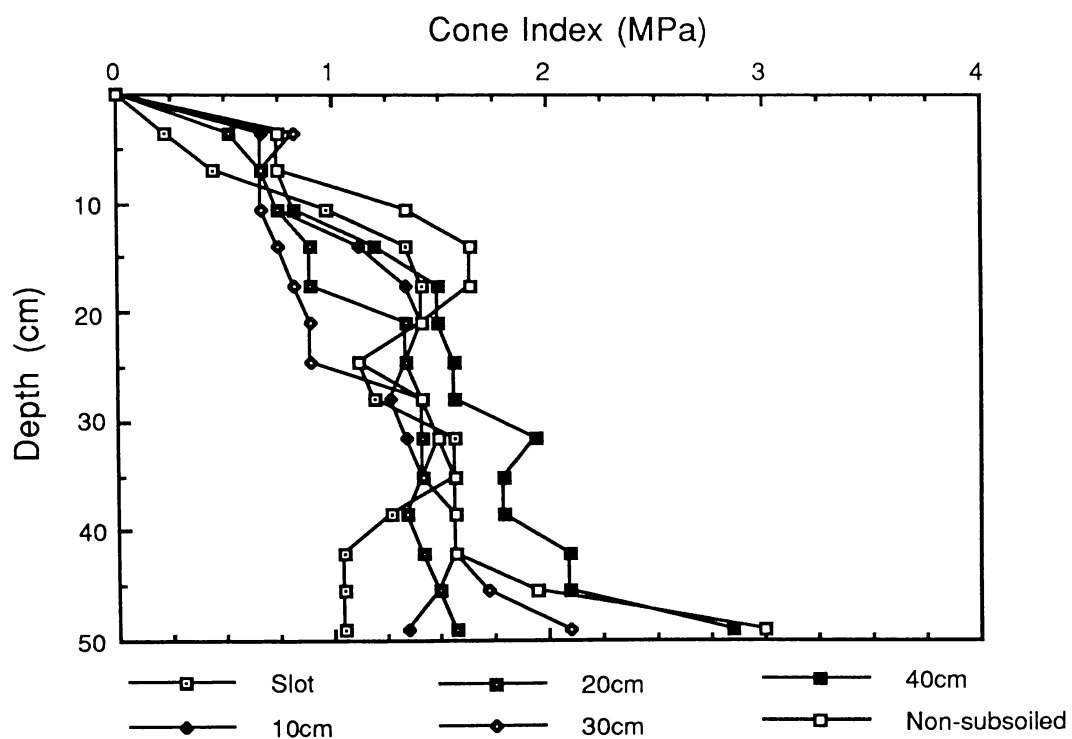


Figure 4.2.4b Te Kowhai soil, 6/7/87, 39% moisture

Figure 4.2.4a shows overload occurred at 17.5 cm depth for non-subsoiled plots compared with 49 cm depth for the subsoiled slot profile. Cone index values were significantly lower in the slot and in the 10 and 20 cm distance from slot profiles down to 42 cm.

Table (a) showed that percentage reductions were greatest in the slot profile in the top 21 cm. However at a depth of 7 cm for the 10, 20, 30 and 40 cm distance from slot profile, there appeared to be a soil layer of higher strength was recorded with a percent increase in cone index.

(b) 6/7/87, 39% moisture

Depth (cm)	Distance from slot				
	Slot	10cm	20cm	30cm	40cm
7	40*	10	10	10	0
14	18*	32*	45*	54*	27*
21	0	0	4	36*	5CI
28	15*	10	0	0	10CI
35	0	9	9	9	14CI
42	33*	0	9	0	33CI
49	65*	55*	47*	30*	5

* = % cone decrease

CI = increase in cone increase

values $\geq 15\%$ significant ($P < 0.05$)

Figure 4.2.4b shows that increased soil moisture has in this case reduced cone index and substantially narrowed the range of values, when compared with Figure 4.2.4a. Table (b) shows a variable response in all profiles, with % cone index fluctuating from -33 to 65. Least effect was recorded in the 21 to 35 cm depths for profiles located between the slot and 30 cm distance from slot. Some re-compaction occurred in the 40 cm distance from slot profile, at 42 cm depth.

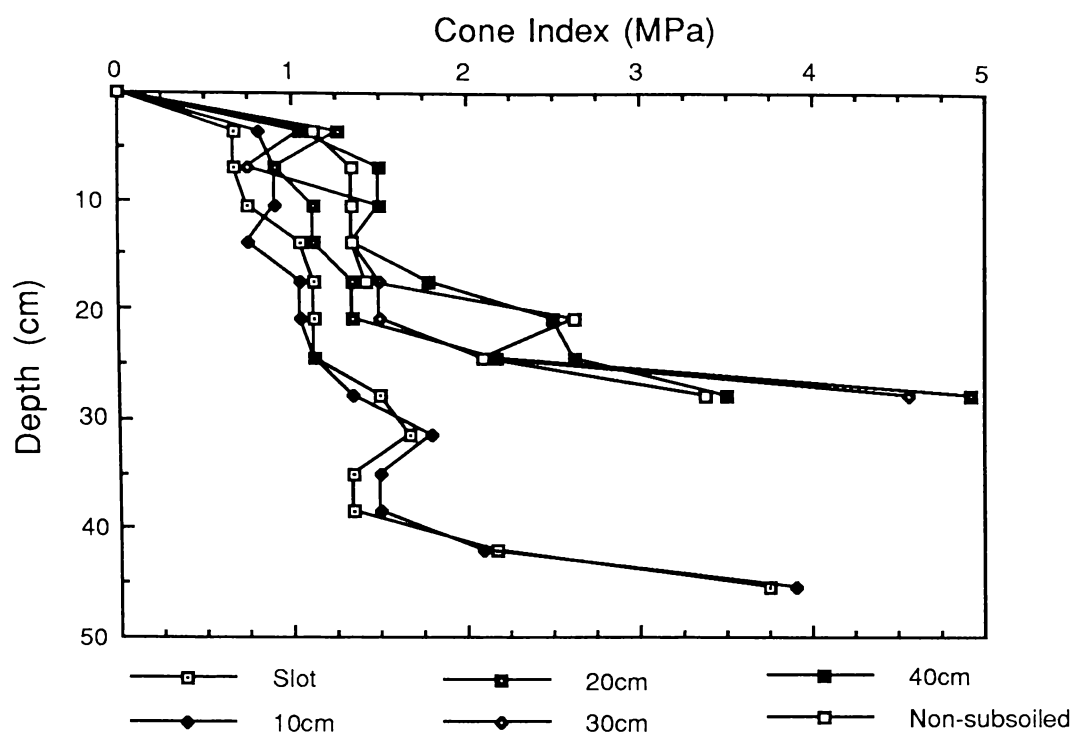


Figure 4.2.4c Te Kowhai soil, 11/12/87, 18% moisture

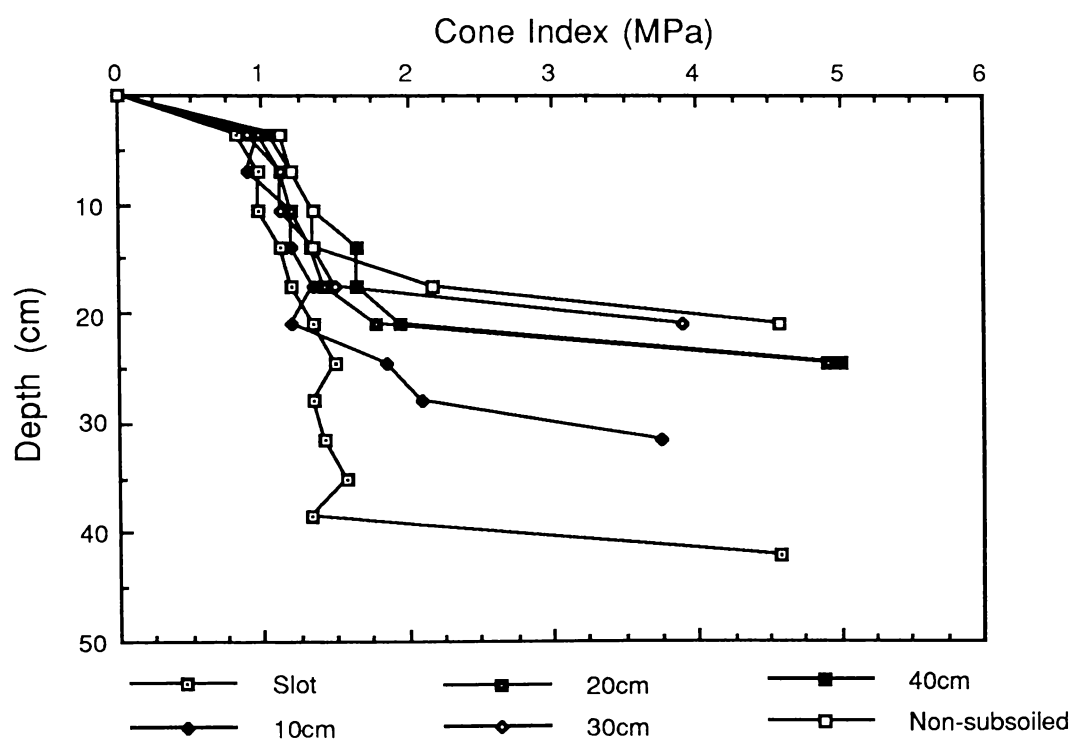


Figure 4.2.4d Te Kowhai soil, 15/12/88, 22% moisture

(c) 11/12/87, 18% moisture

Depth (cm)	Slot	Distance from slot			
		10cm	20cm	30cm	40cm
7	50*	33*	33*	44*	11CI
14	28*	44*	17*	0	0
21	57*	60*	48*	42*	4
28	55*	60*	47CI	35CI	4
35	75*	73*			
42	61*	62*			

* = % cone decrease

CI = % cone increase

values $\geq 15\%$ significant ($P < 0.05$)

Figure 4.2.4c shows cone index values one year after subsoiling were significantly reduced in the slot and 10 cm distance from slot profile. However resistance to penetration had significantly increased for other subsoiled profiles, with overload occurring at 31.5 cm depth for the 20, 30 and 40 cm distance from slot profiles. Table (c) shows a dramatic increase in cone index at the 28 cm depth for the 20 and 30 cm distance from slot profiles.

(d) 15/12/88, 22% moisture, A horizon = 0 - 16 cm depth

Depth (cm)	Slot	Distance from slot			
		10cm	20cm	30cm	40cm
7	19*	25*	6	6	0
14	17*	11	1	0	18CI
21	70*	73*	38*	14	13
28	75*	62*			
35	71*				
42	17*				

* = % cone decrease

CI = % cone increase

values $\geq 15\%$ significant ($P < 0.05$)

Figure 4.2.4d shows a re-compaction trend where overloading was common at progressively shallower depths for measurements taken at increasing distance from the subsoiled slot.

Table (d) shows that the effect two years after subsoiling was limited to the slot profile and to the top 28 cm of the 10 cm distance from slot profile and to a small volume of soil at the 21 cm depth for the 20 cm distance from slot profile.

4.2.5 Whatawhata clay loam

Table 4.2.5 Change in cone index of subsoiled expressed as a percentage of non-subsoiled values.

(a) 15/12/86, 18% moisture, A horizon = 0 - 16 cm depth

Depth (cm)	Distance from slot				
	Slot	10cm	20cm	30cm	40cm
7	100*	37*	37*	31*	25*
14	67*	57*	53*	22*	14
21	80*	76*	65*	65*	45*
28	85*	71*	69*	28*	6
35	83*	73*	38*	5	
42	62*	53*	13		
49	13	12			

* = % cone decrease

Values $\geq 15\%$ significant ($P < 0.05$)

Figure 4.2.5a shows subsoiling significantly reduced cone index values in all subsoiled profiles. The greatest effect is seen for the slot profile down to 49 cm depth and the least effect for the 40 cm distance from slot profile. Overloads occurred at 31.5 cm depth for nonsubsoiled profiles and at greater depths for the subsoiled plots.

Table (a) shows large % cone decrease, the effect decreasing away from the slot profile. Subsoiling in this case is significant to 40 cm distance from slot profile.

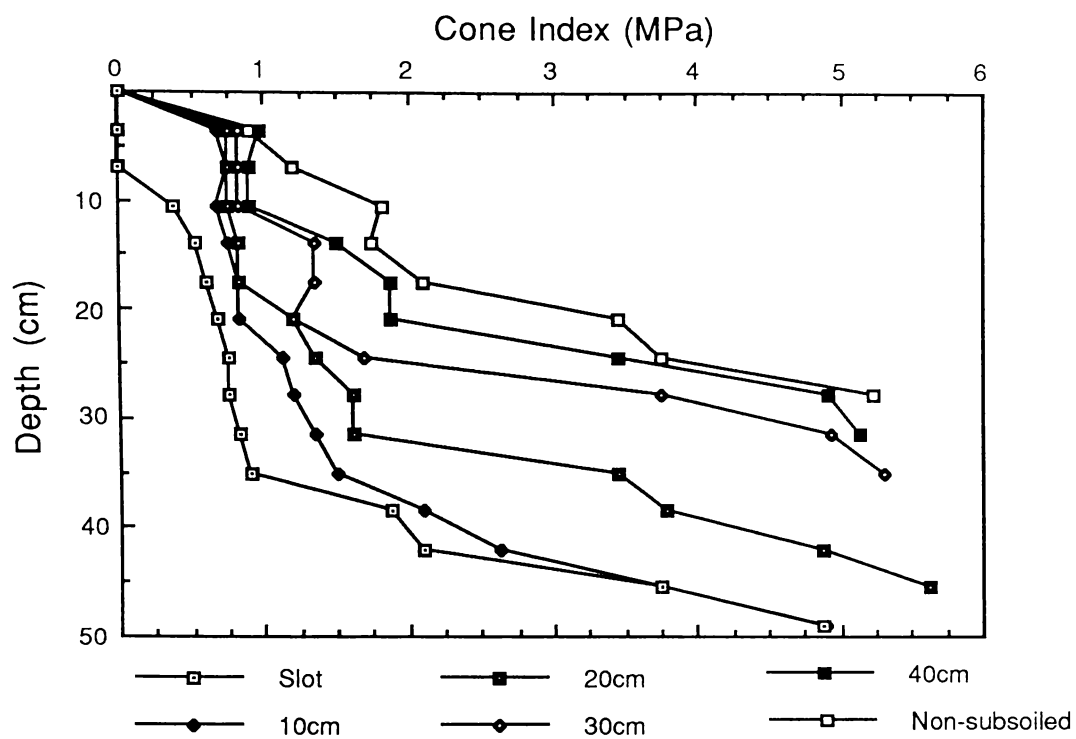


Figure 4.2.5a Whatawhata soil, 15/12/86, 18% moisture

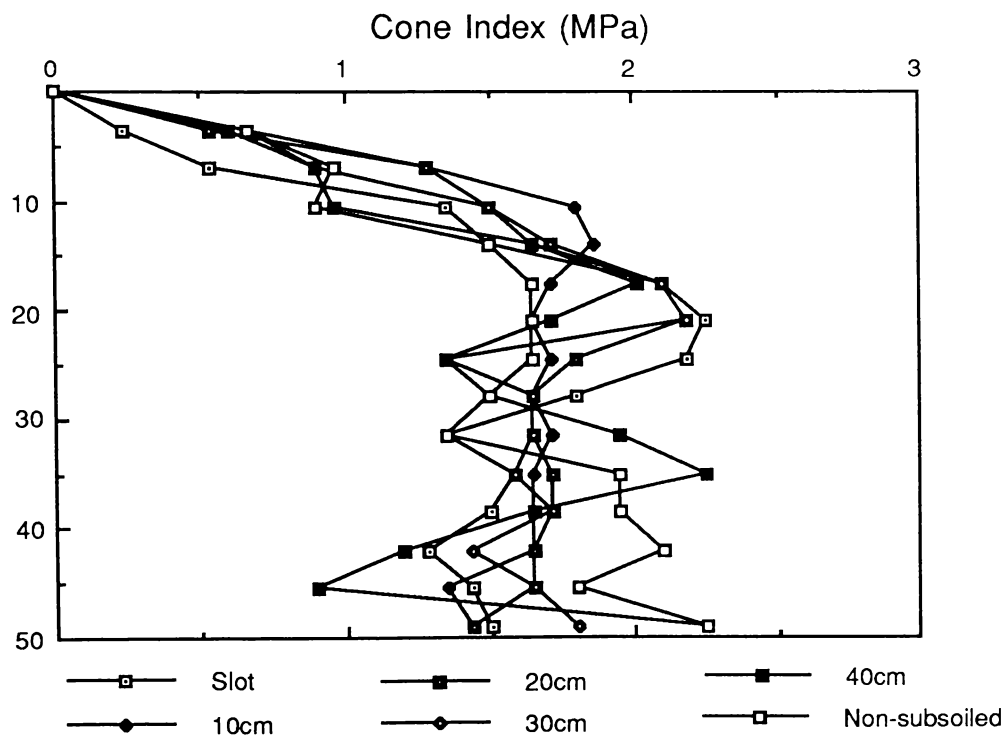


Figure 4.2.5b Whatawhata soil, 7/7/87, 38% moisture

(b) 7/7/87, 38% moisture

Depth (cm)	Distance from slot				
	Slot	10cm	20cm	30cm	40cm
7	45*	31CI	31CI	7	7
14	0	24CI	8CI	10CI	10CI
21	36CI	0	32CI	32CI	7CI
28	20CI	10CI	10CI	10CI	0
35	19*	15*	11	19*	15CI
42	43*	21*	21*	31*	42*
49	33*	36*	36*	20*	

* = % cone decrease

CI = % cone increase

Values $\geq 15\%$ significant ($P < 0.05$)

Figure 4.2.5b shows cone index values under higher soil moisture conditions were restricted to a narrower range (0-2.25 MPa) when compared with Figure 4.2.5a (0-5.65 MPa) under drier conditions.

Table (b) shows a percent increase in cone index values in the top 28 cm. However most cases are non significant.

(c) 14/12/87, 19% moisture

Depth (cm)	Distance from slot				
	Slot	10cm	20cm	30cm	40cm
7	41*	41*	25*	8	8
14	39*	39*	33*	11	11
21	73*	65*	65*	60*	24*
28	84*	65*	51*	30*	0
35	78*	62*			
42	78*	6			

* = % cone decrease

Values $\geq 15\%$ significant ($P < 0.05$)

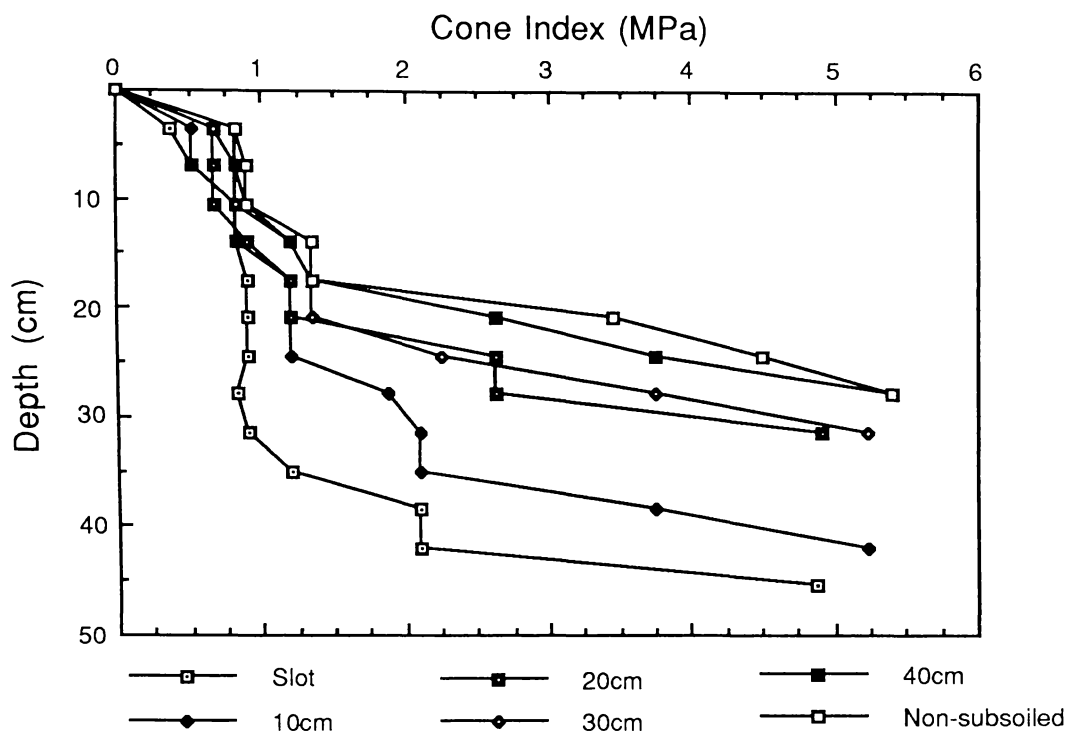


Figure 4.2.5c Whatawhata soil, 14/12/87, 19% moisture

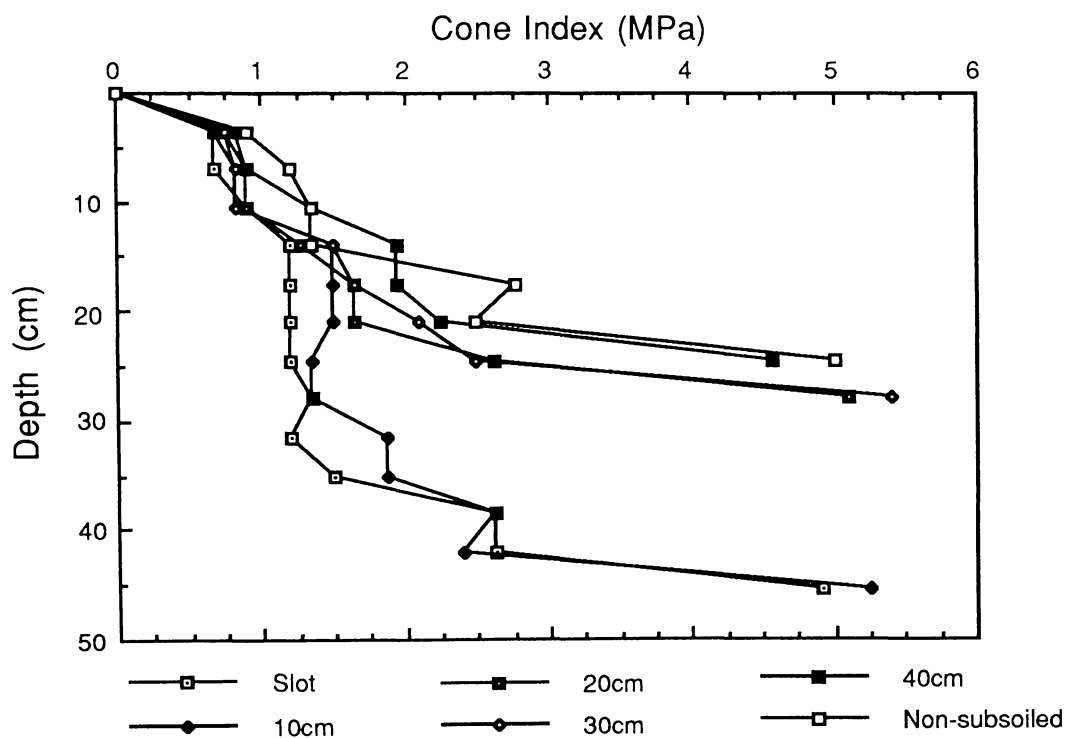


Figure 4.2.5d Whatawhata soil, 16/11/88, 22% moisture

One year after subsoiling, Figure 4.2.5c shows that the effect of subsoiling has persisted, with significant reductions in cone index evident in the near slot profiles. Table (c) shows relatively large % decrease down to 42 cm for the slot profile and down to 35, 28, 28 and 21 cm for the 10, 20, 30 and 40 cm distance from slot profiles respectively.

(d) 16/11/88, 22% moisture

Depth (cm)	Distance from slot				
	Slot	10cm	20cm	30cm	40cm
7	44*	31*	25*	31*	25*
14	11	11CI	5	11CI	44CI
21	52*	40*	34*	16*	10
28	75*	75*	8	0	
35	73*	66*			
42	63*	57*			

* = % cone decrease

CI = % cone increase

Values $\geq 15\%$ significant ($P < 0.05$)

Two years after subsoiling most cone index values for the slot and 10 cm distance from slot profiles are still significantly lower than non-subsoiled plots. Figure 4.2.5d shows that re-compaction has occurred in all profiles when compared with Figures 4.2.5a, c. Table (d) shows that % cone decrease was non significant at the 14 cm depth, for all subsoiled profiles but was significant for other depths down to 42 cm for the slot and 10 cm distance from slot and for shallower depths in the 20, 30 and 40 cm profiles.

4.2.6 Effect of soil moisture on cone index

Table 4.2.6 shows the effect of soil moisture on cone index (soil strength). The non-subsoiled values can be used to directly compare the relationship between increased moisture and cone index. The subsoiled values also show interesting trends, however it must be remembered they also incorporate a re-compaction factor, due to increasing length of time between subsoiling and penetrometer readings.

Table 4.2.6 Effect of moisture on cone index (MPa). Mean profile values

Soil description	Soil moisture	Distance from slot(cm)					Non subsoiled	$\bar{x}$
			slot	10	20	30	40	
Hamilton	33	0.86	0.98	1.52	2.40	2.14	2.31	1.70
	22	1.14	2.05	3.10	3.73	4.00	4.11	3.02
	36	1.44	1.46	1.77	2.13	2.20	2.12	1.85
	19	2.14	2.52	3.57	3.84	3.93	4.00	3.33
Rugby Park	26	1.00	2.27	2.82	3.30	4.63	4.56	3.10
	18	2.50	2.48	3.12	3.87	3.91	3.98	3.30
	35	1.22	2.25	2.37	2.46	3.19	3.33	2.47
Te Kowhai	20	1.10	1.35	1.99	2.90	3.35	4.02	2.45
	39	1.12	1.23	1.15	1.07	1.49	1.41	1.24
	18	1.40	1.44	3.01	3.02	2.94	3.05	2.47
	22	1.51	2.46	3.14	3.32	3.40	3.48	2.88
Whatawhata	18	1.00	1.40	2.10	2.80	3.19	3.47	2.33
	38	1.47	1.56	1.63	1.33	1.43	1.51	1.49
	19	1.32	2.02	2.73	2.88	3.22	3.36	2.59
	22	1.63	1.81	3.10	3.12	3.37	3.46	2.75

For non-subsoiled Hamilton soil, an increase in soil moisture from approximately 20 to 35% decreased cone index from approximately 4.05 to 2.20 MPa respectively, equivalent to a 46% reduction and 3.16 to 1.77 MPa for both subsoiled and non-subsoiled respectively.

For Rugby Park soil a decrease in soil strength was recorded for non-subsoiled plots and the 40 cm distance from slot profile when soil moisture decreased from 26 to 18% over a 2 month period in early summer 1986. Cone index in June 1987, at a soil moisture of 35% was much reduced when compared with the earlier measurements taken in the preceeding December and October.

For Te Kowhai soil an increase in soil moisture from approximately 20 - 39% decreased cone index from 4.02 to 1.41 MPa respectively, equivalent to a 64% reduction.

For Whatawhata soil an increase in soil moisture from approximately 18 - 38%, decreased cone index from approximately 3.47 to 1.51 MPa respectively, equivalent to a 56% reduction.

The data presented here show the relationship between resistance to penetration and soil water content. All soils showed an inverse relationship between soil water content and soil strength. This was the case with some of the soils worked on by Burke *et al.*, (1964), Marshall and Holmes (1979) and Climo and Richardson (1984).

4.2.7 Discussion

Hamilton Soil

Resistance to penetration was greatest for measurements taken in December when soils having approximately 21% moisture were drier in comparison with July soil moistures of approximately 36% moisture. Maximum penetrometer readings for December of about 5.6 MPa were attained in the non-subsoiled and in the 30 and 40 cm subsoiled profiles at relatively shallow depths (17.5 - 24.5 cm). These high soil strengths could limit pasture root penetration at this time of year.

The figures and tables show interesting trends in subsoiling effectiveness and durability. The Hamilton soil was subsoiled at a relatively high soil moisture content (33%). Immediately after subsoiling significant reductions in cone index values were found in the slot and 10 and 20 cm distance from the slot but not 30 and 40 cm distance from the slot. However, five months later in December 1987 significant

reductions were found 30 and 40 cm distance from the slot at 14 cm depth. In this case it seems that the extension of lower strength areas developed along structural cracks emanating from the subsoiler tip as the soil dried through late spring and early summer. One year after subsoiling (5/7/88) there was evidence of increasing re-compaction in the top 17.5 cm for all distances from the slot. The paddock had been grazed numerous times by a dairy herd. However significant reductions in soil strength from 17 to 42 cm depth persisted in the slot and 10 cm distance from slot profiles. Seventeen months after subsoiling the significant lower strength "envelope" persisted in the slot and 10 cm from slot profiles, but was not as extensive at further distances from the slot. Twenty nine months after subsoiling re-compaction had occurred in all subsoiled profiles with the exception of the slot profile, where lower soil strength persisted at depths ranging from 14 to 35 cm. The relatively few areas that showed an increase in soil resistance to penetration as a result of subsoiling, could probably be attributed to zones contiguous to soil fracture lines, where heave and shatter caused compaction. This was most evident for the July 1987 measurement in the 0 - 21 cm depth for the 30 cm distance from slot profile. Overload occurred at 21 cm depth for the non-subsoiled plots for measurements taken in December when drier soil (19-22% moisture) conditions were encountered (Table 4.2.1b). Under wetter soil conditions (33% moisture) resistance to penetration was lowered, when compared with drier soil values.

Horotiu Soil

Immediately after subsoiling, the Horotiu soil cone index was reduced by up to 91% in the slot profile. However one year after subsoiling (Fig 4.2.2b) re-compaction, caused largely by livestock treading and perhaps to some extent by soil textural characteristics had resulted in an increase in soil strength in all subsoiled profiles. Strength levels however remained significantly less when compared with non-subsoiled, for depths (0 - 28 cm) in profiles found within 30 cm of the slot.

Measurements taken two years after subsoiling, but not shown here, indicated that re-compaction had occurred in all subsoiled plots.

A layer of significantly higher strength soil was located at approximately 28 - 40 cm depth for the non-subsoiled plots, perhaps reflecting an area of finer particle size. The 40 cm distance from slot profile was largely unaffected by subsoiling, which implies that for better soil coverage, shank spacing should be reduced.

Rugby Park Soil

Rugby Park was subsoiled at a shallower depth (35 cm) than the other four soils in the study (45 cm). This decision was made in order to reduce the risk of wheel slippage to a minimum. Soil disturbance was therefore limited to shallower depths. The relationship between soil moisture and penetrometer resistance is of particular interest at this site. Overload occurred at shallower depths on 7/10/86 when soil moisture was 26% than on 15/12/86 when soil moisture was 18%. No explanation can be given for this anomaly as measurements taken in June 1987, when the soil was wetter followed trends seen in other wet soils, i.e. lowered cone index. The proliferation of the significantly lower soil strength envelope over five months following subsoiling was however discussed for the Hamilton soil. This could perhaps result from cracks created by subsoiling which further develop in response to changes in drainage and/or root channel patterns, or to soil structural changes in response to the soil drying in early summer. This could have also been the case for Rugby Park soil.

Te Kowhai Soil

Te Kowhai soil is characterised by a significant increase in soil strength at 21 cm depth. This zone of compaction was disturbed by subsoiling allowing penetrometer readings to be taken down to depths of 45.5 cm. The influence of subsoiling extended into the 40 cm distance from slot profile, at the 21 cm depth (Table 4.2.4a). The measured effect, six months after subsoiling under wetter soil conditions (Table 4.2.4b), was more scattered. There were significant reductions for the top and bottom of the slot profile, but with non-significance for the 21 and 35 cm depths. This situation strongly suggests the influence of clay mineralogy causing swell and shrinkage of the soil. Thus higher soil moisture, results in the closing of structural cracks, leading to similar soil strength characteristics as for non-subsoiled soils. Penetrometer values two years after subsoiling, show that for this soil, reduced soil strength persisted in profiles up to 20 cm from the subsoiled slot.

Whatawhata Soil

Two years after subsoiling the effects of subsoiling persisted. Significant reductions in cone index values were measureable up to 30 cm from the slot profile. A characteristic of this soil is high soil strength at approximately 30 cm depth. Subsoiling under dry (18% moisture) soil conditions reduced soil strength in this

layer. The pattern of soil disturbance follows that discussed for other soils, but for the Whatawhata soil a greater volume of soil is affected. Under wetter soil conditions (Table 4.2.5b) the difference in cone index for subsoiled and non-subsoiled plots is relatively non significant. However, although higher soil moistures reduce soil strength, and mask the effect of subsoiling, the effects of soil structural changes are “resurrected” when the soils begin to dry in the early summer (Table 4.2.5c)

4.2.8 Summary

Resistance to penetration is influenced by soil moisture, soil type and soil structural characteristics. Subsoiling disturbs soil and the extent of this disturbance can be measured using a penetrometer. In this study the lowering of soil strength (penetrometer resistance) and the volume of soil affected by subsoiling over a two year period was monitored. When relatively dry soils are subsoiled the area of soil disturbance is greater than for relatively wet soils.

However, in the case of the Hamilton soil, five months after subsoiling, lower soil strength had extended laterally as the soil dried from 33 to 22% moisture. The drying processes resurrected cracks caused by subsoiling.

Relatively high strength (>5 MPa) soils were identified at Hamilton, Rugby Park, Te Kowhai and Whatawhata which could limit root elongation. This was not the case for wetter soils, where soil resistance to penetration rarely exceeded 3 MPa. The durability of the subsoiling effect based on penetrometer data, was greatest for the Whatawhata soil followed by the Hamilton, Te Kowhai, Horotiu and Rugby Park soils respectively.

The lateral extent of soil disturbance was greatest in the Whatawhata and Te Kowhai soils, but rarely extended to 40 cm distance from the slot.

On the basis of these results the subsoiler shank spacing should be reduced to 0.8m for effective subsoil coverage. A question often asked by farmers is how long before the need to re-subsoil? Penetrometer data in this study, would suggest, that subsoiling should be rotated on a two to three year cycle depending on soil type.

4.3 INFILTRATION

Table 4.3.1 shows the mean infiltration rates of four replicates, where the standard deviation never exceeded 15% of the mean. The rates were calculated from the time taken to infiltrate one litre of water.

4.3.1 Results

Table 4.3.1

Infiltration rates (mm h⁻¹) at varying distances from the subsoiled slot and at varying times after subsoiling. All measurements were made in December with the exception of the 7 day measurement for Rugby Park (October).

Soil description	Soil moisture%	Number of days following subsoiling	Distance from slot (cm)			
			Slot	21	43	non subsoiled
Hamilton	26	157	8600*	690*	104	84
	27	520	240*	124	75	68
Horotiu	24	6	15900*	1456*	680	540
	22	355	500	520	590	500
Rugby Park	32	7	16700*	1130*	280*	32
	23	80	280*	220*	200*	76
Te Kowhai	28	6	16400*	870*	90	53
	24	355	210*	82	70	68
Whatawhata	27	7	15600*	1020*	160*	42
	24	370	760*	150*	60	54

* significantly different to non-subsoiled (P<0.05)

Table 4.3.1 shows some interesting trends and differences between the five soils in the study. Following Griffith's (1985) adapted permeability classification, infiltration rates for all soils ranged from moderate to very rapid. For non-

subsoiled plots Horotiu infiltrated rapidly compared with moderate rates for the other four soils. Infiltration rates for the subsoiled slot a few days after subsoiling and in the case of Hamilton soil 157 days later, were in effect a function of the width and continuity of the slot formed by the 5 cm thick and 50 cm long subsoiler shank. The results of these measurements are also shown in Figures 4.3.1 - 5.

Table 4.3.1 shows that 157 days after subsoiling, infiltration occurred at 100 x the rate of non-subsoiled plots. One year later the rate was significantly greater, being 3.5 x that of the non-subsoiled plots. At 21 cm distance from slot (157 days), rates were approximately 8 x greater than non-subsoiled, and one year later 2 x greater. There was no difference for measurements taken at 43 cm distance from slot, but unlike the other soils in the study, Hamilton soil was not infiltrated until 157 days after subsoiling, because of inclement weather and because summer infiltration rates, were of interest in this study.

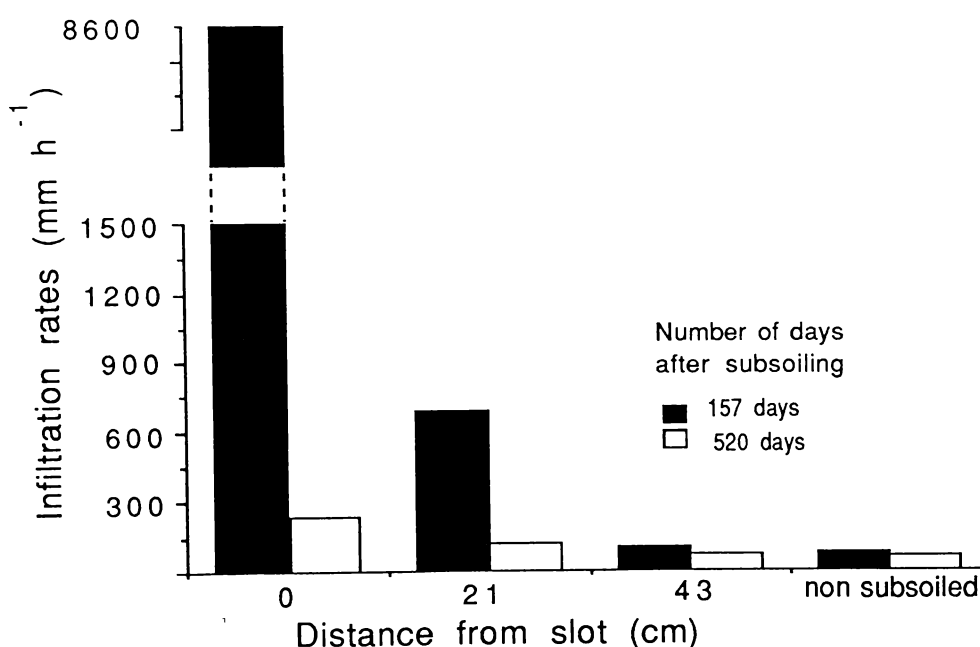


Figure 4.3.1 Hamilton soil, infiltration rates with time.

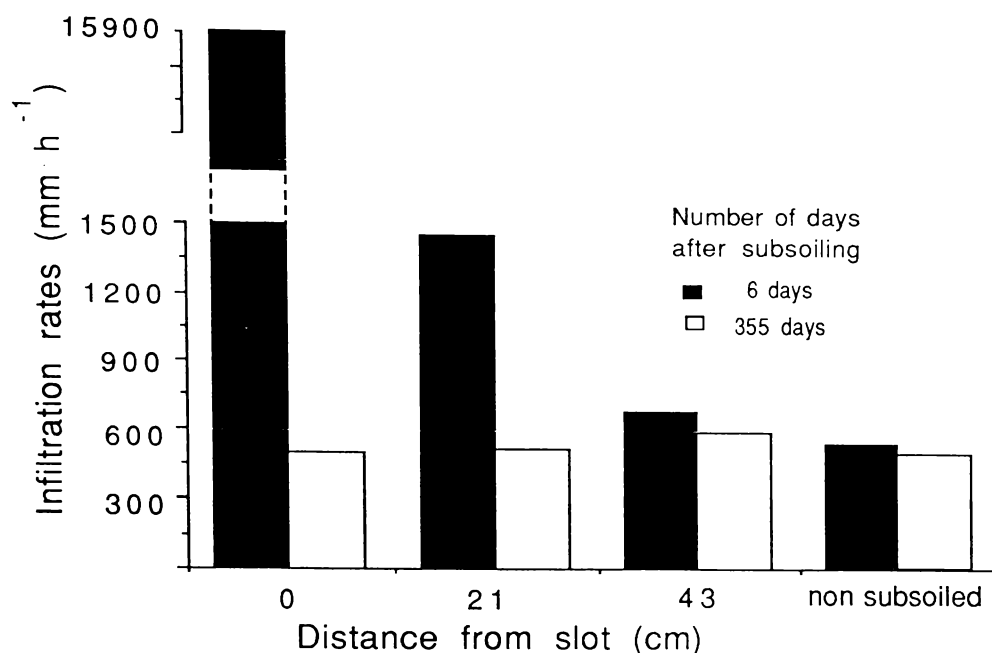


Figure 4.3.2 Horotiu soil, infiltration rates with time.

Table 4.3.1 shows for the Horotiu soil six days after subsoiling infiltration down the slot was about 30 x greater than non-subsoiled plots; one year later there was no difference in rates. At 21 cm distance there was about 3 x faster rate six days after subsoiling; one year later no difference. There was no significant increase at the 43 cm distance.

Table 4.3.1 shows infiltration for the Rugby Park soil in early October, seven days after subsoiling and in December eighty days later; subsequent measurements were not made as the ground was radically aerated in September 1987 one year after subsoiling. Seven days after subsoiling rates were about 500 x greater for the slot profile than non-subsoiled, 35 x for the 21 cm and 9 x for the 43 cm distance from slot profiles. Infiltration of the non-subsoiled plots was twice the rate in December compared to October infiltration, when soil moisture was 32%. Eighty days after subsoiling there was still a significant increase in rates for all subsoiled profiles, when compared with non-subsoiled.

Table 4.3.1 shows the Te Kowhai soil, six days after subsoiling with rates down the slot about 300 x greater than non-subsoiled, at 21 cm about 17 x but at 43 cm there was no significant increase. One year later significantly greater rates were found only down the slot.

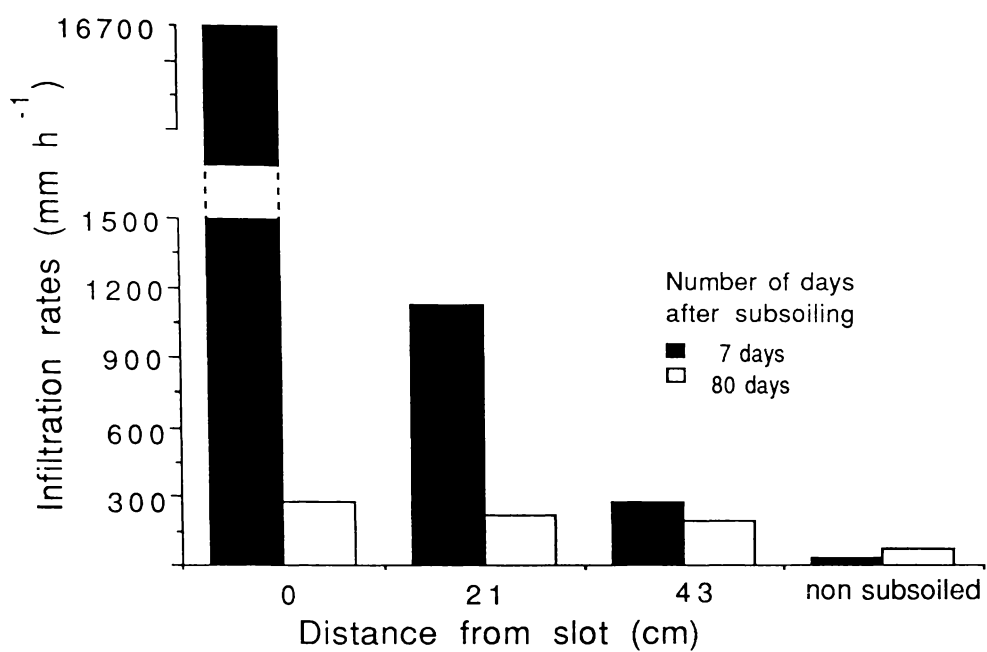


Figure 4.3.3 Rugby Park soil, infiltration rates with time.

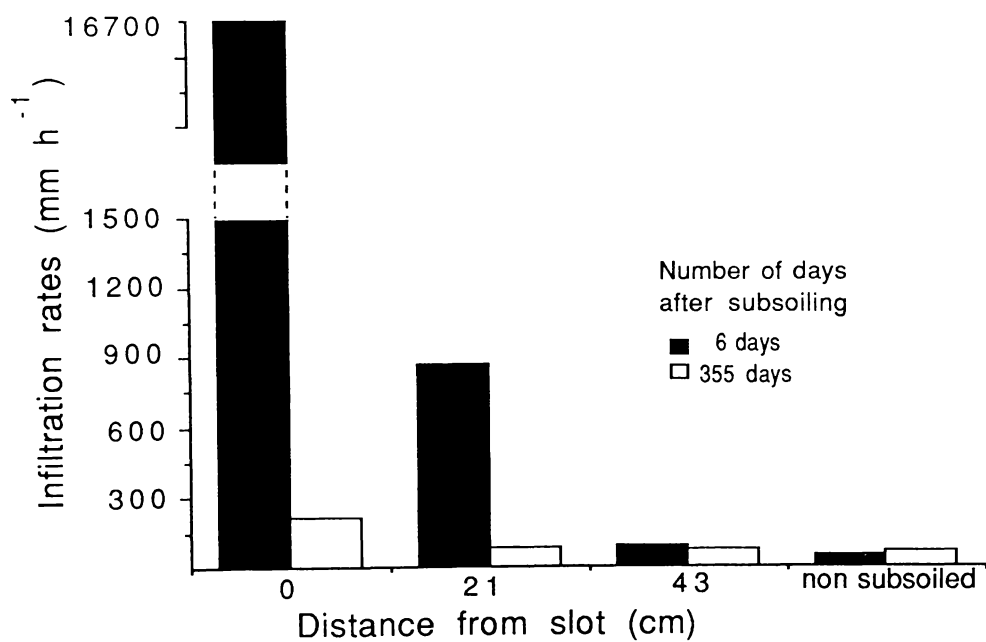


Figure 4.3.4 Te Kowhai soil, infiltration rates with time.

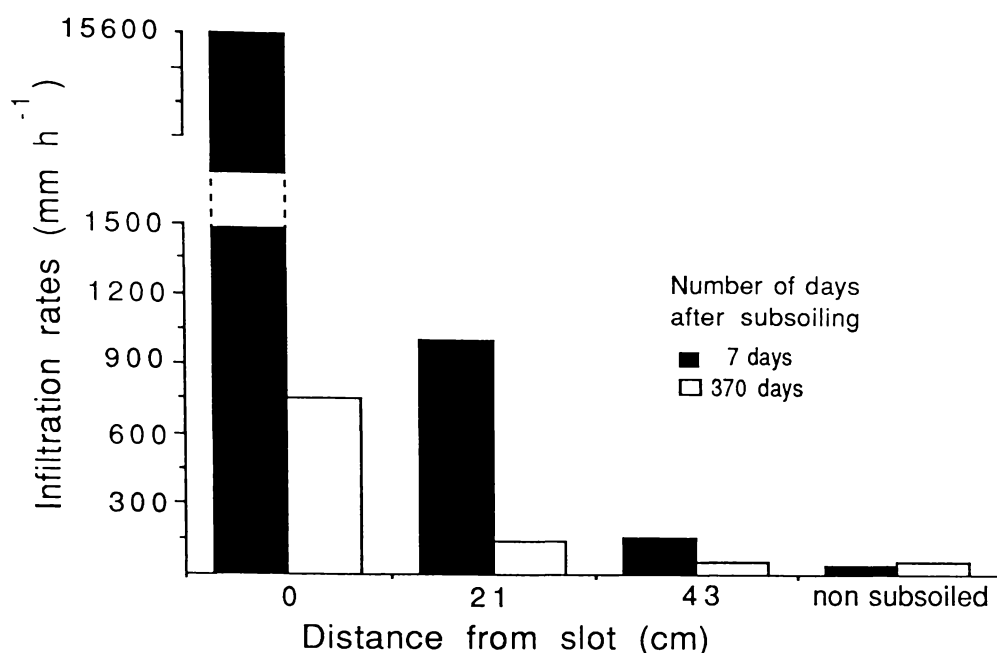


Figure 4.3.5 Whatawhata soil,

Table 4.3.1 shows for the Whatawhata soil, significant increases seven days after subsoiling for the slot and for the 21 cm and 43 cm distance from slot, where the rates were 370, 24 and 4 x greater than the non-subsoiled respectively. These levels had reduced to 14, 3 and 2 x respectively one year later.

4.3.2 Discussion

The five soils as would be expected behave similarly in the slot profile where very rapid infiltration occurs. The rate of infiltration diminishes with time, but is still significantly greater than non-subsoiled plots one year later for all soils, with the exception of the Horotiu soil. Infiltration rates a few days after subsoiling, for the 21 cm distance from slot profile were greatest for Horotiu, which in turn was >Rugby Park >Whatawhata >Te Kowhai. In comparison with non-subsoiled rates, increases were of the order 24, 35, 16 and 3 times for Whatawhata, Rugby Park, Te Kowhai and Horotiu respectively. At the 43 cm distance from slot profile only Rugby Park and Whatawhata showed significant increases. The Hamilton soil could not be compared directly with the other soils, because of different time intervals between measurements. However 157 days after subsoiling very rapid infiltration occurred in the slot profile (8600 mm h⁻¹), suggesting that the slot area was only relatively slowly re-compacting. For the other soils in the study, much re-

compaction and slot closing had occurred; eighty days following subsoiling for Rugby Park, one year for Horotiu, Te Kowhai and Whatawhata soils and seventeen months for the Hamilton soil.

4.3.3 Summary

The results of this study suggest that recently subsoiled soils, have the capacity to intercept and infiltrate rainfall very rapidly. At a sloping site surface water run off will be eliminated. During a high intensity summer storm at the Hamilton site, overland flow was observed on the non-subsoiled plots, but not on the subsoiled area.

The subsoiled slot is a zone where soil physical changes due to subsoiling persist. In the case of the Hamilton and Whatawhata soils and to some extent the Te Kowhai soil this persistence results from a network of semi-permanent structural cracks, which provide longer lasting increased macroporosity and hence greater infiltration rates.

In the case of the Horotiu soil the slot had closed one year after subsoiling. For the other soils the slot had partly closed but there were still significant increases in infiltration. The capacity of subsoiled soils in the Waikato region to infiltrate characteristic intense summer rainfall better than non-subsoiled soils, especially if located on sloping ground where surface run off is prevalent,

Increased soil moisture in the drier summer months, must result in a boost in pasture growth which could realistically be utilised by an increased stocking rate. The durability of subsoiling can also be realistically evaluated through infiltration results. In this study significant increased infiltration for the Hamilton soil occurred in the slot profile seventeen months after subsoiling, when compared with non-subsoiled plots, thus suggesting that the effects of subsoiling had lasted at least that length of time.

4.4 SOIL MOISTURE TENSIONS

Using a quick draw tensiometer readings were taken 10 cm from the subsoiled slots.

Moisture tensions shown in Table 4.4.1 taken from the Hamilton soil on 9/12/87, the day after a summer rainstorm, showed that subsoiled profiles were significantly wetter than non-subsoiled profiles at 10, 30 and 45 cm depths. Measurements taken on 8/8/87 showed no difference in moisture tensions, between subsoiled and non-subsoiled plots.

There was no difference in values for the Horotiu soil, between subsoiled and non-subsoiled plots.

Moisture tensions at Rugby Park measured on the 20/10/86 were significantly higher for subsoiled plots. Measurements taken on 15/6/87 showed no difference for the two treatments.

Soil moisture tensions taken on the 21/12/87 on the Te Kowhai soil showed differences between subsoiled and non-subsoiled plots, at all depths. A 40 mm rainstorm had been recorded on the 20/12/87. Measurements taken on 17/7/87 showed no difference between the two treatments.

Moisture tensions on the Whatawhata soil on 17/7/87 were significantly higher for the subsoiled plots, than non-subsoiled plots. Measurements taken on 9/12/87, the day after a summer rainstorm, showed that at the 10 and 45 cm depth, moisture tensions were significantly lower than for corresponding non-subsoiled depths.

Table 4.4.1 Moisture tensions (kPa) for subsoiled and non-subsoiled plots at various times of year. Values are expressed as means of 20 readings, at 10 cm.

Soil type	Sample date Months after subsoiling ()	Measurement Depth (cm)	Non-subsoiled	Subsoiled
Hamilton	8/8/87 (1)	10	10.9	11.7
		30	8.9	10.0
		45	7.9	8.9
	9/12/87 (5)	10	44.6	17.8*
		30	35.5	19.9*
		45	31.6	21.8*
Horotiu	17/7/87 (7)	10	19.9	21.8
		30	42.6	44.7
		45	16.9	17.8
	20/11/87 (11)	10	56.2	53.7
		30	42.6	44.6
		45	39.8	41.7
Rugby Park	20/10/86 (0)	10	30.9	40.7*
		30	26.9	38.0*
		45	26.9	36.3*
	15/6/87 (8)	10	26.9	25.7
		30	22.9	24.0
		45	20.9	21.8
Te Kowhai	17/7/87 (7)	10	13.8	17.7*
		30	10.9	11.7
		45	10.9	10.9
	21/12/87 (12)	10	34.6	20.9*
		30	24.0	15.8*
		45	18.6	13.8*
Whatawhata	17/7/87 (7)	10	7.9	13.8*
		30	10.0	17.0*
		45	12.8	22.9*
	9/12/87 (12)	10	41.7	27.5*
		30	24.0	26.9
		45	17.8	28.8*

* significantly different to non-subsoiled at corresponding depths ($P < 0.05$)

4.4.1 Discussion

Differences in soil moisture tensions due to subsoiling were recorded for the Hamilton, Rugby Park, Te Kowhai and Whatawhata soils, but not for the Horotiu soil. Although tensions were measured 10 cm distance from subsoiled slots, it was apparent from this study that the slots influenced drainage in winter and rainfall absorption in summer. The Whatawhata soil seemed to derive the greatest benefit in this respect, being drier in winter and wetter at 10 and 45 cm depth after a summer rainstorm. The subsoiled Hamilton soil situated on a 10° slope probably benefited most from an intense summer rainstorm, due to increased infiltration as the subsoiled slot area was able to intercept surface water.

A probable reason why the subsoiled Whatawhata soil was relatively drier (higher tensions) in winter than the Te Kowhai soil can be explained by drainage characteristics. The Whatawhata and Te Kowhai subsoiled plots were linked to existing open drainage systems as discussed (Chapter 3.3) and therefore had the capacity to drain faster than non-subsoiled plots. Te Kowhai soils in winter are often saturated, with the water table on or near the surface. This was the case in this study and therefore as could be expected moisture tensions were not significantly higher for subsoiled plots when compared with non-subsoiled plots. The site at Whatawhata although relatively poorly drained did not experience surface ponding and therefore subsoiled plots were relatively drier in July 1987 than non-subsoiled plots, probably because the subsoiled slots provided a relatively fast route for "excess" soil moisture to drain away. These relatively small but significant changes could probably influence pasture management at critical times of year for pasture utilization.

4.5 SOIL MOISTURE LOSS AS A RESULT OF SUBSOILING WITH AND WITHOUT ROLLERS

Table 4.5.1 Soil moistures percent by weight, with and without rollers. Samples taken at 4 - 10 cm depths and various distances from subsoiled slot, five days after subsoiling.

Soil type	Date	Distance from subsoiled slot (cm)									
		slot	Rollers				slot	No rollers			
			10	20	30	40		10	20	30	40
Hamilton clay loam	11/12/87	20*	24*	26*	30	30	16	18	21	29	32
Horotiu sandy loam	15/12/87	18*	25*	25*	30	29	16	18	20	27	29

*significantly wetter ($P < 0.05$) from subsoiling with rollers, when compared with subsoiling without rollers.

Table 4.5.1 and Figures 4.5.1 - 2 show for the Hamilton and Horotiu soil there was a significant difference in soil moistures between the two treatments. Without rollers there was significant moisture loss from the side of the slot and for the 10 and 20 cm distance from slot respectively. There was however no difference between treatments for the 30 and 40 cm distance from slot profiles for both soils.

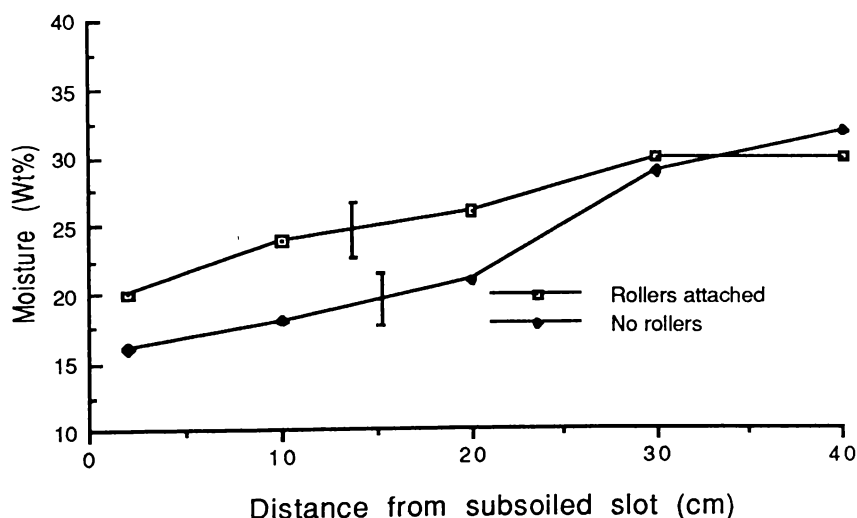


Figure 4.5.1 Hamilton soil, soil moisture changes with distance. LSD ($P = 0.05$)

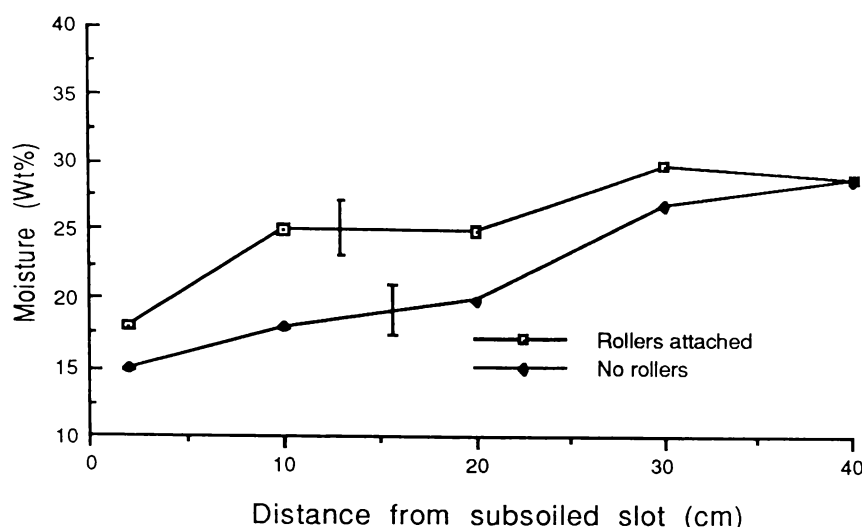


Figure 4.5.2 Horotiu soil, soil moisture changes with distance. LSD ($P = 0.05$)

4.5.1 Discussion

The two soils reacted similarly to the treatments. Soil moisture lost through accelerated evaporation in and around the slot was reduced by roller treatment and risk of pasture wilting was avoided. The loss of pasture may not be acceptable and therefore on the basis of this rollers were attached as a standard feature. Nevertheless subsoiling during the summer months may result in soil moisture loss and subsequent loss of pasture.

4.6 SURFACE SOIL VOLUME CHANGES IN RESPONSE TO NARROW AND WIDE SUBSOILER TIPS AND IN THE CASE OF THE TE KOWHAI SOIL, AN EVALUATION OF AN INTERMEDIATE TIP

In this study, penetrometer and gamma probe measurements were used to quantify the extent of subsurface soil disturbance resulting from vibrating subsoiling. It has been shown that soil bulk density and soil strengths are lowered when the soil is subsoiled hence soil volume must have increased. Much of this volume increase must occur at or near the ground surface. To test this assumption the heaveometer was

used to calculate the extent and volume of surface heave in response to the standard narrow (10 cm) and wide (40 cm) tips plus a 22 cm wide intermediate tip.

Five locations per soil site were subsoiled in the vibrating mode, along twenty metre transects, with various tips, operating at various depths. A one metre shank spacing was used for all treatments.

4.6.1 Results

Percentage increase was calculated from the cross sectional area of the heaved ground in relation to the total potential subsoiled area, which in the majority of cases was 0.45 m depth x 1.0 m width of operation. The increase is expressed as a volume assuming a 1 m length of soil.

Figures 4.6.1 - 6 show the mean of five heaveometer readings per site, centred on the subsoiler shank. Table 4.6.1 shows the volume increase for different soils, tip sizes and operating depths.

Table 4.6.1 Increase in surface soil volume expressed as a percent of total soil volume treated.

Soil description	Soil Moisture weight %	Operating depth (cm)	Tip size	% increase in soil volume
Hamilton	19	40	narrow	6.75
	19	40	wide	9.75
Horotiu	20	40	narrow	3.40
	20	40	wide	5.22
Rugby Park	25	35	wide	8.68
Te Kowhai	18	40	narrow	4.82
	18	50	narrow	1.76
	19	45	narrow	3.95
	19	45	intermediate	4.44
	19	45	wide	5.60
Whatawhata	21	45	narrow	5.9
	21	45	wide	10.0

In all cases the wide tip gave the greater volume. For the Hamilton soil, wide tip treatment, gave a 44% increase in near surface soil volume when compared with narrow tip. Maximum heave heights of 8 cm and 6 cm were recorded for wide and narrow tips respectively. Ground disturbance extended approximately 42 cm to either side of the slot for wide tip and 36 cm for narrow tip (Figure 4.6.1).

For the Horotiu soil Table 4.6.1 shows wide tip treatment created a 53% increase when compared with narrow tip. Ground surface expression was limited to approximately 26 cm and 32 cm either side of the subsoiler shank for the narrow and wide treatment respectively. (Figure 4.6.2). Maximum heave heights of approximately 5 and 4.5 cm were recorded for the wide and narrow tips respectively.

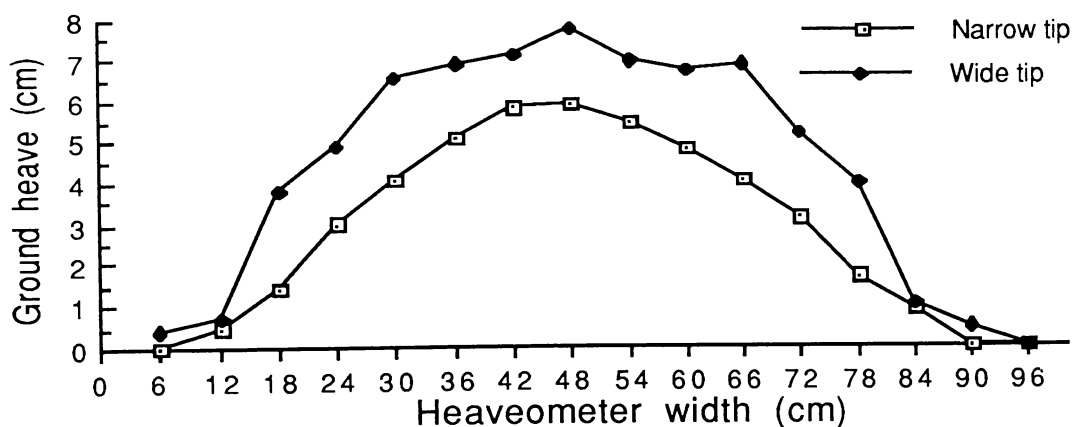


Figure 4.6.1 Hamilton soil, surface heave for narrow and wide tips.

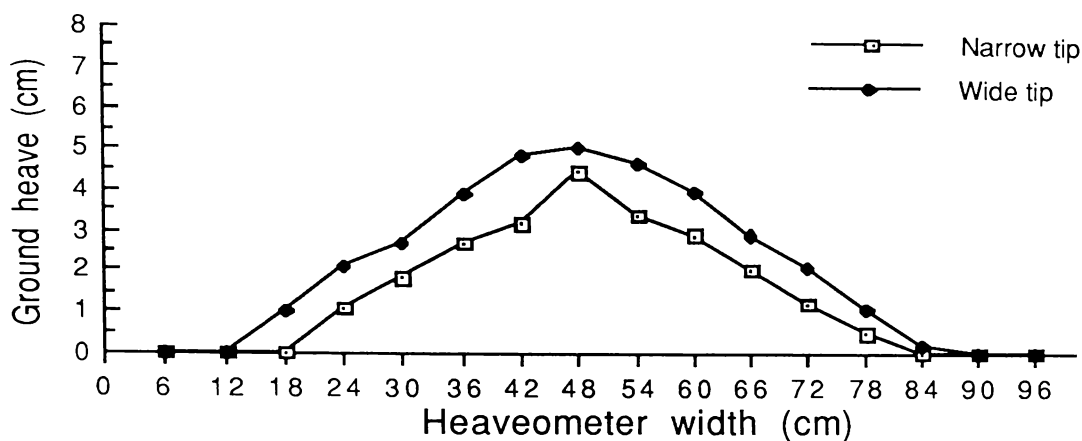


Figure 4.6.2 Horotiu soil, surface heave for narrow and wide tips

A comparison of wide versus narrow tip treatment was not made at Rugby Park due to a mechanical breakdown. Heave extended approximately 38 cm to either side of the slot (Figure 4.6.3), representing 76% of the total ground surface under treatment. Although the soil was more moist than the other soils the heave response (Table 4.6.1) was not significantly different from other wide tip treatments. Maximum heave height of approximately 6 cm (Figures 3.5.6, 4.6.3) was also similar to that recorded for other soils.

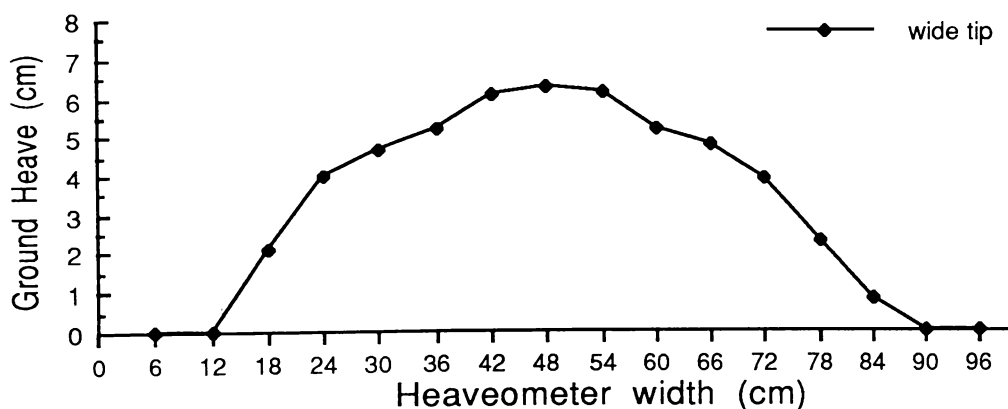


Figure 4.6.3 Rugby Park soil, surface heave for wide tip.

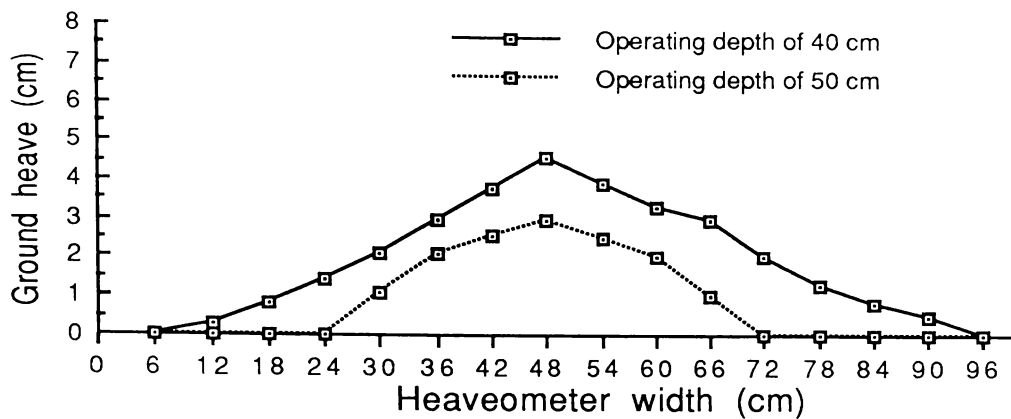


Figure 4.6.4 Te Kowhai soil, surface heave for two operating depths.

The Te Kowhai site was used to compare three tip sizes and the effect of two operating depths, 40 and 50 cm. Table 4.6.1 and Figure 4.6.4 show that the shallower depth resulted in a 174% increase in volume. Figure 4.6.4 shows maximum heights reaching 4.75 and 3 cm for the 40 and 50 cm operating depths respectively. The 40 cm operating depth also disturbed more of the ground surface. Percentage increases in volume of 3.95, 4.44 and 5.60% were recorded for the narrow, intermediate and wide tips respectively. Figure 4.6.5 shows ground heave was greatest for the wide tip, with a maximum height of 5.5 cm. Maximum height for the intermediate and narrow tips were 5 cm and 4.5 cm respectively. Surface heave area increased by 12% for the intermediate tip and 42% for the wide tip over the narrow tip.

The difference between narrow and wide tip was 70% for the Whatawhata soil. Figures 4.6.6 shows that for the narrow tip treatment the maximum was 6.5 cm compared with 7.5 cm for wide tip. The wide tip treatment resulted in a significantly broader hump and surface disturbance extended 42 cm to either side of the slot compared with 36 cm for the narrow tip.

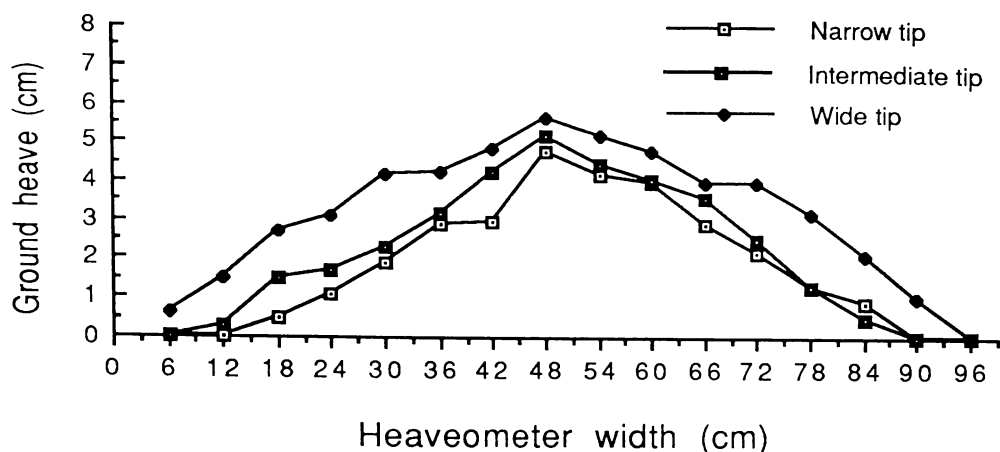


Figure 4.6.5 Te Kowhai soil, surface heave for three tips

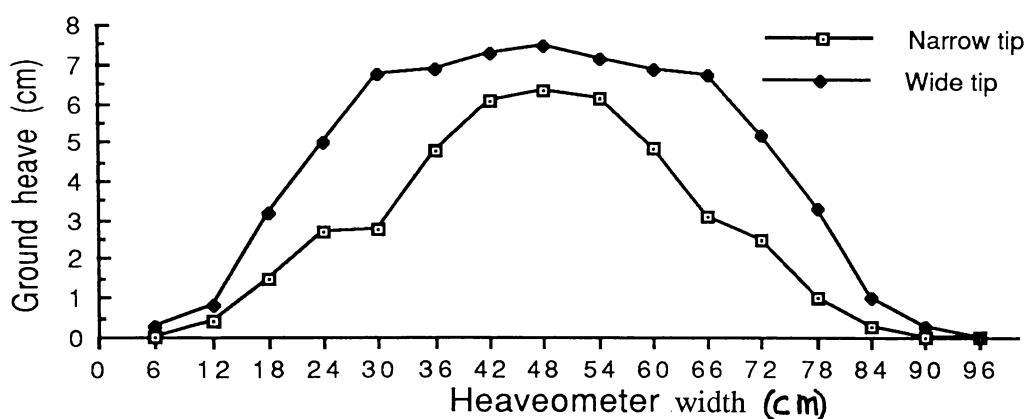


Figure 4.6.6 Whatawhata soil, surface heave for narrow and wide tips

4.6.2 Discussion

Based on heaveometer measurements, the extent of surface heave both vertically and laterally is dependant on operating depth, tip size and soil type.

Wide tips created greatest heave for all soils and in the case of the Te Kowhai soil an intermediate tip produced an intermediate result. All treatments created a hump and swale effect, although the humps were less extensive and lower for the narrow tip.

Under similar soil moisture conditions wide tip treatment caused most surface disturbance for the Whatawhata soil, followed by Hamilton and Rugby Park with Horotiu and Te Kowhai responding least. A similar trend is seen for narrow tip

treatment, albeit at a much lower level. A possible reason for the soil response excluding tip size could be attributable to such soil physical characteristics as soil texture and structure. Both Hamilton and Whatawhata soils have more clayey B horizons than the other three soils. They also exhibit coarser blocky, prismatic structures than the other soils. These two major physical differences may be responsible for increased soil heave, in that the relatively large aggregates found in these soils are forced upwards by the action of subsoiling and thus displace a larger volume of soil than soils such as Horotiu which have a fine granular structure.

The treatments on the Te Kowhai soil suggests that deeper subsoiling can reduce surface heave. Te Kowhai results indicate that even under dry soil conditions operating at depths greater than 45 cm may not produce optimum soil disturbance.

The relationship between surface heave and a reduction in bulk density will be discussed in Chapter 7. The heaveometer results also suggest that shank spacing is too wide under the conditions that the machine was tested. Closer shank spacing would probably reduce the hump and hollow effect by leaving a more level ground surface. Further elaboration on machine design will be discussed later (Chapter 7).

4.7 SOIL DISTURBANCE AS A CONSEQUENCE OF SUBSOILING

This chapter will attempt to quantify the differences in soil disturbances, between vibrating and non-vibrating treatments and between narrow and wide tips at various soil moistures and depths. Results are calculated from bulk density, cone index and heaveometer data.

4.7.1 Results

Table 4.7.1 Soil disturbance for different treatments, calculated from Figures 4.7.1-9

Soil type	Soil moisture % w/w	Operating depth (cm)	Cross sectional soil disturbance % of total **		%increase due to vibrating	Subsoiler tip size
			Nonvibrating	Vibrating		
Hamilton clay loam	18	45	21	30	42*	Narrow
	18	45	41	56	36*	Wide
	38	45	14	16	14	Narrow
	38	45	23	30	30*	Wide
	38	37	18	20	11	Narrow
	38	37	29	41	41*	Wide
	38	30	25	28	12	Narrow
	38	30	34	49	44*	Wide
Horotiu sandy loam	21	45	20	27	35*	Narrow
	21	45	42	50	19*	Wide
Rugby Park soil	27	45	20	30	50*	Narrow
	27	45	45	54	20*	Wide
Te Kowhai silt loam	21	45	18	27	50*	Narrow
	21	45	38	45	18*	Wide
	36	45	16	22	37*	Narrow
	36	45	24	36	50*	Wide
	36	35	22	35	60*	Narrow
	36	35	40	62	51*	Wide
Whatawhata clay loam	19	45	24	31	29*	Narrow
	19	45	47	61	29*	Wide

*significance ($P < 0.05$)

** cross sectional percentages were calculated from the total possible area that could be realistically treated. The total area was calculated from the shank spacing of the machine and operational depth.

For a two shank subsoiler set at one metre spacing, operating at 45 cm depth, with a one-metre gap between passes, the maximum treatable cross-sectional area is 0.9 m². The following figures (4.7.1 - 4.7.9) are centred on one shank and were calculated from data shown in Table 4.7.1 from penetrometer and heaveometer information and from profile inspection.

The **Hamilton** soil under dry conditions (18%), responded differently for the two treatments. The non-vibrating treatment (narrow tips) resulted in 21% of the soil being disturbed, this increased to 30% for the vibrating treatment, representing a significant 42% increase. The wide tip treatment resulted in 41% soil disturbance for non-vibrating, increasing to 56% for the vibrating treatment, representing a 36% increase (Figures 4.7.1, 4.7.2).

Under wetter soil conditions (38% moisture), at the same working depth of 45cm there was virtually no surface heave, for both the narrow and wide tip treatments. (Figures 4.7.3, 4.7.4). Soil disturbance was limited to the area around the tip, with some soil fracturing upwards at a steep angle (70°) towards the surface. Table 4.7.1 shows that in this case vibrating did not significantly change soil disturbance for the narrow tip size but did for the wide tip. At a shallower working depth (37 cm) under the same moisture conditions (38%), there was increased soil disturbance for both treatments. Increases in soil disturbance for the 30 cm operating depth, where appreciable surface heave was measured, extended approximately 30 and 25 cm to either side of the subsoil slot, for the wide and narrow tip respectively. The angle of disturbance emanating from the tip is lowered for the shallower operating depths, to approximately 45°.

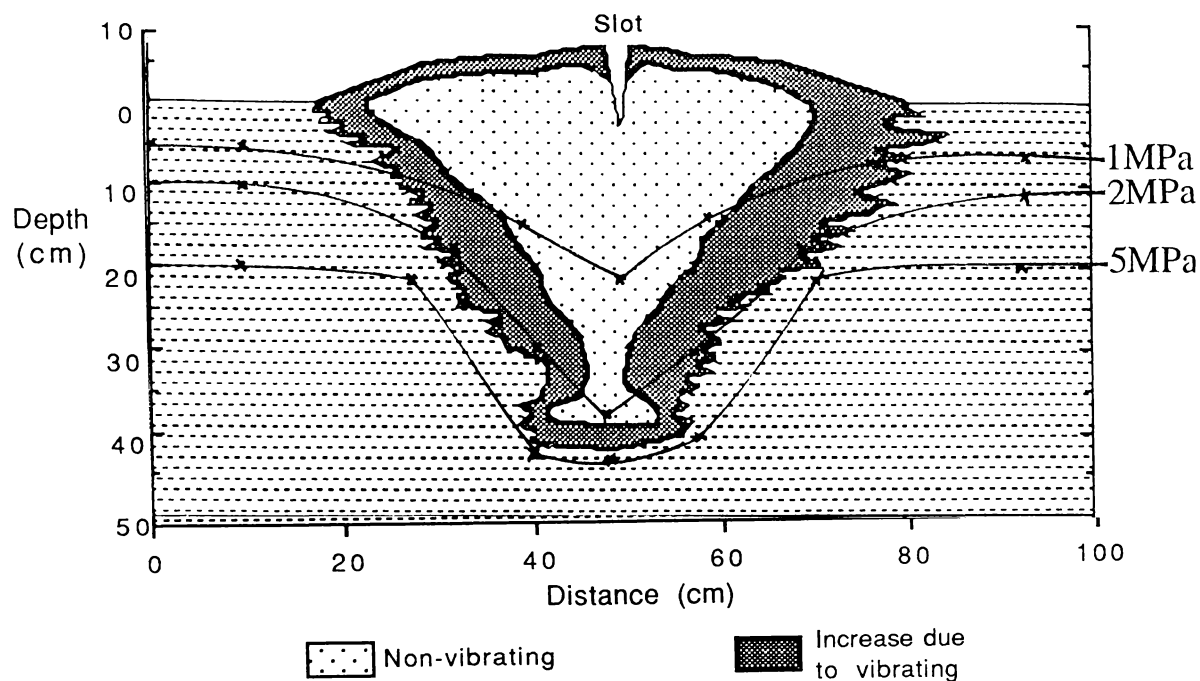


Figure 4.7.1 Hamilton soil, disturbance for narrow tip, 18% moisture.

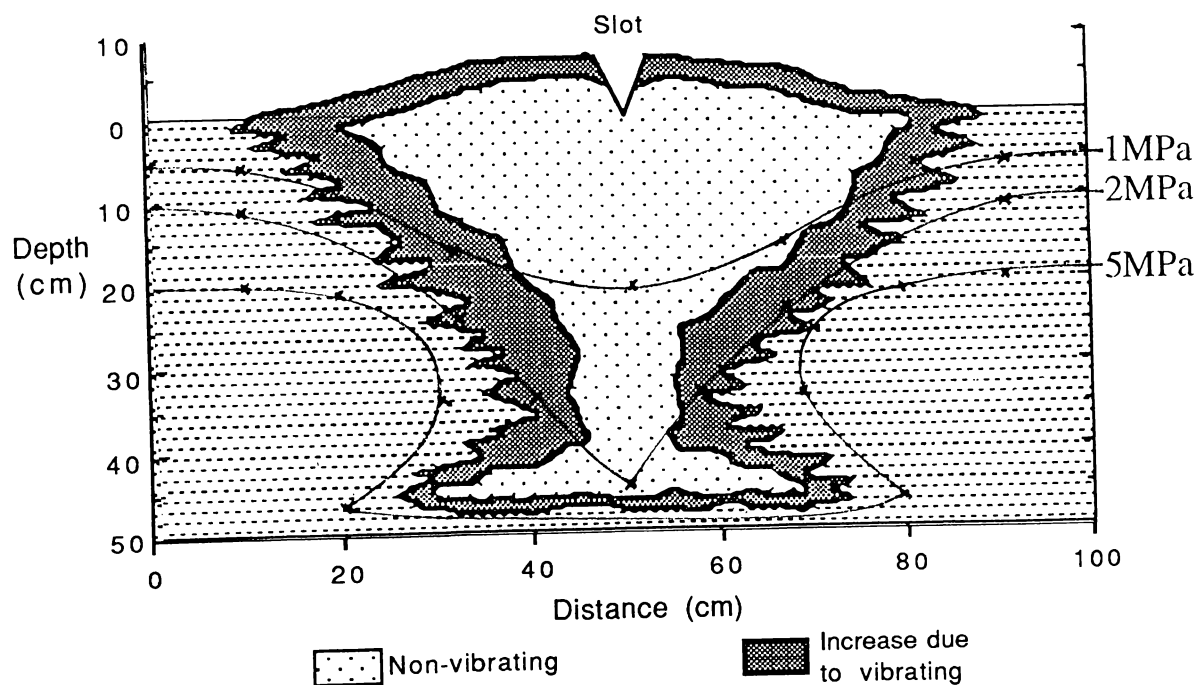


Figure 4.7.2 Hamilton soil, disturbance for wide tip, 18% moisture

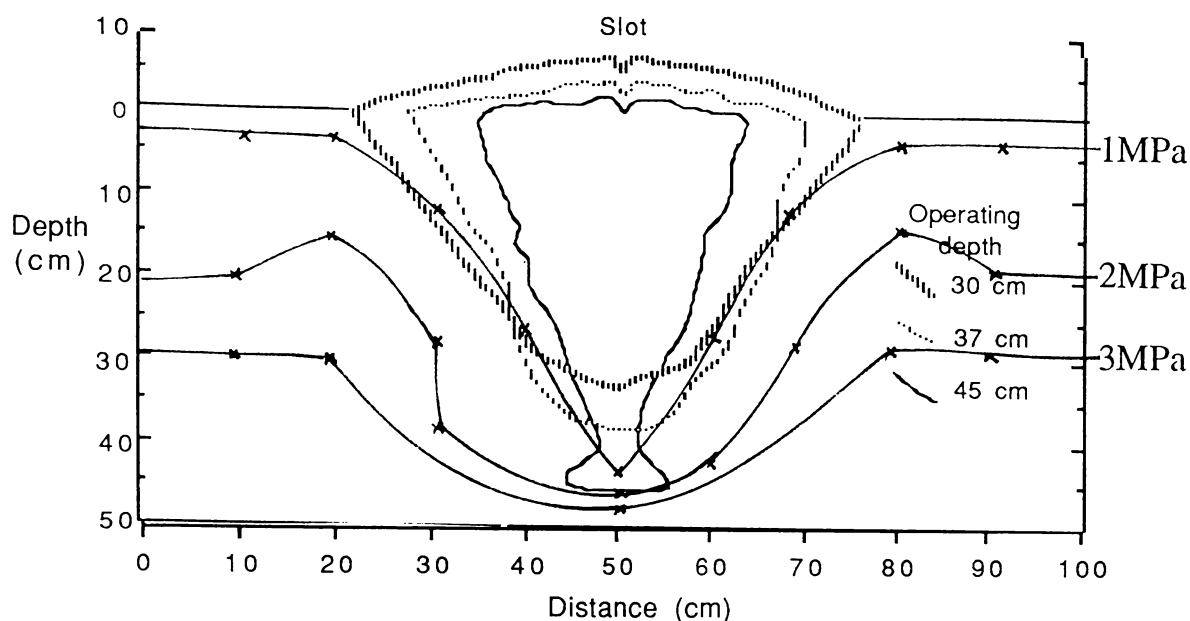


Figure 4.7.3 Hamilton soil, disturbance for three operating depths, narrow tip vibrating, 38% moisture.

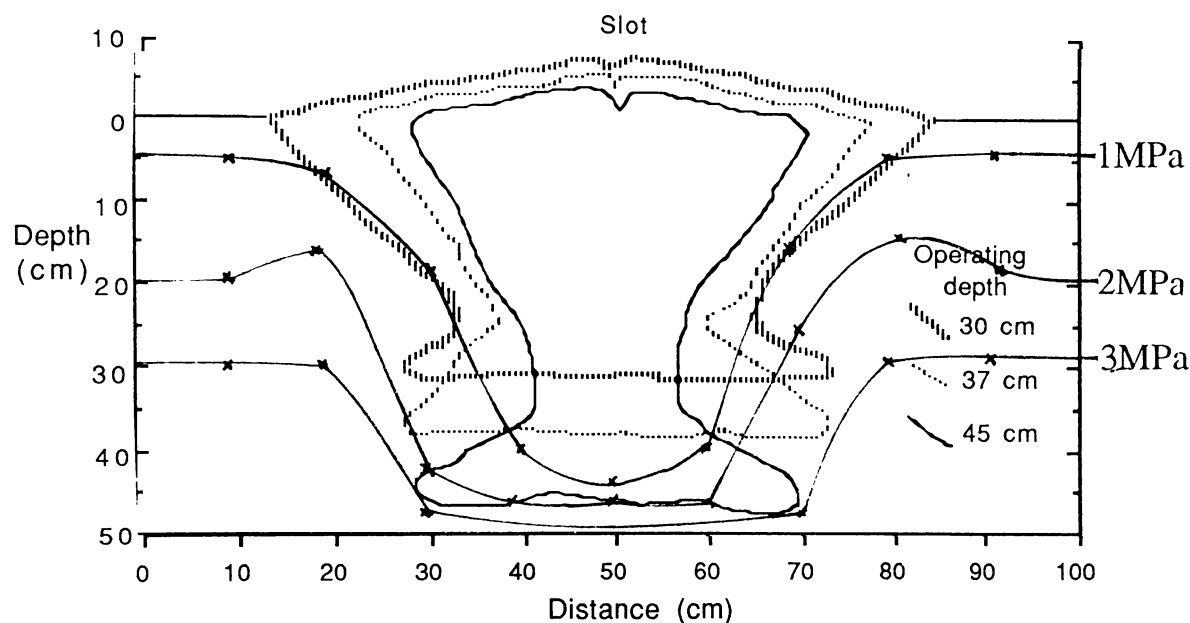


Figure 4.7.4 Hamilton soil, disturbance for three operating depths, wide tip vibrating, 38% moisture.

Table 4.7.1 shows for the **Horotiu** soil vibrating resulted in a 35% and 19% increase in soil disturbance for the narrow and wide tips respectively. Figure 4.7.5 shows the distinctive wedge shaped disturbance at around the 45 cm working depth. The area of disturbance is constricted at 35 cm depth, but then extends upwards towards the surface at a 65° angle. Surface heave extends to 30 cm either side of the subsoiled slot for the wide tip and 20 cm for the narrow tip.

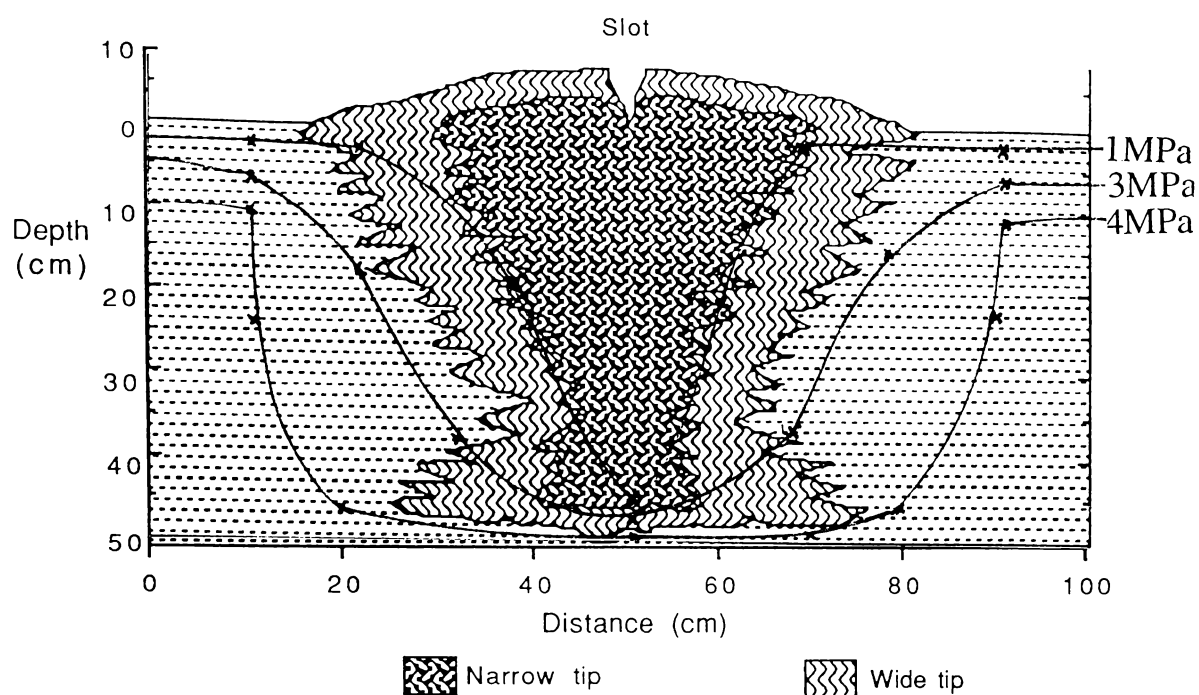


Figure 4.7.5 Horotiu soil, disturbance for narrow and wide tip vibrating, 21% moisture.

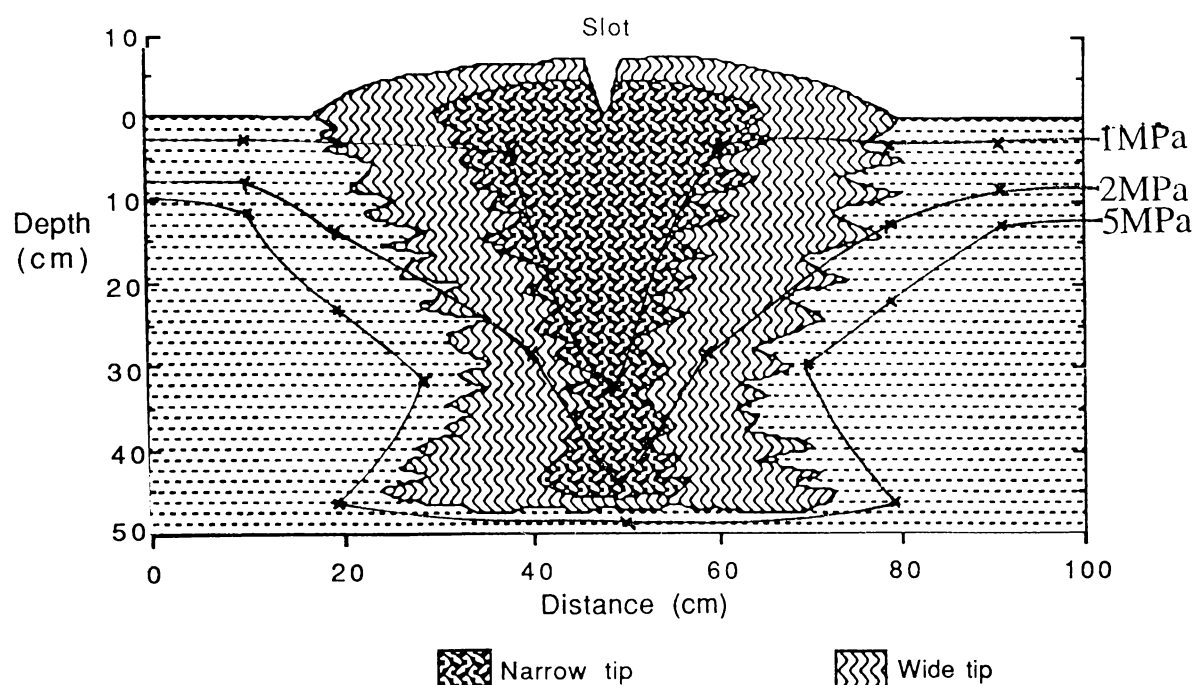


Figure 4.7.6 Rugby Park soil, disturbance for narrow and wide tip vibrating, 27% moisture

Rugby Park soil responded much like the other soils (Table 4.7.1), wide tip treatment resulted in a 125% increase in soil disturbance, in comparison with the narrow tip treatment in the non-vibrating mode. Vibrating treatment resulted in

50% and 20% increases respectively for the narrow and wide tips, when compared with non-vibrating treatment.

Table 4.7.1 shows that at 21% moisture **Te Kowhai** soil responded similarly to the other soils in the trial. Wide tip vibrating treatment resulted in the greatest soil disturbance (45%). However disturbance was significantly less (36%) at 36% soil moisture for the 45 cm depth treatment. There was 62% disturbance for the 35 cm operating depth using a wide tip in the vibrating mode.

Figure 4.7.8 shows that under wetter soil conditions (36%), this soil “behaved” similarly to the Hamilton soil, in that disturbance was greatest at a shallower operating depth of 35 cm, where disturbance under vibrating mode increased by 60% for the narrow tip, when compared with an operating depth of 45 cm.

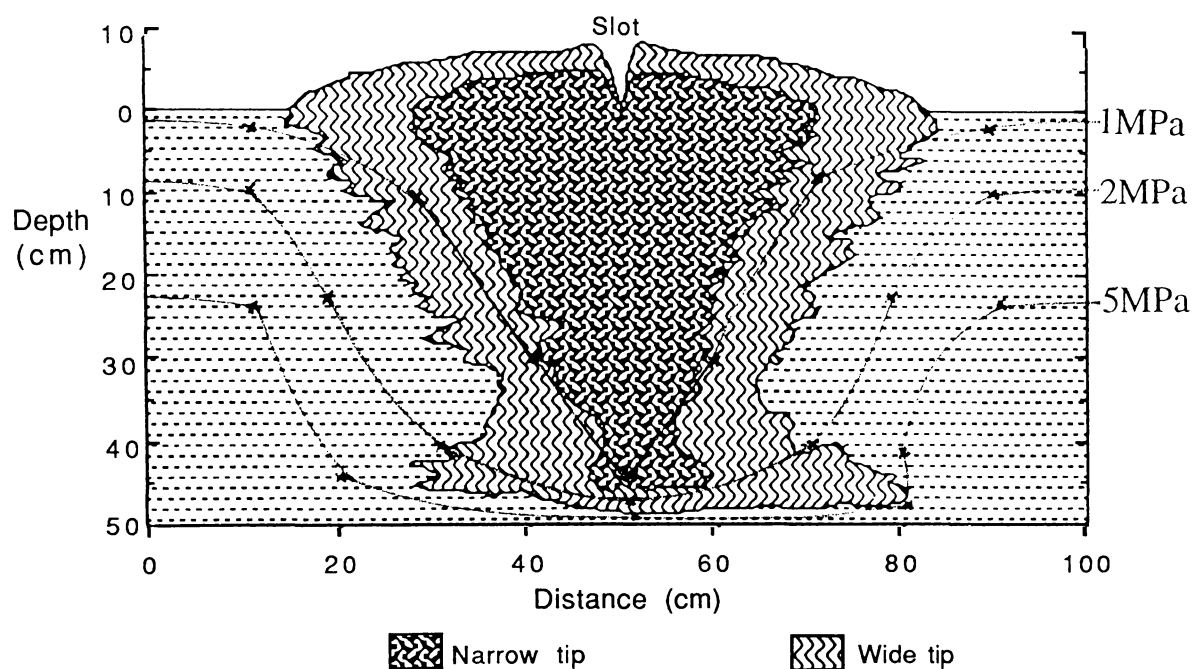


Figure 4.7.7 Te Kowhai soil, disturbance for narrow and wide tip vibrating, 21% moisture.

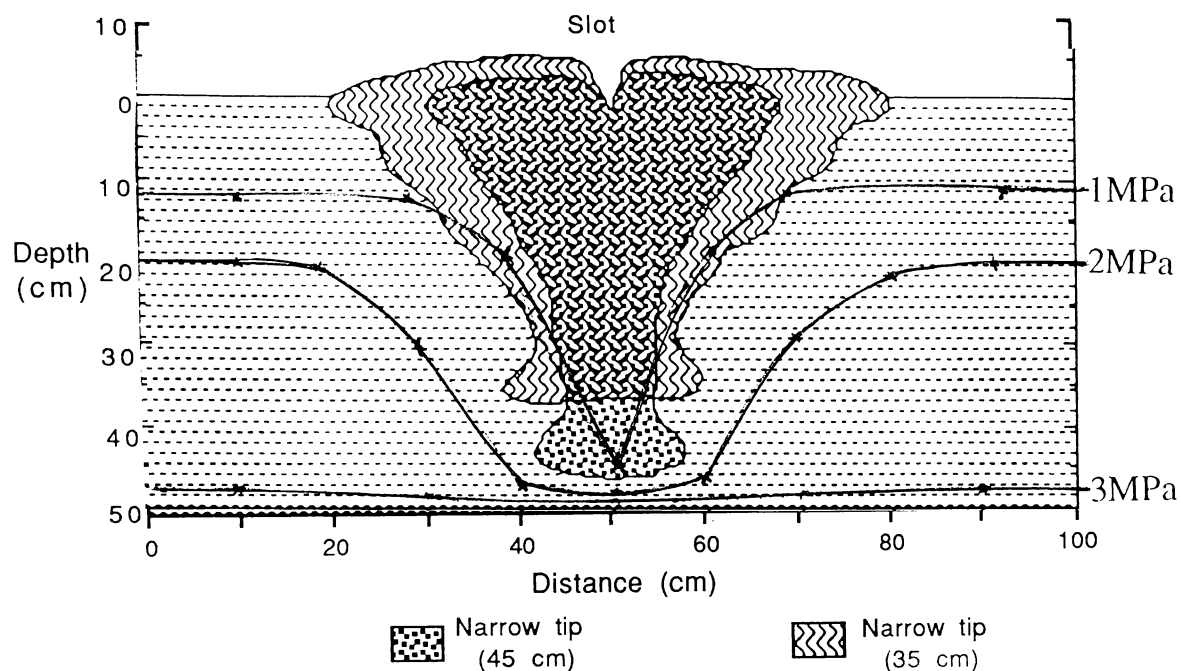


Figure 4.7.8 Te Kowhai soil, disturbance for two operating depths, narrow tip vibrating, 36% moisture.

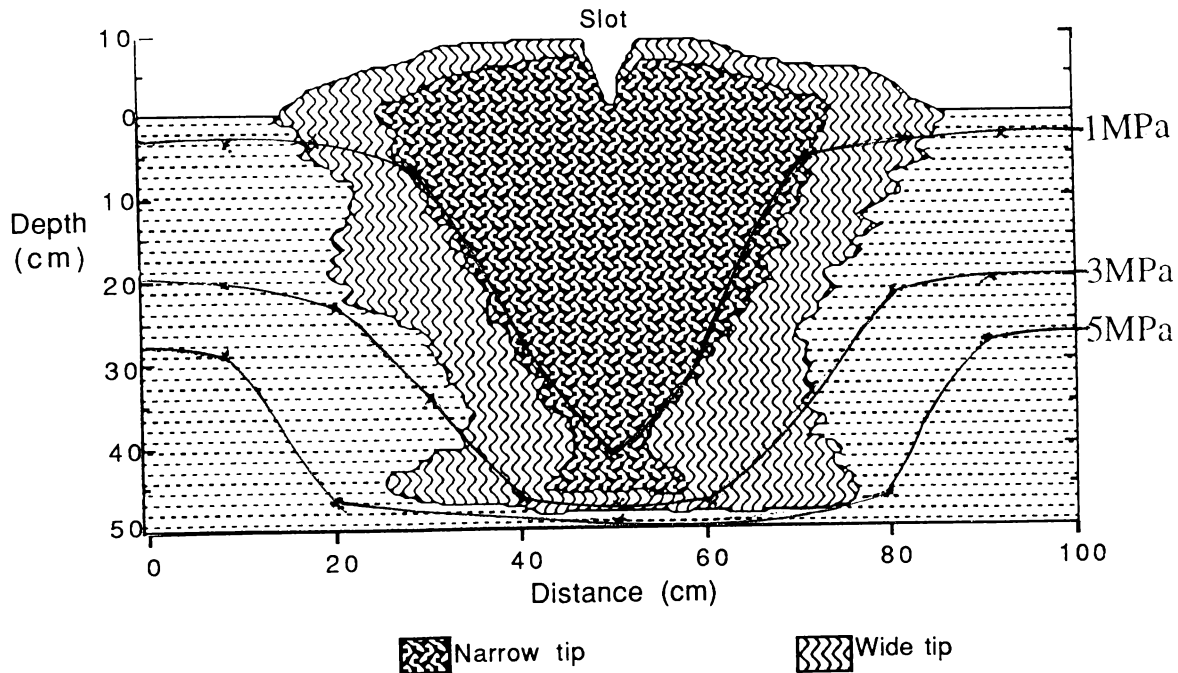


Figure 4.7.9 Whatawhata soil, disturbance for narrow and wide tip vibrating, 21% moisture.

Table 4.7.1 shows the **Whatawhata** soil subsoiled in the wide tip vibrating mode had 61% of soil disturbed, which was an increase of 29% when compared with the non-vibrating treatment. The vibrating treatment resulted in a 100% increase for the wide tip when compared with the narrow tip. When compared with other soils Figure 4.7.9 shows a larger area of disturbance around the 35 - 45 cm depth and also the angle of fracturing emanating from the tip area extends upwards at a relatively steep angle of 60°.

4.7.2 Discussion

Figures 4.7.1 - 9 and Table 4.7.1 indicate that the extent of soil disturbance through subsoiling is influenced markedly by size of subsoiler tip, vibrating action, soil moisture and operating depth.

The vibrating wide tip operating at 45 cm depth under relatively dry soil conditions created the largest volume of soil disturbance. Disturbance was greatest for the Whatawhata soil followed by Hamilton, Rugby Park, Horotiu, and Te Kowhai soils. Under these conditions up to 75% of the near surface soil was disturbed; this compares with only 60% disturbance for the narrow tip treatment. Vibrating wide tips also created distinctive soil shatter around the tip and shank which in the case of the Whatawhata soil resulted in 2.5 x increase in soil disturbance when compared with non-vibrating narrow tip treatment. Vibrating tips resulted in up to 60% increase in soil disturbance when compared with non vibrating tips. Generally wet soils cannot be subsoiled because of wheel slippage. However the Hamilton and Te Kowhai soils were subsoiled at 38% and 36% soil moisture respectively. The results suggested that under these conditions subsoiling at 45cm depth is too deep, with little surface heave and minimal soil disturbance. In this case, subsoiling at 30 - 35 cm resulted in a 100% increase in near surface disturbance, when compared with subsoiling at 45 cm depth. Increased soil moisture therefore has the effect of lowering subsoiler efficiency. However, subsoiling at shallower depths can increase efficiency by disturbing surface soils, but soil deeper than 30 - 35 cm is unaffected.

One metre shank spacing, did not achieve 100% soil disturbance, suggesting that shank spacing should be reduced.

Wide tips as discussed, create greater soil disturbance when compared with narrow tips. However wide tips also require more tractor power and they also leave a more pronounced “humpy” ground surface.

4.7.3 Summary

Under relatively dry soil conditions the mean disturbance percentages for wide and narrow tips, show that Whatawhata soil is most affected with 40.7%, followed by Rugby Park 37.2%, Hamilton 37%, Horotiu 34% and Te Kowhai 32%.

Vibrating treatment (41.1%) was more effective than non-vibrating (31.6%) and wide tips (47.9%) much better than narrow tips (24.8%).

When soils were wetter, shallower operating depths were clearly more effective with disturbance for the Hamilton soil being 20.7% at 45 cm depth increasing to 34% at 30 cm depth. The Te Kowhai soil followed a similar trend, with an increase from 24.5 to 39.7% for operating depths of 45 to 35 cm respectively.

Subsoiling under dry soil conditions results in better soil disturbance than under wetter conditions. For Hamilton at 18% moisture, 37% disturbance compared with 20.7% disturbance for soil moisture of 38%. This was also the case for Te Kowhai soil, where soil disturbance for 21% moisture was 32% compared with 24.5% disturbance for 36% moisture.

4.8 ROOT ELONGATION

Results from measurements of root length on 7/7/87, 90 days after subsoiling at Whatawhata are given in Table 4.8.1

Table 4.8.1 Maximum rooting depth (cm) of ten plants of Matua Prairie grass, taken from 10 cm distance from subsoiled slot.

Plot number	Non-subsoiled	Subsoiled
1	25	31*
2	22	28*
3	24	30*
4	22	27*

*significant (P<0.05) SD = 3.56

4.8.1 Discussion

Plant roots growing within a 10 cm band on either side of the subsoiled slots were significantly longer than roots from non-subsoiled plots. The increase in root length was clearly observed when recovering the plants to be measured. Plant roots could be seen extending down into the trough shaped disturbed soil area, formed by the passage of the vibrating subsoiler shanks and tip (Figure 3.6.6). The average 5.75 cm increase represents a 25% increase in root length and although root volumes were not quantified an idea of the difference can be seen (Figure 3.6.2). As reported earlier, subsoiling at Whatawhata significantly reduced soil bulk density by 25% and soil strength by 56%, in the 20 to 40 cm depth layer. This fact probably facilitated root elongation down into the previously impenetrable compacted and high strength subsoil layer, hence longer roots were found growing in these treated areas. The Whatawhata subsoiled plots showed a significant increase in pasture production (Table 4.9.1). In this case longer roots resulted in an increase in yield. Although these findings were admittedly for only one soil and were of short duration, they are nevertheless a significant factor of which future grassland managers should be aware.

4.9 PASTURE PRODUCTION

Results of pasture production measured at various times of year for the Hamilton, Horotiu, Te Kowhai and Whatawhata sites using the pasture probe are given in Table 4.9.1; Rugby Park was not sampled because of sporting commitments.

4.9.1 Results

Table 4.9.1 Pasture production, kg ha⁻¹ dry matter (SED)

Soil type	Growth period	Treatment		SED	% increase
Hamilton clay loam	15/11/87 to 21/1/88	Non subsoiled	2733	(13.52)	17.7*
		Subsoiled	3214		
Horotiu sandy loam	15/5/89 to 7/7/89	Non subsoiled	2447	(17.28)	12.0*
		subsoiled	2740		
Te Kowhai silt loam	12/8/88 to 16/9/88	Non subsoiled	778	(8.74)	16.4*
		subsoiled	906		
Whatawhata clay loam	15/5/87 to 7/7/87	Non subsoiled	2021	(14.76)	15.3*
		subsoiled	2330		

* significance (P<0.05)

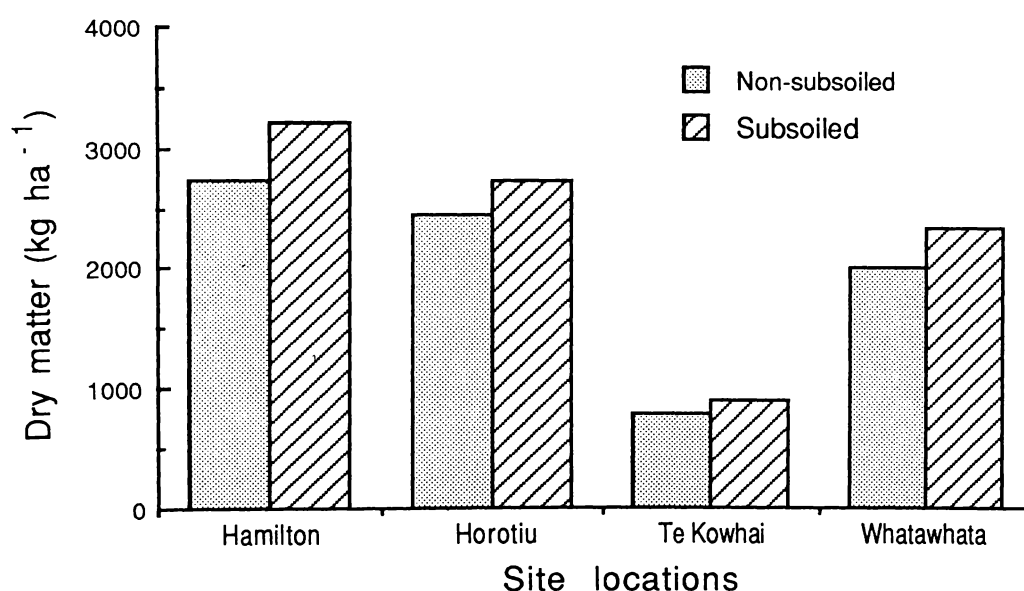


Figure 4.9.1 Pasture production for non-subsoiled and subsoiled.

Subsoiled plots on the Hamilton site grew significantly more pasture than non-subsoiled plots over a summer growing period of 68 days. This increase was equivalent to 481 kg DM ha⁻¹. The Horotiu soil showed a significant increase equivalent to 293 kg DM ha⁻¹ over a 52 day Autumn growth period. Te Kowhai subsoiled plots produced a significant increase equivalent to 128 kg DM ha⁻¹ over a 34 day spring growth period. The Whatawhata subsoiled plots showed a significant, increase equivalent to 309 kg DM ha⁻¹ over a 52 day Autumn growth period.

4.9.2 Discussion

It is beyond the scope of this study to compare and contrast pasture production between the four sites. For this to have been done, accurate records of fertiliser programmes, stocking rates and other pasture management practices would have been required. However, ^{pasture measurements} showed clearly that subsoiled plots on all sites grew significantly more pasture when compared with non-subsoiled plots (Figure 4.9.1).

The Hamilton soil tensiometer results (Chapter 4.4) indicated a wetter soil for subsoiled plots after a summer rainstorm. Hence increased pasture yield is not only a function of changes to soil physical properties, implied at the Whatawhata site, but is also probably related to increased moisture levels. Increased summer pasture would be a welcome bonus for livestock farmers at this time of year, when pasture growth can be occasionally limited by soil moisture deficits (Figure 1.4.2).

Pasture yields for Horotiu soil showed least percentage response, but were nevertheless significant. Certainly soil physical and moisture conditions were not a limiting factor. Horotiu soils are particularly well structured reflecting high allophane clay content, relatively low bulk density (0.8 Mg m⁻³) and free draining (Cotching 1978). The reasons for increased pasture growth at this site are beyond the scope of this study, however it could perhaps be surmised that subsoiling may have resulted in an increased supply of essential elements through mineralisation.

Te Kowhai soils are poorly drained and during winter it is common for water to pond on the surface, reflecting a high water table at this time of year. The subsoiled plots at this site were "connected" to a main drain, which facilitated better drainage. The increased spring pasture growth at this site probably reflects better drainage and aeration, and as shown for the Whatawhata site increased root length and deeper rooting may also be a cause. Increased production at Whatawhata is supported by root elongation studies (Chapter 4.8), which showed increased depth of rooting, especially in the zone of greatest soil disturbance located within 20 cm of the subsoiled slot, where bulk density and soil strength had been significantly reduced.

CHAPTER FIVE

CHAPTER FIVE

CHAPTER FIVE

CHAPTER 5 - LABORATORY WORK

5.1 AGGREGATE SIZE DISTRIBUTION BEFORE AND AFTER SUBSOILING AND IN THE CASE OF THE TE KOWHAI SOIL THE EFFECT OF VIBRATING AND NON-VIBRATING TREATMENTS ON HORIZON MIXING

5.1.1 Introduction

As previously discussed (Chapter 2.5.3), subsoiling is defined as a soil tillage operation which loosens compacted soil, but does not invert or mix the soil to any extent. The Shakaerator, however, with its vibrating action could perhaps be expected to mix and “break up” soil more than non-vibrating conventional subsoilers. The quantification of these two effects was therefore considered an important part of the study as their influence on long term structural, textural and biological characteristics of a soil, may play an important role in the improvement of soil drainage and plant growth.

Three soils, Hamilton, Te Kowhai and Whatawhata were chosen for comparison of aggregate size before and after vibrating subsoiling. Horotiu soil had responded least to subsoiling hence it was not chosen for this part of the study. Rugby Park soil was also not used because the Hamilton Rugby Union were unable to allow further ground disturbance and sample recovery.

The Te Kowhai soil with its distinct colour break at 20 cm depth (Chapter 3.5) was used to test whether subsoiling, vibrating or non-vibrating caused mixing of A and B horizon aggregates. It is suggested that the Te Kowhai model would equally apply to other soils.

5.1.2 Method

Soil samples representing A and B horizons were taken from profile pits as described (Chapter 3.5.8). Samples weighing approximately 2 kg were taken from one side of the exposed pit before subsoiling and from the other side of the pit after subsoiling. The subsoiled samples were taken within 10 cm of the subsoiled slot and represented the same range of depths as the non-subsoiled samples.

Samples were allowed to air dry and were then sieved by hand using a nest of sieves of mesh sizes 0.25, 0.5, 1, 2, 4, 8, 16, 32 and 64 mm (Figure 5.1.1). Aggregates were weighed and expressed as % of total weight.

The Te Kowhai samples collected for the horizon mixing study, were carefully sorted according to aggregate colour anomalies. This involved separating out by hand, grey coloured Bg horizon aggregates incorporated into the predominantly brown A horizon sample and conversely separating out the brown A horizon aggregates from the grey Bg horizon sample. Samples were then sieved and the % of A horizon aggregates found in the Bg horizon and the % of Bg aggregates found in the A horizon were graphed.



Figure 5.1.1 Whatawhata soil, air dried aggregates

5.2 BULK DENSITY

5.2.1 Introduction

The bulk density of a soil is the ratio of the mass to the volume, including air spaces. Low bulk densities from 0.5 - 1.0 Mg m⁻³ are characteristic of allophanic and pumice soils. Other soils average approximately 1.0 Mg m⁻³ in the topsoil increasing to about 1.35 Mg m⁻³ in the subsoil. Compacted soil layers which may limit root penetration may have bulk densities ranging from 1.35 - 1.75 Mg m⁻³.

5.2.2 Method

The determination of bulk density in the laboratory was carried out using air dry aggregates, approximately 2 cm in diameter, which were collected from four subsoiled and four non-subsoiled profiles on each site representing both A and B horizons. Subsoiled aggregates were taken 10 cm from the subsoiled slot. Subsoiling was carried out in the vibrating mode. The aggregates were allowed to air dry, then weighed and coated with wax at 60°C and weighed again. The coated aggregates were then weighed in water.

$$\begin{aligned} \text{Density of wax} &= 0.92 \text{ Mg m}^{-3} \\ \text{Weight of aggregate} &= W \\ \text{Weight of aggregate plus wax} &= W_x \\ \text{Weight of aggregate plus wax in water} &= W_w \end{aligned}$$

$$\text{Volume of aggregate plus wax} = W_x - W_w$$

$$\text{Volume of wax} = \frac{W_x - W}{0.92 \text{ Mg m}^{-3}}$$

$$\text{Volume of aggregate} = (W_x - W_w) - \frac{(W_x - W)}{0.92 \text{ Mg m}^{-3}}$$

The Horotiu aggregates floated and therefore a sinker was used. The volume of the sinker was found from $S - S_w = V_s$ where:

$$\text{weight of sinker} = S$$

$$\text{weight of sinker in water} = S_w$$

$$\text{Volume of sinker} = V_s$$

$$\text{Weight of aggregate plus wax plus sinker in water} = S W_w$$

$$\text{Volume of aggregate plus wax plus sinker} = (W_x + S) - S W_w$$

$$\text{Volume of aggregate} = ((W_x + S) - S W_w) - V_s - \frac{(W_x - W)}{0.92 \text{ Mg m}^{-3}}$$

$$\text{Bulk density} = \frac{\text{Weight of aggregate}}{\text{Volume of aggregate}}$$

5.3 PARTICLE SIZE DISTRIBUTION

5.3.1 Analysis

The pipette method of analysis was used to determine 2 - 63 μ m silt and <2 μ m clay sized particles. Particles >63 μ m were determined by sieving (Day 1965).

5.3.2 Method

Soil samples at field moisture were tested for allophane (Fieldes and Perrott 1966). Approximately 10 g of soil was placed on a piece of dry filter paper, which had previously been treated with phenolphthalein indicator. One drop of sodium fluoride solution (0.85 M) was added to the soil sample. Allophane releases hydroxyl ions when treated with NaF, which turns the filter paper red. The intensity of the reaction can be qualitative and expressed as strong, moderate or weak. The reaction intensity was strong for Horotui and weak for Hamilton, Te Kowhai and Rugby Park, with a negative reaction in the Whatawhata soil. A slightly different technique was therefore required in preparing the Horotui soil for analysis due to the chemical behaviour of allophane.

50 g of air dry Horotui soil were weighed into a 600 ml beaker with 100 ml of distilled water and 25 ml of 6% hydrogen peroxide. The pH of the A horizon was adjusted to pH 8 using sodium hydroxide and left to stand overnight. The B and C horizons had 2 g zirconium nitrate added (Ahmad and Prashad 1970) and then were warmed gently on a hot plate for about 30 minutes and boiled. The same procedure was followed for the A horizon, after a further 25 ml of hydrogen peroxide had been added. The suspensions were allowed to cool, the A horizon pH was again adjusted to pH 8 and the B horizon to pH 3.

Similar preparation of the Hamilton, Rugby Park, Te Kowhai and Whatawhata soils was carried out, except all horizons had 30 ml of 5% calgon added in the pre-treatment phase instead of zirconium nitrate or sodium hydroxide, and all horizons were adjusted to pH 8 after boiling.

The suspensions were dispersed using a high speed stirrer for 15 minutes and then transferred into 1 litre measuring cylinders and made up to the 1000 ml mark. The suspensions were homogenised using a brass plunger and the time at which the

plunger was removed noted. Cylinders were then placed underneath a pipette stand and suspensions were drawn up into the pipette at the appropriate depths and times, from which it was possible to determine settling time required for size fractions using Stokes equation for settling velocities of particles in suspension (Day, 1965). Pipette samples were transferred into pre-weighed containers and oven dried. The weight of the silt and clay fractions per 100 g were calculated after allowing for the weight of dispersing agent. Suspensions were then wet sieved using a 63 μm mesh sieve. The sand fraction was left to dry and used to calculate the total sand fraction percentage.

5.4 CLAY MINERALOGY

5.4.1 Introduction

Clay is the most reactive constituent of soil. The response of soils dominated by different clay minerals to subsoiling may therefore be different.

The identification of clay minerals in soils is made after considering the evidence from a number of different analytical techniques. Differential thermal analysis (DTA), X-ray diffraction (XRD) and the Fieldes and Perrott (1966) test for allophane were used in the determination.

5.4.2 Clay mineral identification

Allophane is a poorly ordered short range order hydrous alumino-silicate. It is recognised by its typically single sharp endothermic peak within a temperature range of 120 to 160°C (DTA). The peak is caused by dehydration and loss of structural hydroxyl groups. An absence of X-ray diffraction pattern is also a distinguishing factor. Allophane dominant clays react strongly to the Fieldes and Perrott (1966) test.

Halloysite and kaolin are common kaolinite clay minerals. These layer silicate clays both exhibit endothermic peaks at about 500°C (DTA). Relative abundance can be determined from the endothermic peak areas (Bramao *et al.*, 1952). The symmetry of the peak using the slope ration (Appendix 4) to determine relative abundance of halloysite and kaolin was used here. Slope ratios for halloysite are normally ≥ 1.5 where endotherms are asymmetric, with the ascendant side being steeper than the

descendant. Lower slope ratio values ≤ 1.2 are normally associated with the presence of kaolin. Hamilton soil whose A horizon contains some allophane was treated with ethylene glycol before DTA analysis. This process replaces water in the clay lattice which suppresses the 120 - 160°C endothermic peak.

It is difficult to distinguish between halloysite and kaolin by XRD when all the halloysite is in the dehydrated form, because both clays give XRD peaks at approximately 7 Å. The presence of halloysite is substantiated if the 7 Å peak occurs in combination with 10 Å halloysite and where the 7 Å peak is broad and relatively poorly defined. The presence of the more ordered clay mineral kaolin, is associated with 7.1 Å and 3.5 Å peaks.

5.4.3 Method

At the completion of particle size analysis the remaining suspension containing the clay fraction was decanted and divided, one part was flocculated with magnesium chloride and the other with potassium chloride. Orientated slides of the magnesium and potassium saturated clays were then prepared and allowed to dry slowly in a desiccator over distilled water. Slides were analysed using X-ray diffraction (XRD) from 3° to 28° 2 θ at a speed of 2° min⁻¹, with a chart speed of 20 mm min⁻¹ using a PW 1729 X-ray generator, PW 1840 diffractometer and a PM8203A on line recorder.

Dried magnesium saturated clay was finely ground and kept at a relative humidity of approximately 56% for 48 hours. 50 mg of clay were mixed with 150 mg of aluminium oxide and heated using a Stone P202 differential thermal analysis (DTA) apparatus. A heating rate of 10°C min⁻¹, thermocouple amplifier = 300 μ v, chart speed = 0.1 inch min⁻¹ was used. The samples were heated in ambient air to 650°C.

5.5 IMAGE ANALYSIS

5.5.1 Introduction

The measurement of soil pores, their size, shape and continuity can be used to characterize soil structure (Murphy, Bullock and Biswell, 1977). Systems have been developed, which use image analysers to recognize and measure the different types of pores in impregnated soil blocks (Ringrose-Voase and Bullock, 1984).

This study demonstrates the use of image analysis, in providing quantitative information on the effect of subsoiling.

5.5.2 Method

Core samples were taken before and after subsoiling at the Hamilton, Te Kowhai and Whatawhata sites. Thin gauged stainless steel cylinders, measuring 6 cm in diameter and 5 cm in length were pushed into the soil horizontally, at 15 and 35 cm depth, representing topsoil and subsoil respectively. The cores taken from the subsoiled plots were taken from profiles located 4, 10, 20, 30 and 40 cm distance from the subsoiled slot. The cores were sealed in plastic bags. On returning to the laboratory the cores were treated with a 1:1 solution of water and acetone for 30 minutes and allowed to drain for 12 hours. Cores were then treated with extra dry 100% acetone for 20 minutes.

Cores were next treated with acetone and resin at ratios indicated below:

Acetone:	Resin (Araldite)	Time
75	25	2 hours
50	50	Overnight
25	75	2 hours
-	100+ fluorescent dye (fluorescein)	2 hours

Resin was drained off after each step. The cores were then allowed to harden in an oven set at 60°C, for two days. A plane face was cut through the centre of each sample, parallel to the face on which it was originally taken. Large sections (5 x 5 cm) were scanned using the Imageplus Automatic Image Analyser (Dapple 1986) (Figure 5.1.2).

This system uses a video image, which by binary division, determines areas of pre-set light intensity. An apple IIe computer scans the image and records it as an array of 256 x 256 pixels. A pixel represents a picture point (pp) and thus the scanned image is composed of 65, 536 pp. Each picture point is square and joins neighbouring points in horizontal and vertical directions and can therefore be considered as units of area or of linear measurement. Calibration of a picture point is determined by the magnification; with a 20 x objective the length of a picture point is $\frac{50000}{256} \times \frac{1}{20} = 9.76 \mu\text{m}$.

Pixels were digitised with specific grey-levels, with values ranging from 0 (black) to 64 (white). The green fluorescent resin infilling the pores was “targeted” with a specific grey value, which distinguished pores $>9.76\ \mu\text{m}$ from their surroundings. In this way soil pores could be recognised and their fractional area expressed as a percentage of the total were calculated..

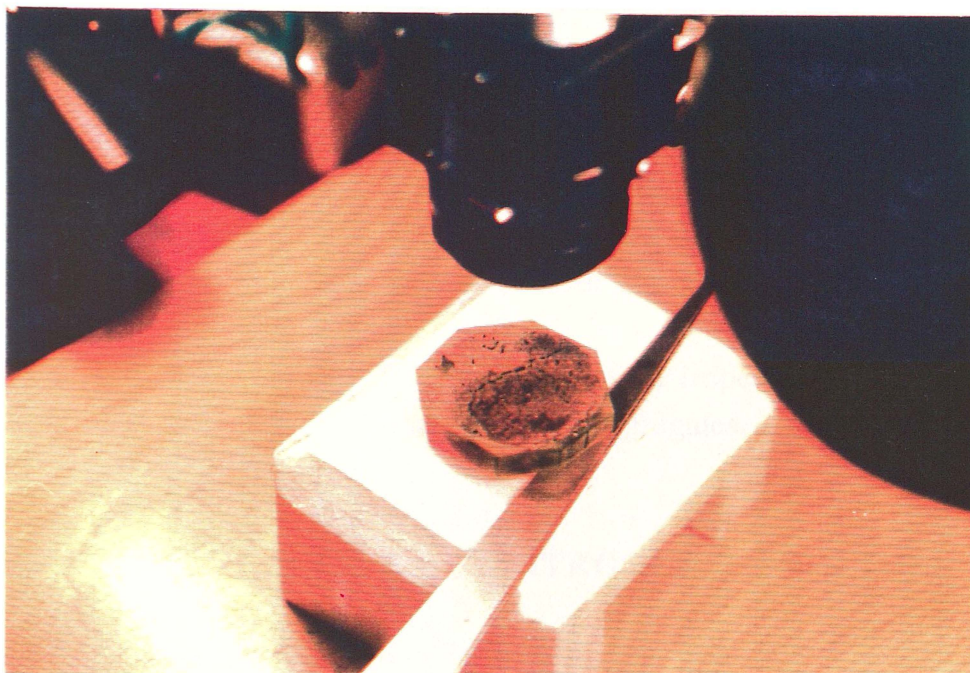


Figure 5.1.2 Soil core impregnated with fluorescent resin being scanned by automatic image analyser.

5.6 SCANNING ELECTRON MICROSCOPY (SEM)

5.6.1 Introduction

A microscopic investigation of soil aggregates was carried out to substantiate compositional clay data derived from other techniques. SEM provides a 3-dimensional view with high depth of focus, of relatively unmodified microstructure at a high magnification, and is therefore used to determine the shape, size and packing characteristics of intra aggregate particles.

5.6.2 Method

Soil aggregates from subsoiled and non-subsoiled plots, 5 to 10 mm in diameter were freeze dried and mounted on aluminium stubs, with acrylic cement. They were then coated with a fine carbon film and sprayed with a film of gold in a diode sputtering system (POLARON E5000), and scanned with a JEOL JSM-35 SEM. The samples were next examined and areas which most characterised a given soil were photographed. Each area was studied at several magnifications, ranging from 40 to 1500 times. The high magnification made it possible to study the fine details, such as contact between clay particles, their size and shape, the nature of clay surfaces, inclusion of organic residue and inter and intra particle porosity. The lower magnification was useful in studying sand and silt grains and related porosity.

It also provided some evidence for root elongation impedence. SEM could not distinguish between subsoiled and non-subsoiled aggregates.

5.7 ORGANIC CARBON, TOTAL NITROGEN, C/N RATIOS

5.7.1 Introduction

Carbon and nitrogen are the major constituents of organic matter. Organic matter plays a crucial role in aggregation and water-holding capacity, it has a higher cation absorption capacity than mineral colloids and it is a powerful absorber of essential elements. (Brady 1974)

The carbon-nitrogen ratio is relatively constant because carbon makes up a large proportion of organic matter. The carbon-nitrogen ratio in soil organic matter commonly ranges from 8 to 20. The ratio is generally smaller for B horizons, than for A horizons. Carbon and nitrogen values were determined, as a possible means of demonstrating soil mixing.

5.7.2 Methods

Soil samples from four subsoiled profiles and from four non-subsoiled profiles were collected from various depths representing A and B horizons over a period of two years from Hamilton and Te Kowhai sites.

5.7.2.1 Determination of organic carbon

Organic carbon was determined using a method similar to that of Schollenberger (Allison 1965). For the A horizon samples 0.5 g of soil and for the B horizon 1.0 g, was weighed into separate 500 ml conical flasks. 0.785 g potassium dichromate was added and 10 ml distilled water used to wash down any soil or chemical left on the sides of the flask. A blank containing no soil was prepared for each batch of samples. 20 ml concentrated sulphuric acid was added rapidly to all flasks, which were then warmed on a hotplate for 30 minutes. The flasks were allowed to cool before 100 ml distilled water added and further left to cool. 5ml orthophosphoric acid and 1 ml of diphenylamine sulphonate indicator were then added and the solutions titrated with 0.5 M ferrous ammonium sulphate solution to a green end-point.

Calculation

0.785 g of $K_2 Cr_2 O_7$ will oxidise 48 mg of carbon to carbon dioxide or 32 ml of 0.5 M ferrous solution to ferric.

Therefore $\frac{\text{titration for blank}}{16}$ is the factor for the ferrous solution.

$$K_2 Cr_2 O_7 \text{ used} = \frac{\text{titration for blank} - \text{titration for sample}}{\text{titration blank}} \times 0.785$$

Since 0.785g $K_2 Cr_2 O_7$ oxidises 48mg C to CO_2 or $32cm^3$ of 0.5M Fe^{2+} to Fe^{3+} then 1g $K_2 Cr_2 O_7$ oxidises 61.14 mg of C

$$\% \text{ Carbon} = \frac{K_2 Cr_2 O_7 \text{ used} \times 61.14 \times 1.15 \times 100}{\text{weight of oven dry soil} \times 1000}$$

1.15 is an empirical factor due to incomplete oxidation of organic matter.

5.7.2.2 Determination of total nitrogen

Total nitrogen was determined using the Kjeldahl method.

5 g of soil was ground to a fine powder. 0.5 g of A horizon or 1.0 g of B were weighed into 50 ml kjeldahl flask. One kjeldahl tablet for the A horizon or two for the B horizon were added, plus a speck of selenium. 1 ml of distilled water was used to wash down any soil in the neck of the flask and to wet the soil. 5 ml of concentrated sulphuric acid was added and the flasks were placed on a stand for the contents to digest. Flasks were swirled during digestion to ensure mixing and to prevent sticking to the bottom of the flask. After the solution became white, heating continued for a further 30 minutes and allowed to cool.

20 ml of distilled water was next added slowly to dissolve crystallised salts and the flask contents were then transferred to a 50 ml volumetric flask. A further 20 ml of water was used to wash out all soluble material, leaving the sand grains behind. The volumetric flask was made up to the mark with distilled water and mixed well. 10 ml of 1% boric acid, containing an indicator, was added to a 25 ml conical flask. 10 ml of the diluted digest was pipetted into a Markham apparatus. Excess 40% sodium hydroxide solution was added and the contents steam distilled until the 25 ml mark on the flask was reached. The green coloured distillate was then titrated with 0.01 M hydrochloric acid to a pink end point. Two distillations whose titrations agreed within 0.3 ml were made for each sample.

Calculation

1 ml of 0.01 M HCl = 0.14 mg nitrogen

$$\text{nitrogen \%} = \frac{\text{titration} \times 0.14 \times 5 \times 100}{1000 \times \text{weight of sample}}$$

Results were expressed as %N, from which C/N ratio was calculated.

CHAPTER SIX

CHAPTER 6: LABORATORY RESULTS AND DISCUSSION

6.1 AGGREGATE SIZE DISTRIBUTION BEFORE AND AFTER SUBSOILING IN VIBRATING MODE

6.1.1 Introduction

Soil samples were taken from Hamilton, Te Kowhai and Whatawhata sites, before and after subsoiling in the vibrating mode, in order to test the effect of subsoiling. The method of sampling is given in Chapter 5.1.2.

6.1.2 Results

Figures 6.1.1 - 6.1.3 were prepared from aggregate size distribution data given in Appendix 5.

A description of aggregate distribution parameters consisting of aggregate mean, a measure of sorting and the degree of skewness and peakedness is described according to Folk and Ward (1957).

Figure 6.1.1(a) shows that Hamilton A horizon aggregate distribution before subsoiling, exhibited a poorly sorted, strongly fine skewed, leptokurtic, unimodal size, with a mean weight diameter of 13,

Subsoiling had the effect of reducing the 8 - 16 mm peak from 38 - 30% and increasing the 4 - 8 mm size from 8 - 22%. The larger aggregates ranging from 8 - 64 mm were significantly broken up. Mean weight diameter was reduced to 8.57 and the shape of the histogram remained strongly fine skewed leptokurtic.

Similarly Figure 6.1.1(b) shows subsoiling reduced B horizon aggregate larger than 8 mm to the 1 - 8 mm size, resulting in a reduction in mean from 8.22 to 6.06 and a change in skewness to fine skewed from strongly fine skewed.

Figure 6.1.2(a) shows that Te Kowhai A horizon aggregate distribution before subsoiling exhibited a poorly sorted strongly fine skewed, leptokurtic unimodal size with a mean weight diameter 15.35. Subsoiling had the effect of reducing the mean weight diameter to 12.13 and skewness to fine skewed.

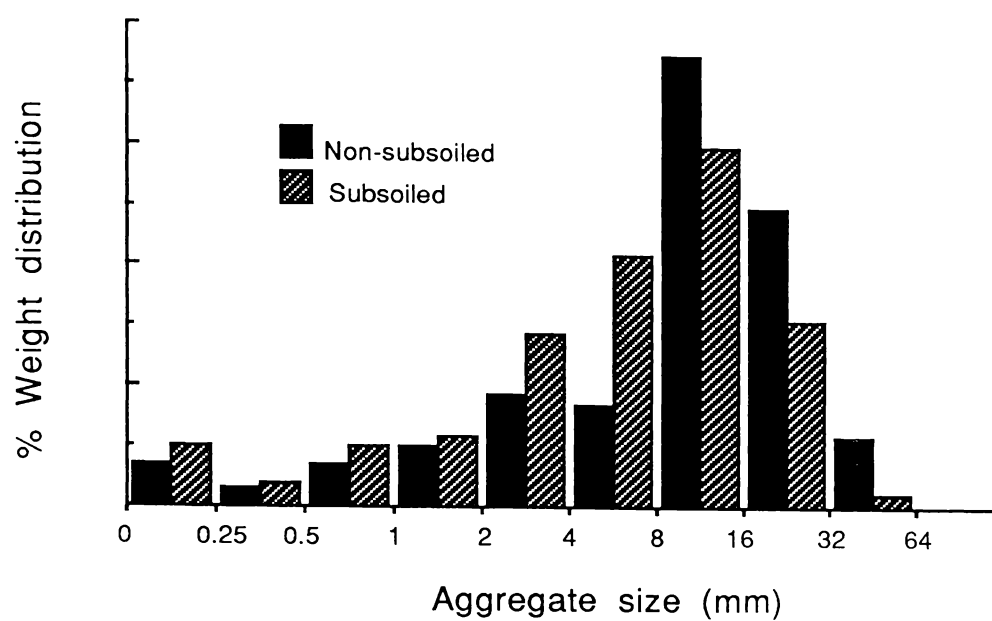


Figure 6.1.1a Hamilton soil, A horizon (0 - 25 cm)

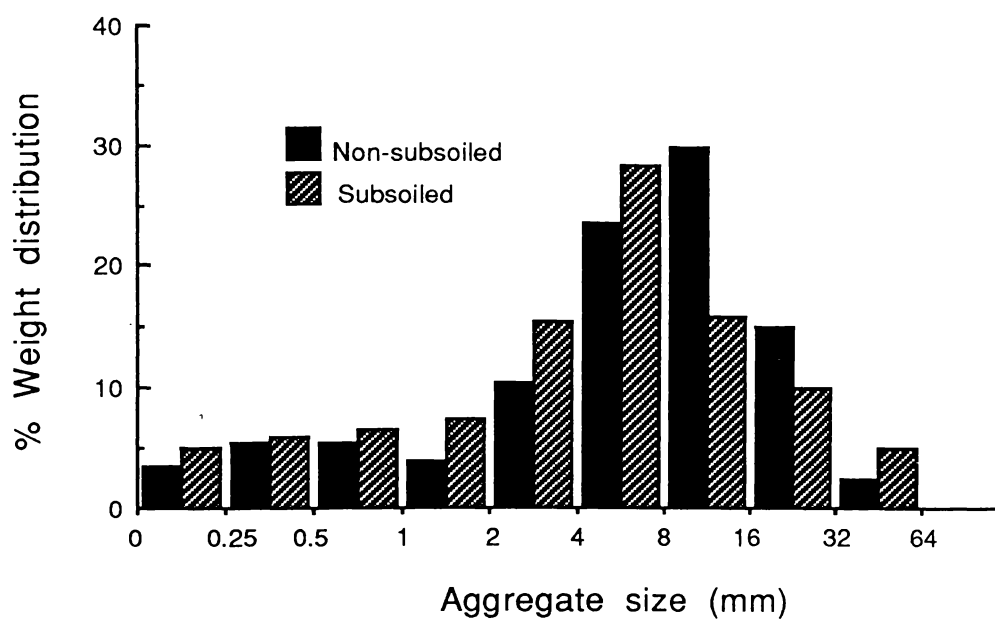


Figure 6.1.1b Hamilton soil, B Horizon (25 - 45 cm)

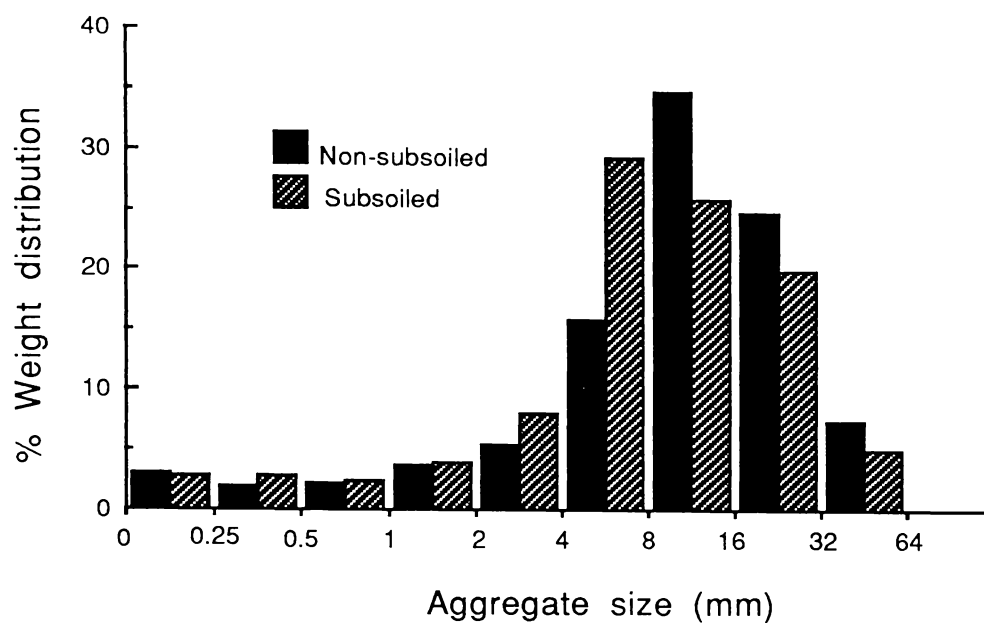


Figure 6.1.2a Te Kowhai soil, A horizon (0 - 20 cm)

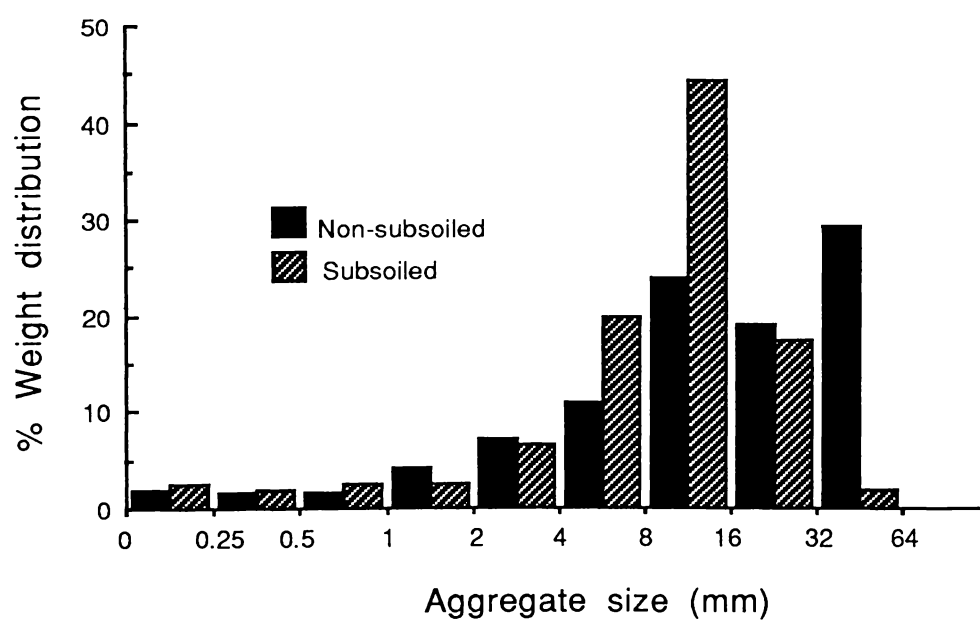


Figure 6.1.2b Te Kowhai soil, Bg horizon (20 - 45 cm)

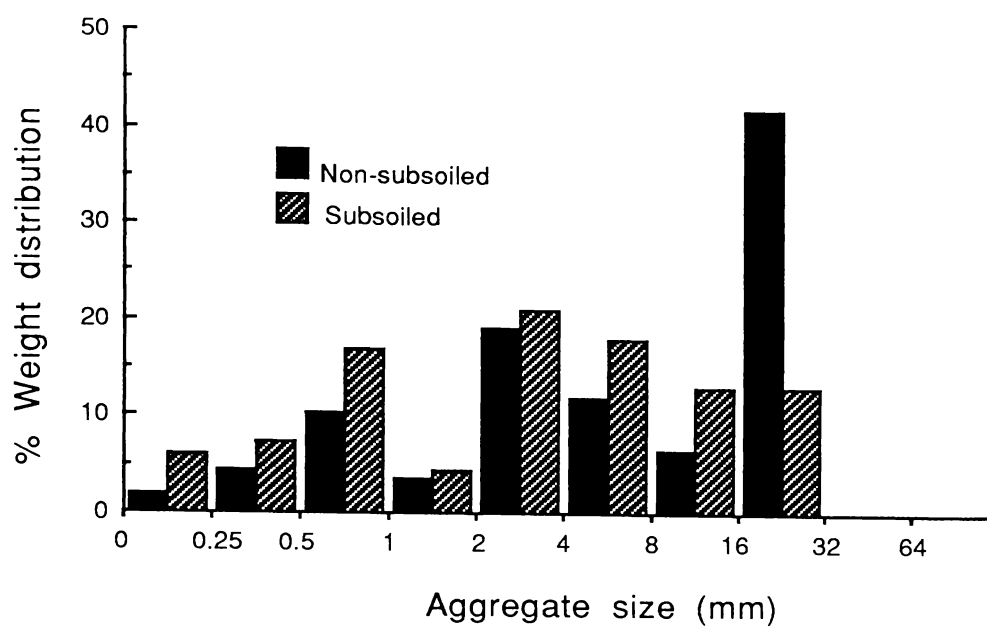


Figure 6.1.3a Whatawhata soil, A horizon (0 - 15 cm)

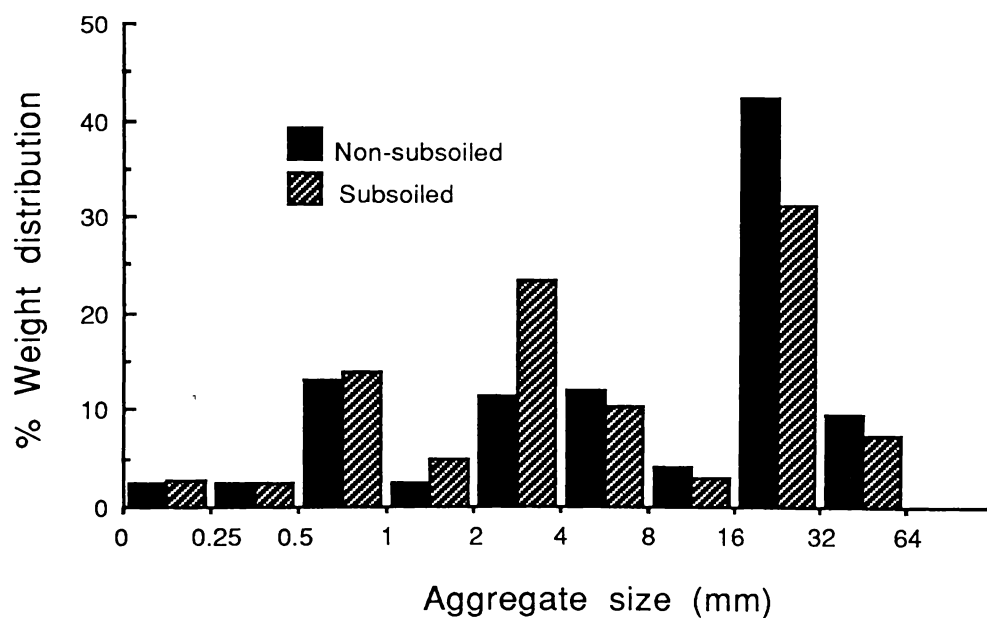


Figure 6.1.3b Whatawhata soil, Bg horizon (15 - 45 cm)

Figure 6.1.2(b), shows for the Bg horizon that the 32 - 64 mm aggregates were reduced mainly to the 8 - 16 mm size, with the mean value accordingly lowered to 13 - 55 from 18 - 50. In this case, the degree of peakedness changed from mesokurtic to very leptokurtic as a consequence of subsoiling.

Figures 6.1.3(a) shows that Whatawhata A horizon aggregates before subsoiling are very poorly sorted strongly fine skewed, platykurtic. The major effect of subsoiling on A horizon aggregates was to reduce the 16-32 mm class mainly to the 2 - 4 mm size, which resulted in a reduction in mean weight diameter from 11.31 to 7.11 and a change in skewness to near symmetrical.

In the Bg horizon, subsoiling reduced 16 - 32 mm aggregate size from 42 - 12% with a subsequent increase in the 2 - 4 mm size. The mean weight diameter was reduced from 8.28 to 4.38 and strongly fine skewed changed to fine skewed.

6.1.3 Discussion

The aggregate size distribution shows clearly that subsoiling reduces aggregate size. In the non-subsoiled soils there is a larger proportion of aggregates >16 mm when compared with subsoiled. In the subsoiled soils there is a larger proportion of aggregates <8 mm when compared with non-subsoiled.

All three soils showed large reductions in large aggregates reflecting the influence of the shaking tip and shank.

The reduction in aggregate size is a key factor in ameliorating compacted soils. This reduction and consequent increase in the number of aggregates must by implication change the physical characteristics of the soils in this study. The increased number of aggregates must result in more interaggregate space, therefore providing greater opportunity for plant roots to grow both laterally and vertically, which could subsequently increase crop production. The re-distribution of soil aggregates found in this study due to subsoiling may also influence soil drainage and soil moisture loss.

6.2 HORIZON MIXING OF SOIL AGGREGATES AFTER VIBRATING AND NON-VIBRATING SUBSOILING

6.2.1 Introduction

A mixing of aggregates within the soil profile could alter soil physical, biological and chemical characteristics, which in turn may influence soil and pasture management practices. The transferring of A horizon aggregates to lower levels of the soil profile might enhance soil development, especially in “young” soils. It would also change the texture of a soil and might enhance soil fertility and soil moisture content, thus improving pasture production especially during the drier summer months. The transfer of B horizon aggregates to higher levels of the soil profile, would increase the clay content of A horizons and decrease organic matter.

6.2.2 Results

Figure 6.2.1 and 6.2.2 show the aggregate size distributions following vibrating and non-vibrating treatments. Both vibrating and non-vibrating treatments resulted in some horizon mixing, but vibrating caused more. Vibrating resulted in the incorporation of 17% B_g horizon aggregates into the A horizon and 19% A horizon aggregates into the B_g horizon. Non-vibrating resulted in 15% of the A horizon incorporated into the B_g horizon and 10% of the B_g horizon forced up into the A horizon.

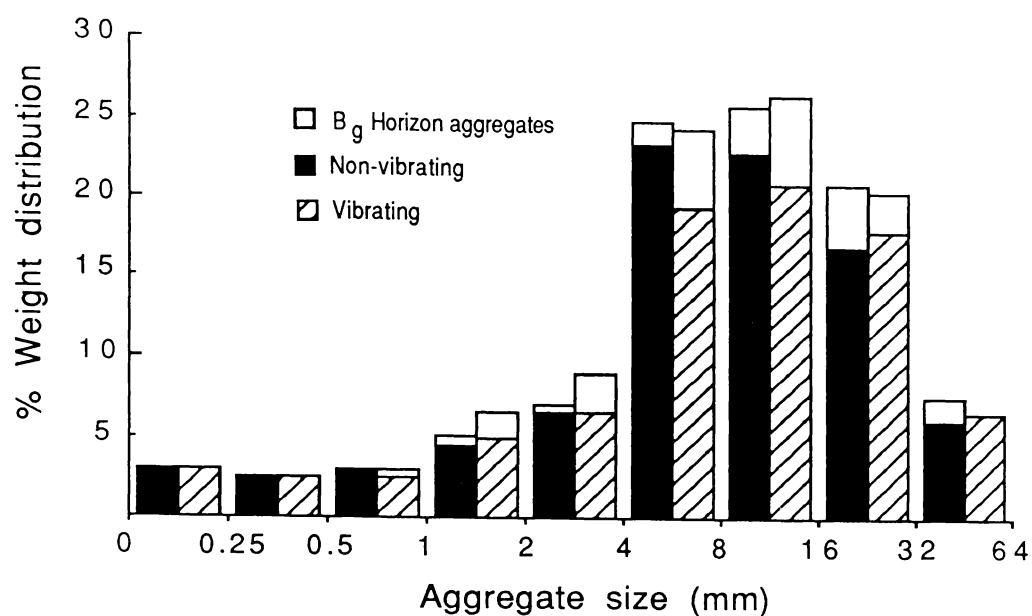


Figure 6.2.1 Te Kowhai soil, A horizon following subsoiling

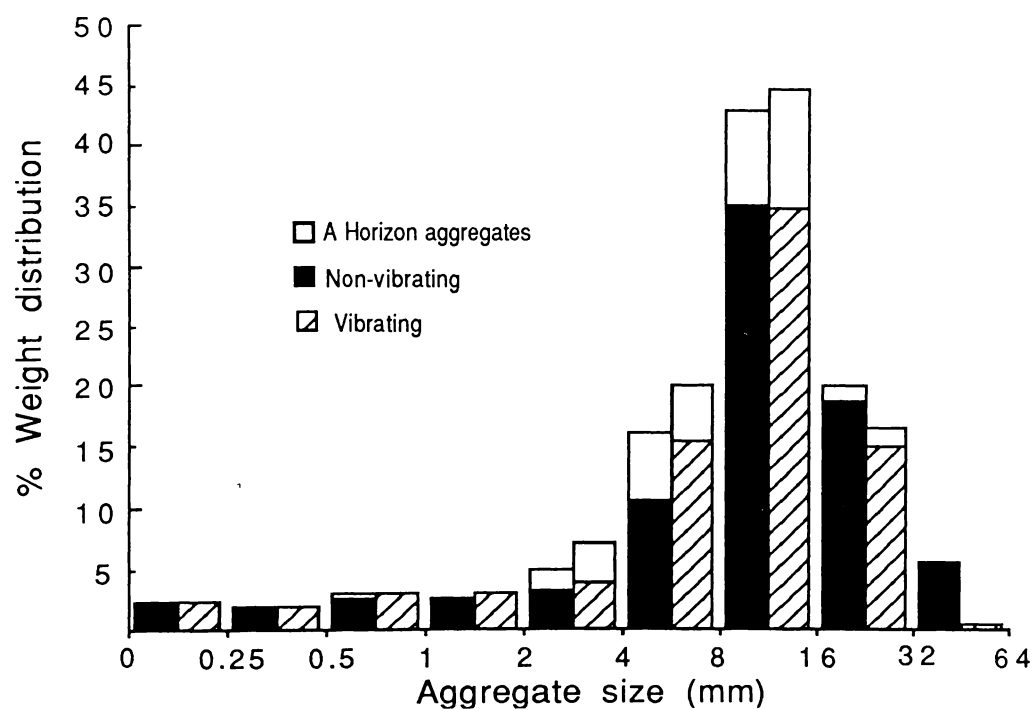


Figure 6.2.2 Te Kowhai soil, B_g horizon following subsoiling

6.2.3 Discussion

Since subsoiling caused mixing in the Te Kowhai soil it is presumed to occur in other soils. The mechanism by which aggregate interchange occurs between A and Bg horizons is probably a function of the shape and orientation of the subsoiler shank and tip, tractor speed, vibration speed, depth of operation and soil moisture. Soil aggregates from deeper layers are forced into upper layers, by flowing up and over the subsoiler tip and are further disturbed as they fall in behind the subsoiler shank (Spoor and Godwin, 1978). The greater mixing for the vibrating treatment is probably due to the increased soil disturbance as reported in Chapter 4.7. The greater difference for A horizon aggregate mixing into B horizon in the two treatments was probably due to the fact that aggregates simply drop down behind the subsoiler shank under the influence of gravity.

Subsoiling as defined earlier (Chapter 2.5.3) loosens compacted soil, but does not mix the soil to any extent. In this study subsoiling was found to cause a significant interchange of A and Bg horizon aggregates within 10 cm distance of the subsoiled slot, with consequent textural and organic changes which are reported in Chapters 6.4 and 6.8.

6.3 BULK DENSITY (BD)

6.3.1 Introduction

The determination of bulk densities in the laboratory, was carried out on soil aggregates to check and compare with *in situ* measurements made with the subsurface density gauge for both non-subsoiled and vibrating subsoiled treatments.

6.3.2 Results

Bulk density (BD) values in Table 6.3.1 show that the Horotiu soil has a low value for both A and B horizons as would be expected for this allophane rich soil. For all soils, with the exception of Rugby Park, BD increases with depth. Although bulk density was reduced by subsoiling for all soils it was only in the Rugby Park A horizon was significant change.

Table 6.3.1 Bulk density - (Mg m^{-3}) - wax method

Soil description	Horizon	Non subsoiled	Subsoiled	SD
Hamilton	A	1.24	1.20	0.06
	B	1.42	1.36	0.09
Horotiu	A	0.78	0.75	0.06
	B	0.88	0.86	0.07
Rugby Park	A	1.36	1.22*	0.09
	B	1.02	0.98	0.08
Te Kowhai	A	1.04	1.00	0.05
	B _g	1.30	1.28	0.07
Whatawhata	A	1.26	1.20	0.06
	B _g	1.51	1.54	0.07

* significantly different from non-subsoiled ($P < 0.05$)

6.3.3 Discussion

The relatively high bulk density values for Rugby Park A horizon (non-subsoiled) in comparison with the B horizon, indicates a compacted surface layer. This compaction can be directly attributed to many seasons of winter sports use. The significant reduction in A horizon bulk density values in response to subsoiling probably reflects the fact that this site was subsoiled at 35 cm depth, rather than the standard depth of 45 cm carried out on the other soils. Although ground heave (Figure 4.6.3) at this site* was not significantly different to other sites there was observational evidence which indicated extensive soil disturbance in the A horizon.

The determination of bulk density did not discriminate between subsoiled and non-subsoiled soil aggregates because subsoiling shatters and breaks up large structural soil units, creating a larger soil volume, it does not in this study change the density of individual aggregates. The comparison of this method and the *in situ* subsurface density gauge method is discussed in Chapter 7.3.

* Time constraints and sports use did not allow for further quantitative analysis

6.4 PARTICLE SIZE DISTRIBUTION AND SOIL TEXTURAL CHANGES IN RESPONSE TO SUBSOILING

6.4.1 Introduction

Subsoiling may lead to textural changes, particularly within 10 cm of the subsoiled slot due to soil mixing as was suggested in Chapter 6.2.1. Soil mixing at distances further than 10 cm from the slot, seems not to occur. Soil samples representing A and B horizons were taken from subsoiled profiles as detailed in Chapter 3.6.8. Particle size analysis was carried out on these samples using the method detailed in Chapter 5.3.

Table 6.4.1 Particle size analysis before and after vibrating subsoiling

Soil	Horizon	Depth (cm)	Nonsubsoiled (NS) Subsoiled (S)	%sand	%silt	%clay	Textural class
Hamilton clay loam	A	0-25	NS	29	34	37	Clay loam
	A		S	26	26*	48*	Clay
	B	25-45	NS	8	21	71	Clay
	B		S	14*	24	62*	Clay
Horotiu sandy loam	A	0-15	NS	52	28	20	Sandy loam
	A		S	50	35*	15*	Sandy loam
	B	15-40	NS	60	32	8	Sandy loam
	B		S	55	30	15*	Sandy loam
Rugby Park soil	A	0-21	NS	65	16	19	Sandy loam
	A		S	50*	26*	24*	sandy clay loam
	B	21-35	NS	38	37	25	sandy loam
	B		S	42	28*	30*	clay loam
Te Kowhai silt loam	A	0-20	NS	27	54	19	silt loam
	A		S	25	51	24*	silt loam
	B _g	20-45	NS	28	42	30	clay loam
	B _g		S	26	46	28	clay loam
Whatawhata clay loam	A	0-25	NS	28	32	40	clay loam
	A		S	20*	28	52*	clay
	B _g	25-45	NS	11	23	66	clay
	B _g		S	16*	25	59*	clay

*significantly different from non-subsoiled ($P < 0.05$).

6.4.2 Results

Table 6.4.1 gives the results of the particle size analysis for subsoiled and non-subsoiled soils, from which Figures 6.4.1 - 5 were compiled.

Table 6.4 shows that the distribution of the silt and clay of Hamilton clay loam was significantly altered; the clay fraction percentage increased from 37 to 48 in the A horizon, with a consequent decrease in the B horizon from 71 to 62. Although the silt fraction dropped from 34 to 26% in the subsoiled A horizon, there was only a 3% increase in the B horizon. The sand fraction decreased slightly in the subsoiled A horizon but significantly increased in the B horizon (Figure 6.4.1).

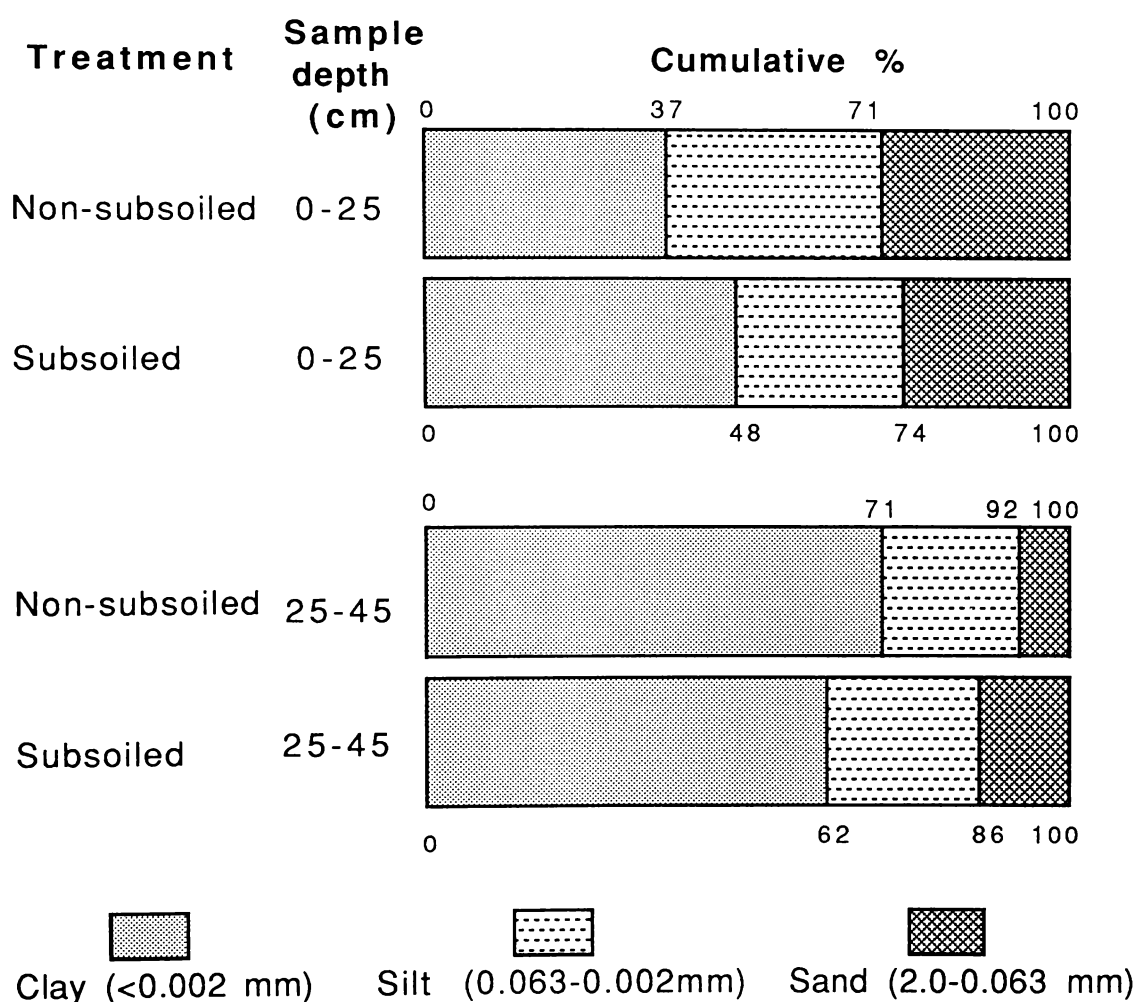


Figure 6.4.1 Hamilton soil, particle size distribution

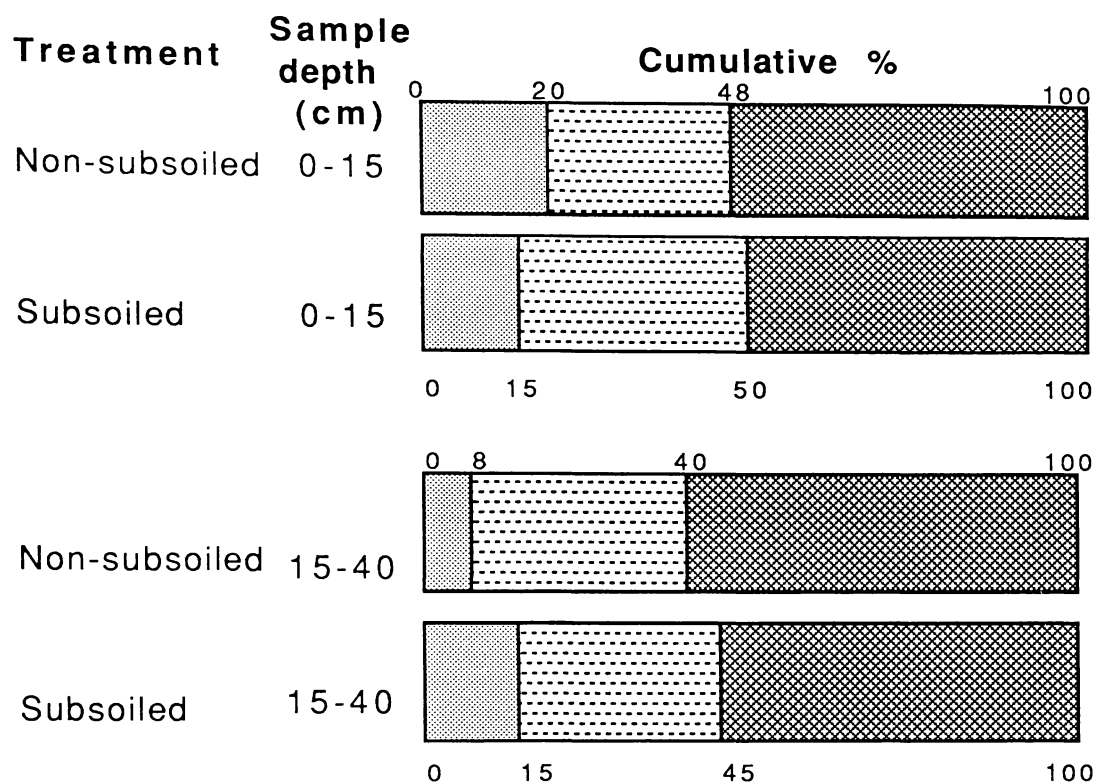


Figure 6.4.2 Horotiu soil, particle size distribution

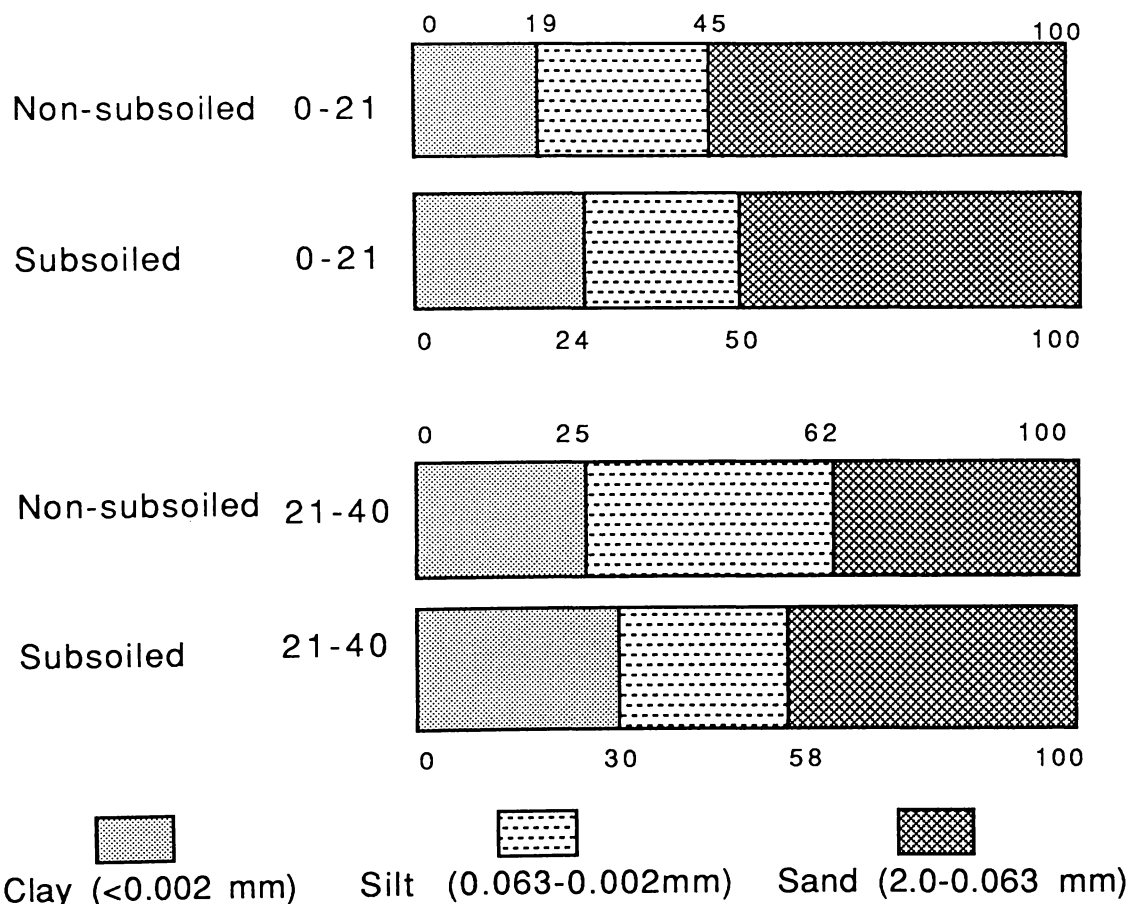


Figure 6.4.3 Rugby Park soil, particle size distribution

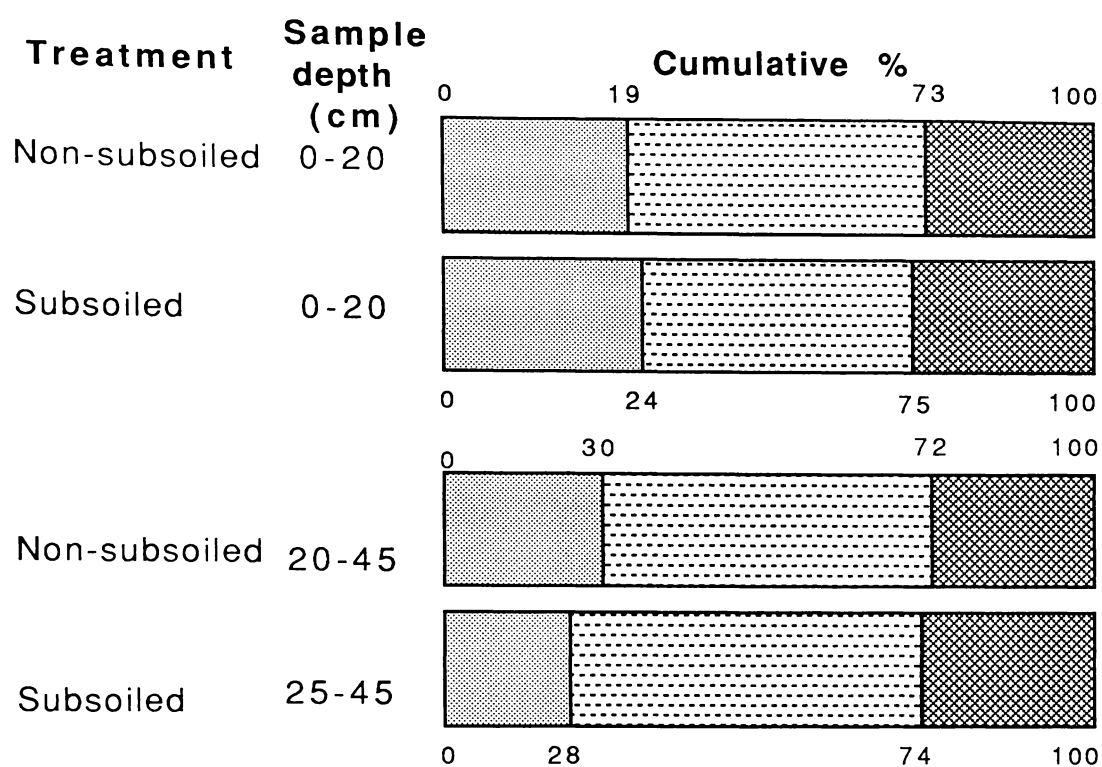


Figure 6.4.4 Te Kowhai soil, particle size distribution

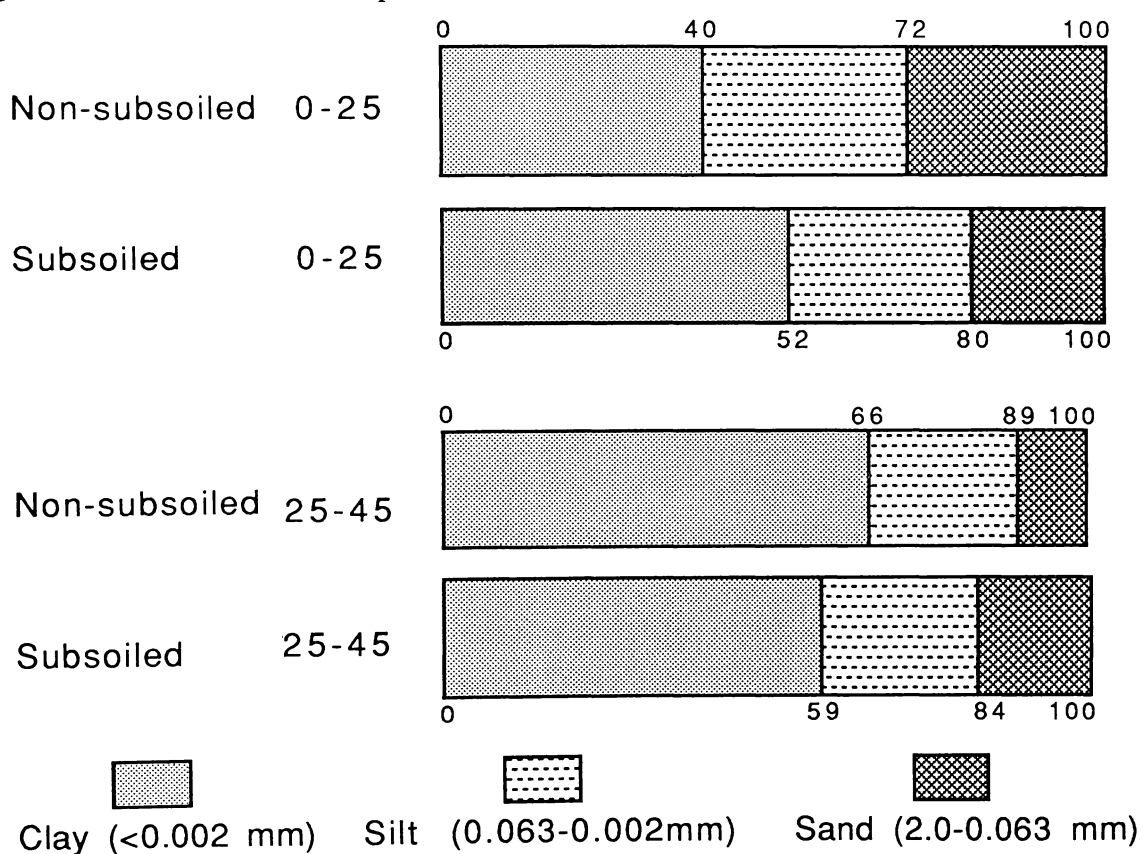


Figure 6.4.5 Whatawhata soil, particle size distribution

Table 6.4.1 shows that for Horotiu A horizon, subsoiling increased the silt fraction by 7% and decreased the clay fraction by 5%, sand fraction was not significantly changed. For the B horizon, there was a significant 7% increase in clay content with silt and sand largely unchanged (Figure 6.4.2).

Table 6.4.1 shows that for Rugby Park A horizon, subsoiling caused a significant 15% decrease in sand and a 7 and 5% increase in silt and clay respectively. For the B horizon, silt and clay were increased by 9 and 5% respectively but the sand fraction was relatively unchanged (Figure 6.4.3).

Table 6.4.1 shows that for Te Kowhai A horizon, subsoiling caused a significant 5% increase in the clay fraction, but other fraction percentages in this horizon and in the B horizon were not significantly changed (Figure 6.4.4).

Table 6.4.1 shows that for the Whatawhata A horizon, subsoiling caused a 12% increase in clay content and a 8% decrease in sand. For the B horizon, sand increased by 5% and clay decreased by 7%. Changes to the silt fraction were non-significant (Figure 6.4.5).

6.4.3 Discussion

Since a re-distribution of aggregates has already been reported (Chapter 5.1) it is suggested that particle size analysis and aggregate mixing are two aspects of the same thing, viz. the consequence of soil mixing. Textural change, could influence the workability of A horizon soil, especially under horticulture and cropping regimes. The timing of cultivation practices, such as ploughing or reseeding, which are to some extent dependant on a narrow range of soil moisture could also be influenced by this change. It must be remembered that this effect only occurs within 10 cm of the slot, which is equivalent to only 20% of soil under treatment. Nevertheless for Hamilton and Whatawhata soils a textural change from clay loam to clay for the A horizon may be important.

The redistribution of particle size fractions in response to subsoiling was variable. The clay fraction of the A horizons increased and the B horizon clay decreased in the Hamilton, Te Kowhai and Whatawhata soils. This response was predictable in that clay rich B horizons aggregates were forced up into higher soil horizons with a proportion of coarser A horizon aggregates falling into lower soil horizons

In Horotiu this effect is shown by a decrease in clay in the A and an increase in the B horizon due to its coarser B horizon..The overall increase in clay and decrease in sand content for Rugby Park soil in response to subsoiling is not easily explained.

6.5 CLAY MINERALOGY

6.5.1 Introduction

The final identification of clay minerals in soils is made after considering the evidence from a number of different analytical techniques. Differential thermal analysis (DTA), X-ray diffraction (XRD) and the Fieldes and Perrott (1966) test for allophane were used.

6.5.3 Results

Results presented in Table 6.5.1 were derived from assessment of results obtained from the various analytical methods shown in Appendix 4. The Hamilton soil contains trace amounts of allophane in its upper horizon; halloysite was present in both horizons, increasing for lower horizon samples. A small quantity of kaolin was detected in the B horizon. Horotiu soil is allophane dominant, with more present in the A horizon than in the B. Rugby Park and Te Kowhai soils are similar. Halloysite is common with lesser amounts in A horizon than in B horizon samples. Whatawhata Bg horizon is dominated by kaolin with lesser amounts in the A horizon. Halloysite is also present in both horizons.

Table 6.5.1 Clay Mineral Analysis

Soil Type	Horizon	Allophane*	Halloysite*	Kaolinite*
Hamilton clay loam	A	Trace	Common	Nil
	B	Nil	Common	Trace
Horotiu sandy loam	A	Common	Trace	Nil
	B	Present	Present	Nil
Rugby Park soil	A	Nil	Common	Nil
	B	Nil	Common	Nil
Te Kowhai silt loam	A	Nil	Common	Nil
	B _g	Nil	Common	Nil
Whatawhata clay loam	A	Nil	Present	Present
	B _g	Nil	Trace	Common

* For all clay minerals, common = >50%, present = 10-50%, trace = <10%

6.5.4 Discussion

The importance of clay mineralogy in this study is the effect it may have on the response of soils to subsoiling. Clays identified in this study fall into two groups, allophane, and the layer silicates halloysite and kaolin.

The Hamilton soil contains trace amounts of allophane in the A horizon, which is derived from the weathering of Late Pleistocene and Holocene tephras. The occurrence of a trace amount of kaolin in the B horizon is probably a function of the age of the older Hamilton Ash Formation. A characteristic of the Hamilton B horizon in summer is the appearance of large prismatic structure, which is a reflection of the shrinkage characteristics of halloysite. The durability of subsoiling in this soil, may be related to the permanence of structural cracks, originally created by the subsoiler tip and shank but maintained by the distinctive swell and shrink characteristics of this relatively high clay soil.

The Horotiu A horizon exhibits a strong granular structure, with a characteristic "fluffy feel" attributed to the presence of allophane, its high permeability favours allophane over halloysite.

Te Kowhai and Rugby Park soil contain halloysite, shown by typically large asymmetric endothermic peaks at about 500°C (Appendix 4). Allophane is absent reflecting the low permeability of this soil, which favours the formation of halloysite rather than allophane (Parfitt *et al.*, 1983, Singleton *et al.*, 1989).

The Whatawhata soil is characterised by a kaolin rich B_g horizon, with only small amounts of halloysite and no allophane. The formation of kaolin in this soil is probably a function of the parent material, which is alluvium of sedimentary and volcanic rocks. The degree and rate of weathering, has created a clay dominant B_g horizon, of low permeability, resulting in a poorly drained soil. The factors of low permeability and poor drainage are conducive to the formation of kaolin. The three methods used for clay mineral analysis are semi quantitative, three clay minerals, allophane, halloysite and kaolinite, were identified which individually impose certain pedological controls on soil structure. The blocky to prismatic subsoils of the Hamilton, Te Kowhai and Whatawhata soils exhibit relatively large structural cracks in summer, which reflects the presence of halloysite and kaolin. Horotiu soil however exhibits a characteristic "fluffy" granular structure reflecting the presence of allophane. Structural cracks caused by subsoiling are not maintained in the granular allophane Horotiu and the effect of subsoiling is not as long lasting. Hence the durability of subsoiling may to some extent be a function of clay mineralogy, that is structural cracks are more likely to be maintained, where crystalline clays shrink and swell in response to seasonal fluctuations in soil moisture.

6.6 IMAGE ANALYSIS

6.6.1 Introduction

The description of soil structure has historically revolved around the size and shape of aggregates, rather than their arrangement in the soil. More recently image-analysing computers (Ringrose-Voase and Bullock 1984) have shown how to quantify the size and shape of pores between and within soil aggregates. These measurements provide information on the volume of pores in the soil and their

configuration. This is fundamental to the understanding of water transmission and storage, the movement of gases and the penetration of roots. Image analysis in this study was used to quantify pore volume for both subsoiled (vibrating) and non-subsoiled core samples.

6.6.2 Results

Table 6.6.1 shows pore volume calculated from image analysis data (Chapter 5.5) at two depths and at distances up to 40 cm from the slot for subsoiled and non-subsoiled profiles. There was no attempt to recognize and measure the different types of pores as described by Ringrose-Voase and Bullock (1984). A typical two-dimensional image obtained by fluorescent photography of an impregnated Hamilton non-subsoiled B horizon soil core is shown in Appendix 6. The shaded 4% fractional area represents pores $>9.76\mu\text{m}$.

Table 6.6.1 % total pore volume $> 9.76\mu\text{m}$

Soil Type	Core depth (cm)	Horizon	Distance from slot (cm)					Non-subsoiled
			4	10	20	30	40	
Hamilton Clay Loam	15	A	38*	34*	26*	26*	21	20
	35	B	30*	21*	5	7	5	4
Te Kowhai silt loam	15	A	34*	31*	24	23	21	23
	35	B _g	26*	22*	7*	4	4	3
Whatawhata clay loam	15	A	32*	31*	29*	30*	20	19
	35	B _g	35*	32*	21*	6*	3	3

* significantly different from non-subsoiled ($P < 0.05$)

There were significant increases in porosity following subsoiling in all soils up to 30 cm distance from the slot. The greatest percentage increases were recorded at the 4 and 10 cm distance from slot, for the B, B_g and B_g horizons for Hamilton, Te Kowhai and Whatawhata soils respectively, where porosity $>9.76\mu\text{m}$ increased from approximately 3% for non-subsoiled to 21 - 35% for subsoiled. Similarly the approximate increases for A horizons were from 20 for non-subsoiled to 35% for subsoiled. The Hamilton and Whatawhata A horizons had significant increases to 30 cm distance from slot, whereas in the Te Kowhai it was restricted to 10cm.

6.6.3 Discussion

Samples taken before subsoiling give the usual characteristics of the soils, where mean porosity ($>9.76 \mu\text{m}$) was approximately 20% for the A horizon and 3.5% for the B and Bg horizons. Soils were reasonably dry when subsoiled and structural cracks formed emanating from the subsoiler shanks and tips causing increased porosity in all soils.

The increases in the B and Bg horizons can be attributed to the vibrating tip whereas the increases in A horizon porosity can be attributed to the near surface heave described earlier in Chapter 4.6. Subsoiled lower horizons show the greatest response, with porosity within 10 cm distance of the slot increasing to equal the levels in the A horizon. Increase in porosity extended further away from the slot for Hamilton and Whatawhata soils, compared to Te Kowhai soil perhaps reflecting a greater volume of soil disturbance in these more clayey soils.

6.7 SCANNING ELECTRON MICROSCOPY (SEM)

6.7.1 Introduction

A microscopic investigation of soil aggregates non-subsoiled and subsoiled was carried out to help explain the complex organisation of skeletal grains, pores and clays. SEM provides an enlarged three-dimensional view of essentially unmodified skeleton grains, from which it is hoped to elucidate evidence for skeletal coatings and densely packed skeletal grain frameworks. Such features contribute to bulk density, porosity and can influence root elongation. A number of aggregate fracture surfaces were examined. A selection of micrographs are shown (Figures 6.7.1 - 6) to illustrate distinctive soil features.

6.7.2 Results.

Figure 6.7.1 shows a pore and fracture surface of a Hamilton B horizon aggregate. The micrograph consists of mainly pseudo hexagonal shaped kaolinite platelets, which in the lower left quarter of the micrograph are characterised by their staggered appearance and have formed through the displacement of successive clay layers. The arrangement of the clay platelets is predominantly face to face, forming a laminar or book microstructure. The clay layers bound an irregular pore varying

in width from 60 to 30 μm and about 30 μm deep. Distinctive clay bridge- like structures can be seen within the pore, which appear to partially seal the pore in this area.

Figure 6.7.2 shows a Horotiu B horizon aggregate. The fracture surface consists of poorly sorted silt sized skeletal grains, which are thinly coated with clay. A minority of the grains are linked by thin bridges, but the majority are bounded by irregular, but seemingly continuous pores, ranging in width from 8 - 2 μm .

Figure 6.7.3 shows a Rugby Park A horizon aggregate. The micrograph shows a pore and fracture surface of predominantly uncoated silt-size grains, which are aligned in close-packed layers, orientated parallel to the ground surface. The dense interlocking arrangement of the grains is characteristic of a low porosity, high strength soil layer.

Figure 6.7.4 shows a Te Kowhai B horizon aggregate. The micrograph shows a pore and fracture surface, consisting of clay coated grains which consist of clay plates orientated to the grain surfaces. Virtually all skeletal grains are bridged by clays at points of contact. The prominent triangular shaped, 30 μm size grain, seen in the lower right quarter, appears to have been displaced along the fracture surface bounding it; thus creating an inter-grain pore, 2 - 4 μm in width and approximately 10 μm in depth.

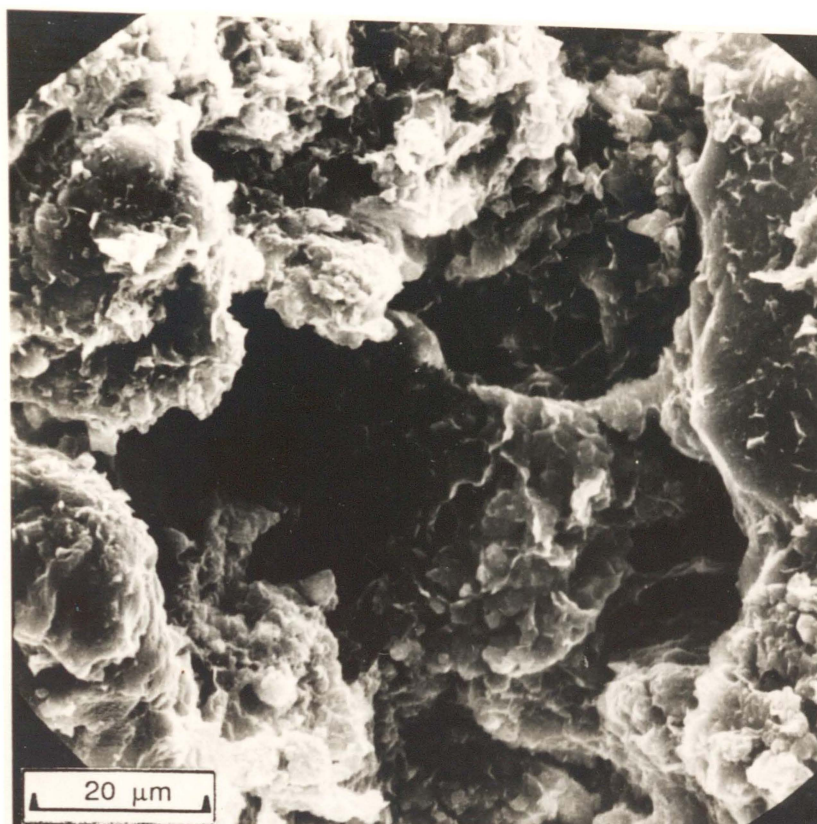


Figure 6.7.1 Hamilton clay loam, high resolution SEM of a B horizon aggregate (subsoiled).

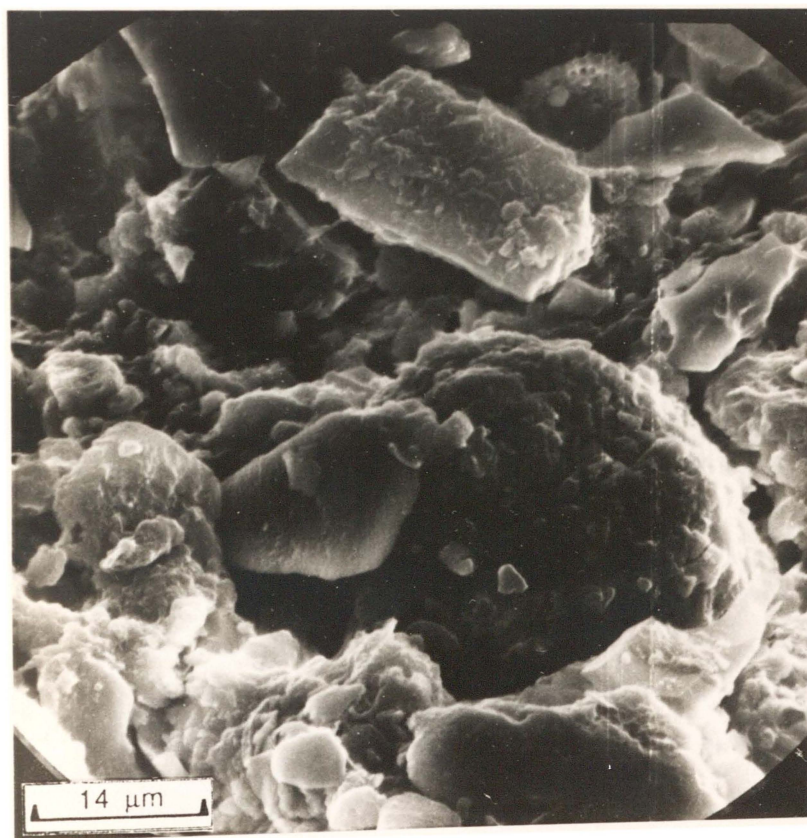


Figure 6.7.2 Horotiu sandy loam, high resolution SEM of a B horizon aggregate (subsoiled).



Figure 6.7.3 Rugby Park soil, high resolution SEM of A horizon aggregate (non-subsoiled)

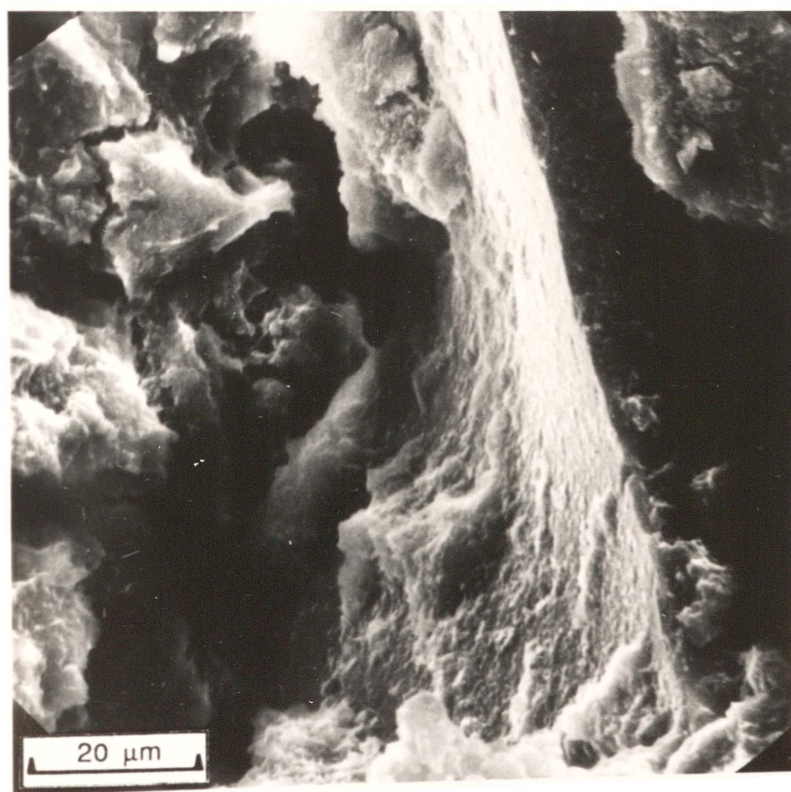


Figure 6.7.4 Te Kowhai silt loam, high resolution SEM of B horizon aggregate (subsoiled).

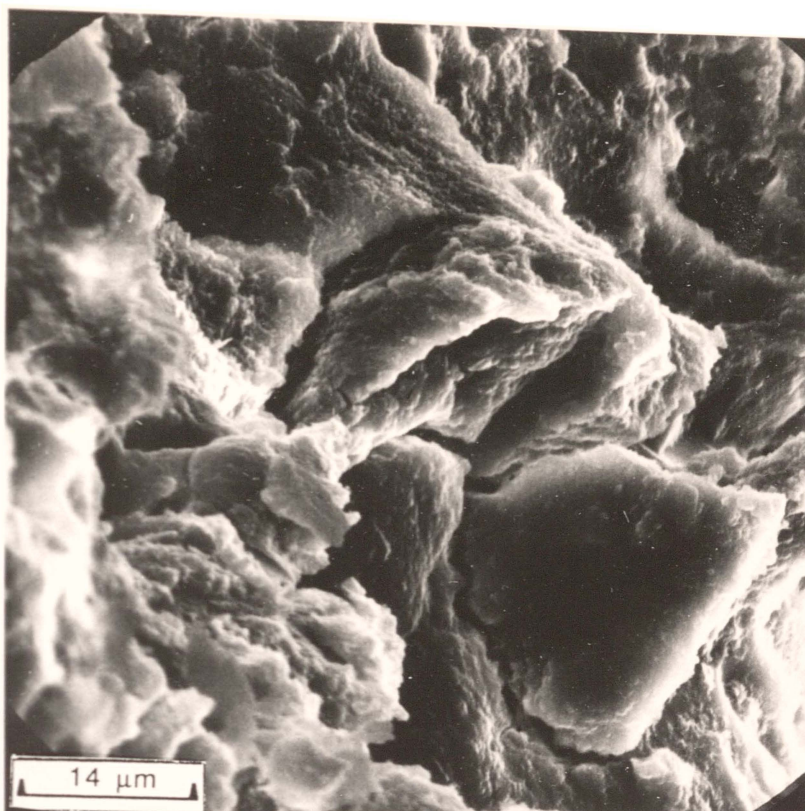


Figure 6.7.5 Te Kowhai silt loam, high resolution SEM of A horizon aggregate (non-subsoiled)

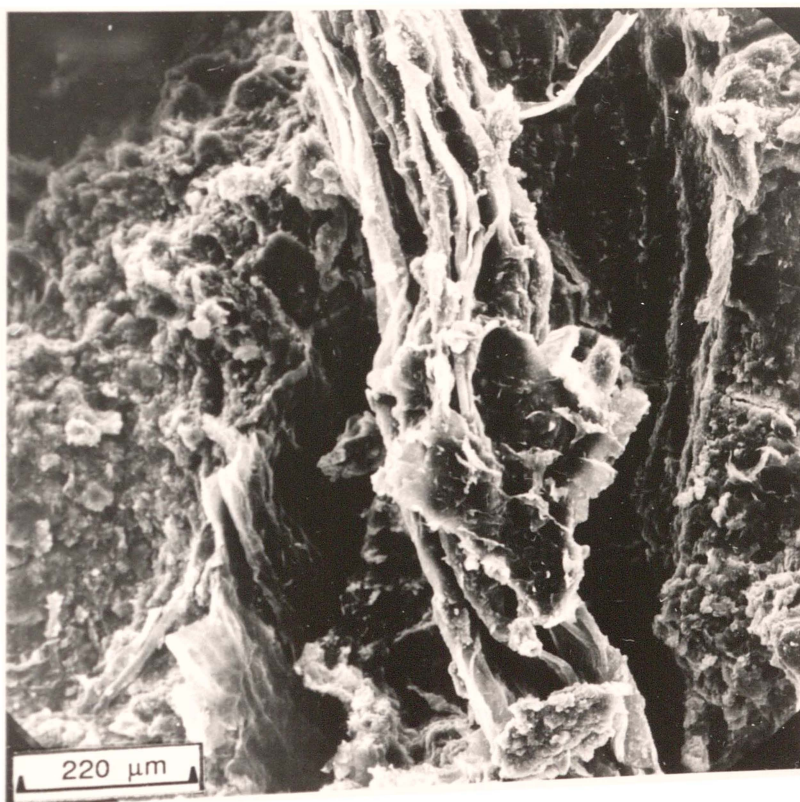


Figure 6.7.6 Whatawhata clay loam, high resolution SEM of B horizon aggregate containing grass rootlet (non-subsoiled).

Figure 6.7.5 shows a Te Kowhai A horizon aggregate. The micrograph shows a pore and fracture surface, dominated by a silt sized grain. The grain is coated with scattered amorphous particles, which in some areas become more organised and thicken into pseudo triangular layered structures which protrude up to 6 μm from the grain surface. The inter-granular pores are predominantly continuous and range from 15 - 40 μm in diameter.

Figure 6.7.6 shows a Whatawhata B horizon aggregate containing a grass rootlet. The micrograph shows a pore and fracture surface, and corrugated root trace. The section of rootlet displayed is 1000 μm long and varies in diameter from 60 - 100 μm , thickening towards the bottom of the micrograph. The root has elongated along and parallel to the orientation of the layered clay platelets. The clay layers in this aggregate are orientated horizontally with respect to the ground surface. The rootlet appears to have ruptured in the centre of the micrograph, with cell tissue torn away, exposing the inner cells of the growing root. The increase in rootlet diameter could be in response to increasing impedance, caused by the densely packed kaolinitic clay layers, which are characteristic of this soil.

6.7.3 Discussion

The more ordered closely packed clays of the Hamilton and Whatawhata B horizon with their continuity and linking of skeletal grains suggest bonding or cementation. Such features contribute to relatively high bulk density and low macroporosity that is sometimes encountered in these soils.

The dense interlocking arrangement of skeletal grains, many of which are bridged at points of contact is characteristic of the Te Kowhai B horizon and reflect the relatively high strength, low permeability of this soil.

The Rugby Park sample also showed a dense interlocking arrangement of grains but these were largely uncoated. Failure of the soil mass as a result of subsoiling or penetration will require displacement of grains from the plane of shearing to overcome interlocking effects. This action must involve an increase in soil volume and hence a reduction in bulk density.

The relatively low clay content of the Horotiu soil and “open” fabric reflects the low bulk density and low strength of this soil. The profile description of this soil

(Chapter 3.5) shows that root growth is extensive thus corroborating micromorphological observations which show a relatively "open" structure with continuous pores.

Plant roots are rarely seen at depths greater than 25 cm in the Whatawhata soil, this may be a reflection of water logging and/or high soil strength. In this study microscopic evidence suggests that the nature of the densely packed clay platelets which bridge skeletal grains in this soil must result in enhanced soil strength, which in turn must be restrictive to root penetration. The resistance to root elongation shown, further corroborates the relatively high strength nature of the Whatawhata Bg horizon.

SEM provided much information on the microstructure of aggregates but the technique was not able to discriminate between subsoiled and non-subsoiled aggregates.

6.8 ORGANIC CARBON, TOTAL NITROGEN, C/N RATIOS

6.8.1 Introduction

The determination of organic carbon (C) and total nitrogen (N) and C/N ratio is a method of characterising organic matter in the soil.

In this study soil mixing between A and B horizons occurs as a result of subsoiling. The analysis for carbon and nitrogen may therefore provide further information on the degree of mixing and whether changes in organic status are transient or long lasting. Horotiu, Rugby Park and Whatawhata sites were not chosen for this part of the study because of time constraints. Nevertheless the results obtained for Hamilton and Te Kowhai soils should be applicable to other soils.

6.8.2 Results

Results for carbon %, nitrogen % and C/N ratio are given in Tables 6.8.1 and 6.8.2. The Tables show changes with time, following subsoiling for Hamilton and Te Kowhai soils. Figures 6.8.1 - 4 show a comparison of percent carbon values for the B horizon for up to two years after subsoiling.

Table 6.8.1 Chemical analyses - results from the means of four plots

Soil type	Sampling Date	Depth** (cm)	%C	%N	C/N	Subsoiled (S) Non subsoiled (NS)
Hamilton clay loam Subsoiled 7/10/86	7/10/86	5	9.6	0.60	16	NS
		25	1.6	0.16	10	NS
		35	0.5	0.12	4	NS
	2/2/87	5	9.8	0.54	18	NS
		5	9.7	0.60	16	S
		25	1.6	0.19	8	NS
		25	1.9*	0.18	10	S
		35	0.5	0.16	3	NS
		35	0.8*	0.17	5	S
	2/6/87	5	9.2	0.62	15	NS
		5	9.6	0.72	14	S
		25	1.6	0.21	8	NS
		25	1.9*	0.30*	6	S
		35	0.5	0.12	4	NS
		35	0.9	0.15	6	S
	11/12/87	5	9.3	0.54	17	NS
		5	9.4	0.69	15	S
		25	1.6	0.26	7	NS
		25	2.1*	0.31*	7	S
		35	0.5	0.12	4	NS
		35	0.9*	0.16*	6	S
	3/6/88	5	10.2	0.70	14	NS
		5	10.0	0.69	14	S
		25	1.5	0.18	8	NS
		25	2.0*	0.20	10	S
		35	0.5	0.10	5	NS
		35	1.0*	0.15*	7	S
	6/9/88	5	9.0	0.56	16	NS
		5	11.0	0.68	16	S
		25	1.5	0.19	8	NS
		25	1.9*	0.20	10	S
		35	0.5	0.11	5	NS
		35	0.9*	0.14	7	S

* significantly different from non-subsoiled ($P < 0.05$)

** 5 cm = A horizon 25, 35 cm = B horizon.

Table 6.8.2 Chemical analyses - results expressed as the means of four plots.

Soil type	Sampling Date	Depth** (cm)	%C	%N	C/N	Subsoiled (S) Non subsoiled (NS)
Te Kowhai subsoiled 2/3/87	2/3/87	5	7.8	0.55	14	NS
		15	4.4	0.41	10	NS
		25	1.4	0.12	12	NS
		35	0.2	0.04	6	NS
	2/6/87	5	7.4	0.59	13	NS
		5	7.3	0.52	14	S
		15	4.5	0.40	10	NS
		15	4.6	0.41	10	S
		25	1.3	0.14	9	NS
		25	2.1*	0.18*	11	S
		35	0.1	0.04	2	NS
		35	0.5*	0.11*	5	S
	11/12/87	5	8.2	0.72	12	NS
		5	8.6	0.61	14	S
		15	3.7	0.46	8	NS
		15	4.0	0.45	9	S
		25	1.3	0.13	10	NS
		25	1.7*	0.17*	10	S
		35	0.1	0.02	9	NS
		35	0.5*	0.12*	4	S
	3/6/88	5	7.7	0.64	12	NS
		5	7.9	0.68	12	S
		15	4.6	0.44	10	NS
		15	4.3	0.57	8	S
		25	1.3	0.14	9	NS
		25	1.7*	0.18*	9	S
		35	0.3	0.06	5	NS
		35	0.7*	0.10*	7	S
	6/9/88	5	7.2	0.70	10	NS
		5	7.4	0.76	10	S
		15	4.3	0.40	10	NS
		15	4.9	0.50	10	S
		25	1.3	0.11	12	NS
		25	1.6*	0.17*	9	S
		35	0.2	0.04	6	NS
		35	0.5*	0.07	8	S

* significantly different from non-subsoiled (P<0.05)

** 5, 15 cm = A horizon 25, 35 cm = B_g horizon

Table 6.8.1 shows that for Hamilton soil, four months following subsoiling there was a significant increase in B horizon carbon. This increase persisted throughout the duration of the trial as shown in Figures 6.8.1 - 2. B horizon nitrogen levels, however, fluctuated over this time period, increasing significantly eight months after subsoiling, but falling to non-subsoiled levels twenty months after subsoiling. A horizon carbon was not significantly changed, nitrogen values generally increased but not significantly and C/N ratios were essentially unchanged throughout the monitoring period.

Table 6.8.2 shows that for Te Kowhai soil, three months following there was a significant increase in Bg horizon carbon. Levels thereafter were lower but were nevertheless significantly higher than non-subsoiled, as shown in Figures 6.8.3 - 4.

Bg horizon nitrogen trends were similar to carbon, hence C/N ratios were largely unchanged. A horizon carbon and nitrogen levels, over an eighteen month period, were not significantly changed, following subsoiling.

6.8.3 Discussion

The main effects of subsoiling were to increase subsoil carbon and nitrogen^{due to mixing}. This increase was maintained over a two year period. The incorporation of A horizon aggregates into lower soil layers after subsoiling is the most likely cause of the increase. Deeper rooting of plants into the subsoil as discussed (Chapter 4.8) must also increase organic matter at these soil depths.

Generally both soils responded similarly, although Hamilton soil exhibited a higher carbon content when compared with Te Kowhai. Interestingly the carbon and nitrogen values for the A horizon in both soils was not significantly changed following subsoiling. It was expected that values would drop, in response to the interchange of A and B horizon aggregates^{but}. This did not occur.

These changes could significantly enhance soil fertility by increasing moisture holding capacity. Increased B horizons moisture could play an important role in sustaining pasture growth, through dry summer conditions which often occur on Hamilton and Horotiu soils and to a lesser extent on Te Kowahi and Whatawhata soils.

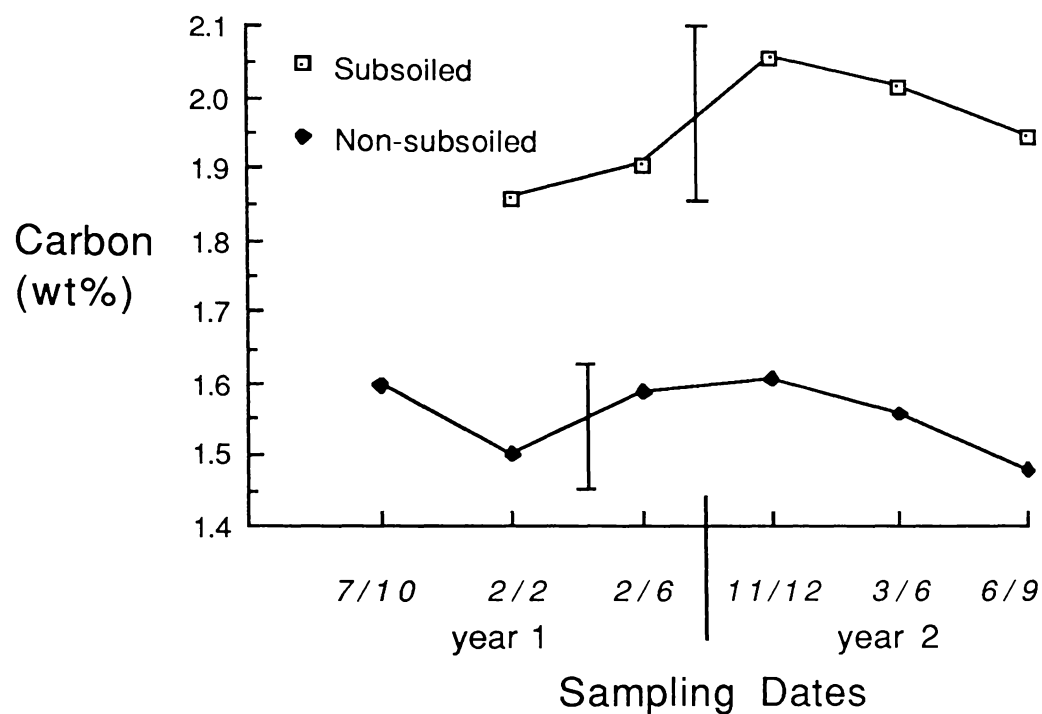


Figure 6.8.1 Hamilton soil (25 cm depth), % carbon with time LSD ($P = 0.05$)

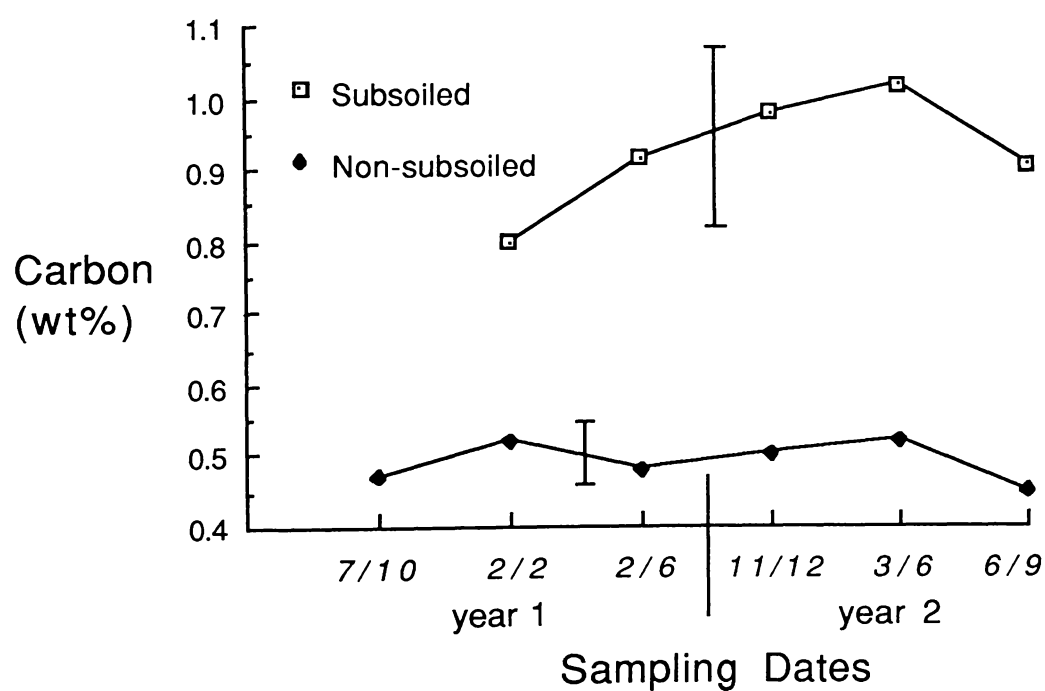


Figure 6.8.2 Hamilton soil (35 cm depth), % carbon with time LSD ($P = 0.05$)

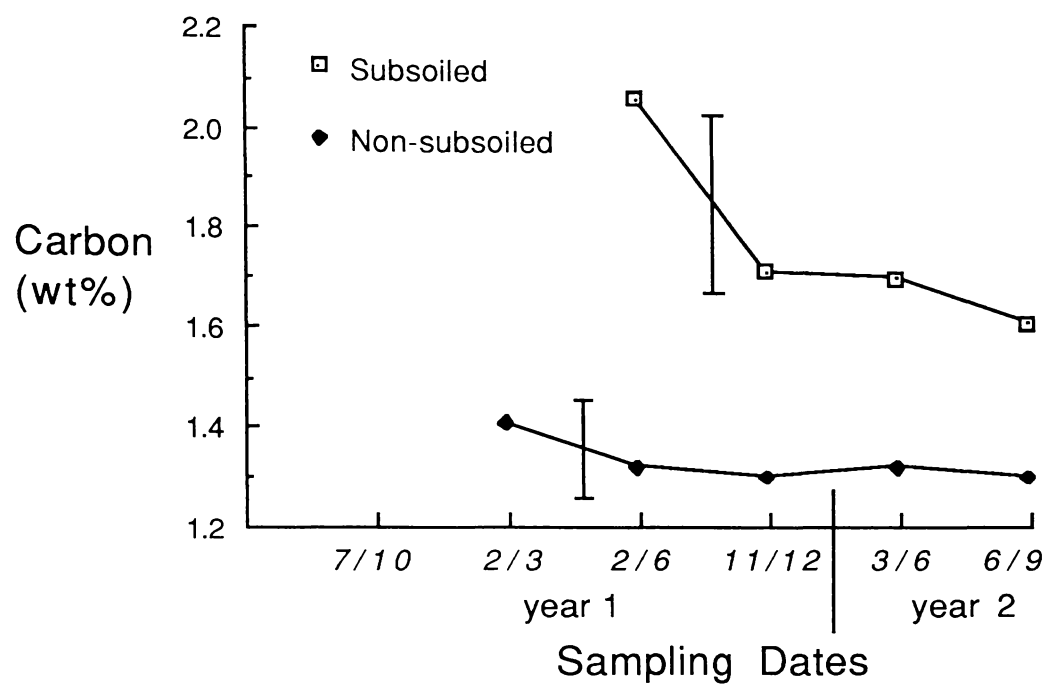


Figure 6.8.3 Te Kowhai soil (25 cm depth), % carbon with time. (LSD ($P = 0.05$))

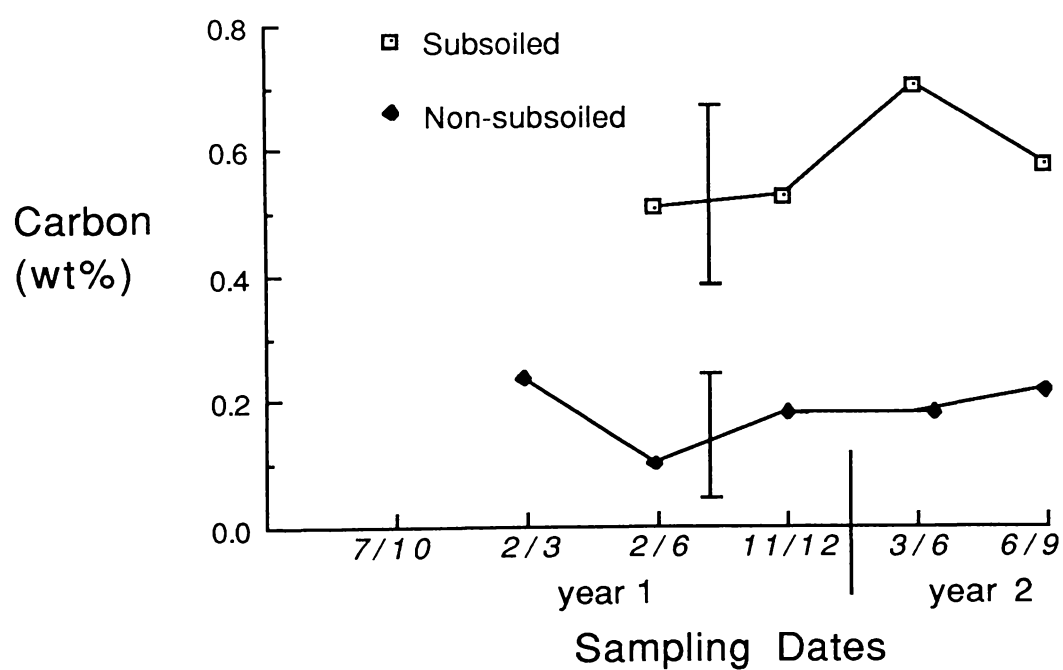


Figure 6.8.4 Te Kowhai soil (35 cm depth), % carbon with time. (LSD ($P = 0.05$))

CHAPTER SEVEN

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CHAPTER 7: DISCUSSION AND CONCLUSION

7.1 REVIEW OF AIMS AND OBJECTIVES

The aims of this study were to design a subsoiler suitable for soils under pasture, to make recommendations on subsoiler operational parameters, to characterise the effect of subsoiling on soil physical properties and crop production and to assess those soil properties which maintain the effects of subsoiling.

These aims were accomplished by testing a number of prototype subsoilers under various soil conditions, operating speeds and depths on different soils. The effect of subsoiling was assessed by extensive field and laboratory determinations which included bulk density, penetrometer resistance, infiltration rates, moisture tension determination, soil disturbance and volume changes, aggregate size distribution, horizon mixing and carbon and nitrogen content. Image analysis was used to assess changes in porosity and SEM was used to evaluate the microstructure of soil aggregates. Root growth and pasture dry matter were measured.

Soil properties affecting subsoiling were assessed, these included particle size analysis (which was to some extent affected by subsoiling), mineralogical analysis of the clay fraction, soil structural characteristics and gravimetric soil moisture.

7.2 BASIC SOIL CHARACTERISTICS OF THE FIVE SOILS IN THIS STUDY

Hamilton, Horotiu and Te Kowhai soils are widely distributed within the Hamilton Basin. Whatawhata soil however occupies a relatively small area (15,000 ha) and Rugby Park, an artificially constructed soil is only 0.8 ha. The distribution and differences between the natural soils is a function of parent material, topography and time.

Hamilton clay loam is formed from the upper members of the late Pleistocene Hamilton Ash Formation and occupies the more stable slopes of the rolling Hamilton Hills, consequently weathering is advanced and clay contents dominated by halloysite are

high. The B horizon has a coarse blocky to medium prismatic structure and is moderately well drained.

Horotiu sandy loam is formed from the coarser material of the Hinuera sediments and occupies the ridges of the Hinuera surface. The B horizon has a fine granular structure, is well drained and the clay fraction is dominated by the mineral allophane.

The high sand content of the Rugby Park A horizon is due to annual top dressing of sand and is highly compacted by players, reflecting winter sports use under high soil moisture. The B horizon has a blocky to massive structure, is well drained (artificially) and the clay fraction is halloysite dominant.

Te Kowhai silt loam is formed from the more silty alluvium of the Hinuera sediments and occupies the swales of the Hinuera surface. It has a weakly developed blocky to prismatic gleyed B horizon and the clay fraction is dominated by the mineral halloysite.

Whatawhata clay loam is developed on alluvium from sedimentary and volcanic rocks. The B horizon is dominated by kaolin clay and is yellowish brown in colour with many prominent orange mottles. It has moderately developed medium prismatic structure and is poorly drained. Livestock treading causes pugging in winter months, the effect of which persists into summer when the soil dries out and hardens.

7.3 MEASURING THE EFFECTS OF SUBSOILING

In order to test the effectiveness of subsoiling under various operating modes and soil conditions a number of soil physical properties were measured over time. These included bulk density, soil strength and soil mixing. Root growth and pasture production effects as a result of subsoiling were also measured.

7.3.1 Bulk density

Table 7.3.1 summarises bulk density data found in Figures 4.1.1 - 5. The values clearly indicate the magnitude and extent of changes in bulk density and the durability of these changes with time.

Table 7.3.1 Bulk density *in situ* (SDG) mean profile values (Mg m⁻³)

(a) Hamilton clay Loam

Months following subsoiling in July		Distance from subsoiled slot (cm)			
		10	20	30	Non-subsoiled
0	(33)	0.85	1.12	1.24	1.23
5	(23)	1.07	1.20	1.24	1.31
12	(36)	1.12	1.22	1.23	1.25
17	(19)	1.14	1.22	1.25	1.29

(b) Horotiu Sandy loam

December					
0	(18)	0.67	0.74	0.86	0.95
11	(20)	0.87	0.88	0.93	1.00

(c) Rugby Park soil

October					
0	(26)	1.09	1.10	1.15	1.22
2	(18)	1.16	1.19	1.20	1.23

(d) Te Kowhai Silt loam

December					
0	(20)	0.73	0.99	1.08	1.17
7	(39)	0.89	1.05	1.07	1.12
12	(18)	0.85	1.03	1.09	1.15
24	(22)	1.02	1.05	1.10	1.14

e) Whatawhata Clay loam

December					
0	(18)	1.01	1.07	1.23	1.32
12	(19)	1.04	1.15	1.28	1.30
23	(22)	1.17	1.24	1.32	1.36

Soil moisture % is given in parentheses

The magnitude of bulk density reduction due to subsoiling is closely related to distance from the subsoiled slot. Largest reductions at 10 cm distance reflect the area of greatest soil disturbance and soil heave. After detailed analysis of data (Chapter 4.1.7) it was decided that changes in bulk density for the 20 cm distance from slot profile would be

used to explain the persistence of subsoiling effects for different soils. Figure 7.3.1 shows general trends and relationships between soils at 20 cm distance. The percentage difference between subsoiled and non-subsoiled values decrease with time, this is a measure of ^{structural} instability of the soils.

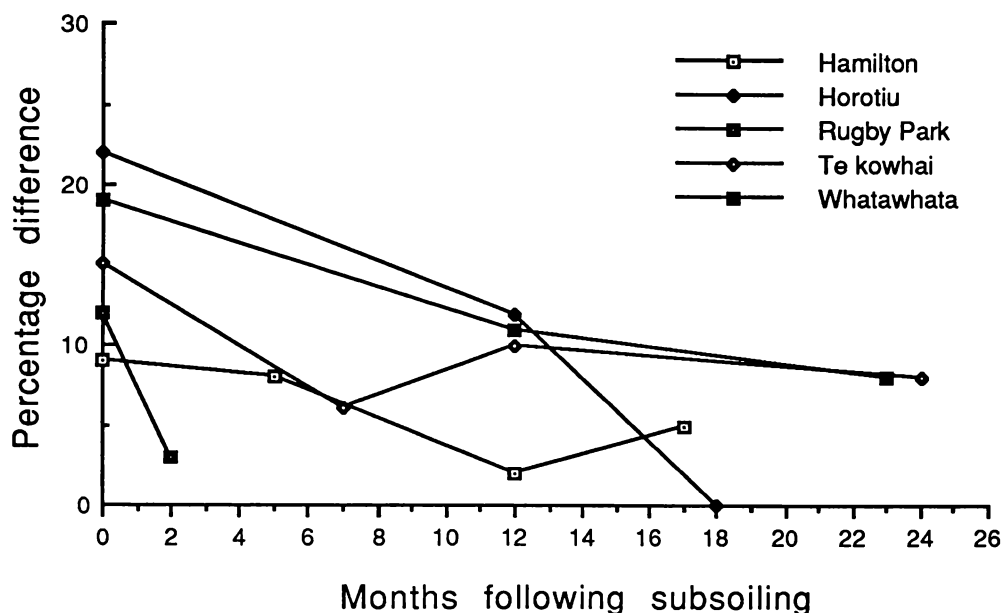


Figure 7.3.1 Percentage reduction in bulk density at the 20 cm distance from slot for subsoiled in comparison with non-subsoiled

Long term assessment of the effects of subsoiling for Rugby Park is uncertain, but a rapid return towards pre-subsoiling levels is likely. Horotiu soil showed the largest response to subsoiling but the effects were less durable than the other soils (excluding Rugby Park) and returned to pre-subsoiling values in eighteen months. Hamilton, Te Kowhai and Whatawhata soils show better stability with effects lasting more than 17, 24 and 23 months respectively. The reasons for differences in durability will be discussed in Chapter 7.3.11.

Figures 7.3.2 and 7.3.3 show the relationship between the wax and SDG methods for determining bulk density. The non-subsoiled column (Table 7.3.2) gives mean values obtained over the duration of the study, whereas subsoiled values were determined immediately following subsoiling.

Soil shrinkage effect on bulk density was probably the cause of fluctuations in bulk density for non-subsoiled plots (Table 7.3.1). Both Hamilton and Te Kowhai soils

recorded higher values for dry soils (18 - 23% moisture) when compared with wet (33 - 39% moisture). The effect of soil shrinkage on bulk density was briefly mentioned (Chapter 4.1.1). Shrinkage due to loss of water was shown in smectite soils by McGarry and Daniells (1987). Allbrook (in press 1992) suggests that shrinkage is a general phenomenon and not only confined to smectite soils. The importance of this is that all soils with at least a moderate clay content shrink, and therefore bulk densities change with moisture and this must be allowed for in such calculations as soil moisture on a volume basis.

The two methods correlated closer for non-subsoiled determinations ($R^2 = 0.83$) than for subsoiled ($R^2 = 0.39$). The differences can be explained by the fact that SDG is a measure of bulk density *in situ*, whereas the wax method is applied to discrete soil aggregates in the laboratory. SDG integrates both inter and intra-aggregate density and therefore incorporates the extensive inter-aggregate cracks found within 10 cm distance of the subsoiled slot, hence SDG values are significantly lower when compared with the wax method and do not closely correlate because of the random nature of cracking.

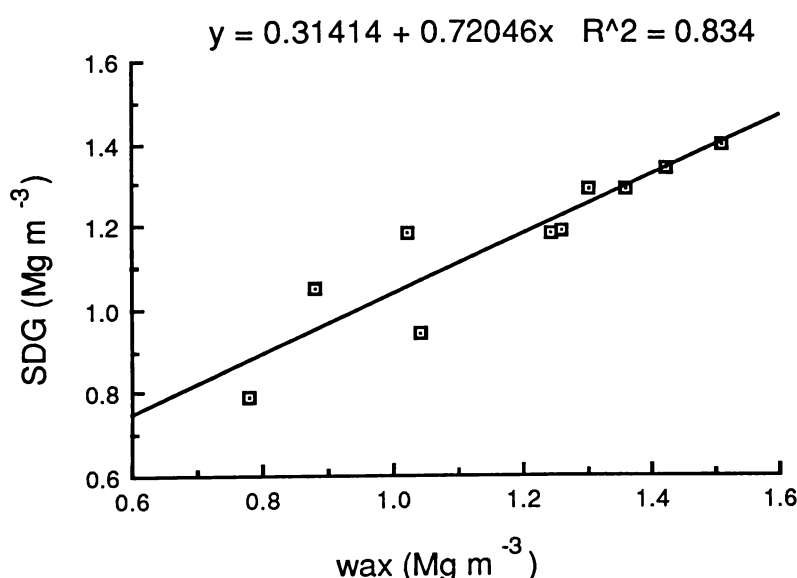


Figure 7.3.2 Relationship between bulk density determinations for five non-subsoiled soils.

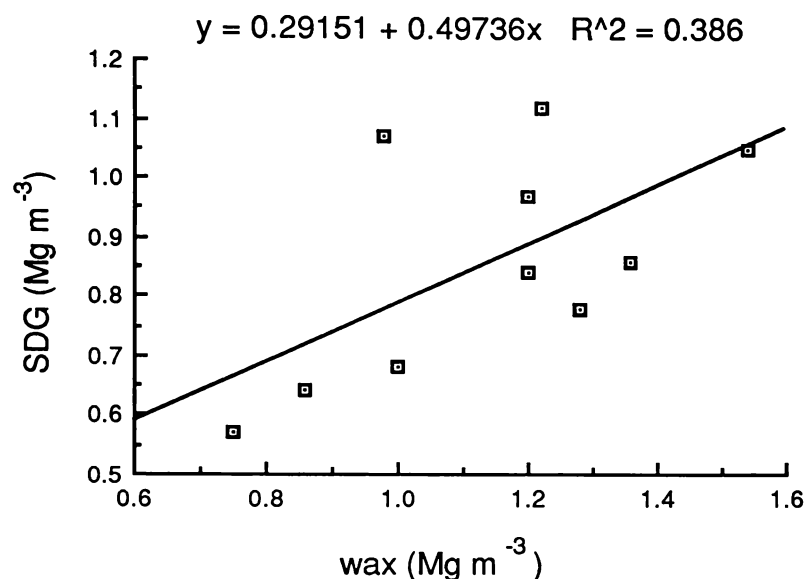


Figure 7.3.3 Relationship between bulk density determinations for five subsoiled slots.

Table 7.3.2 Bulk density wax method (Mg m⁻³), SDG values in ()

Soil Type	Horizon	Non-subsoiled		Subsoiled (10 cm from slot)	
Hamilton	A	1.24	(1.18)	1.20	(0.84)**
	B	1.42	(1.34)	1.36	(0.86)**
Horotiu	A	0.78	(0.79)	0.75	(0.57)**
	B	0.88	(1.05)**	0.86	(0.64)**
Rugby Park	A	1.36	(1.29)*	1.22	(1.12)*
	B	1.02	(1.18)**	0.98	(1.07)*
Te Kowhai	A	1.04	(0.94)*	1.00	(0.68)**
	Bg	1.30	(1.29)	1.28	(0.78)**
Whatawhata	A	1.26	(1.19)	1.20	(0.97)**
	Bg	1.51	(1.40)*	1.54	(1.05)**

SDG values significantly different from wax method * (P<0.05) **(P<0.01)

In this study the effectiveness of subsoiling was effectively measured by bulk density (SDG) determinations. Bulk density was significantly reduced immediately following subsoiling and gradually increased as the disrupted soil re-compacted towards pre-subsoiling levels. Similar trends have been reported by Vepraskas (1988) and Greenwood (1989).

7.3.2 Soil strength

Soil strength as measured by a penetrometer provided valuable information on the magnitude, extent and sustainability of soil disturbance.

Table 7.3.3 summarises data found in Chapter 4.2 showing changes in soil strength with time following subsoiling. Figure 7.3.5 shows a graph of percentage reduction in soil strength against time at 21 cm depth and 20 cm distances from slot profile. These distances were chosen because they are midway between the slot and the outer limits of disturbed ground hence representing the “middle ground”. The soils were subsoiled at various soil moistures (Table 7.3.3) and this is reflected in a wide range of strength measurements. Hamilton was subsoiled at 33% moisture and recorded profile strength of 2.31 MPa, five months later at 23% moisture mean strength had increased to 4.11 MPa. The effect of soil moisture on soil strength is shown in Figures 7.3.6a, b, c, d, e. Data show that soil strength is moderately well correlated with soil moisture for Hamilton, Te Kowhai and Whatawhata soils and weakly correlated for Horotiu (narrow moisture range) and Rugby Park. The figures show that at 30% moisture the more clayey soils, Hamilton and Whatawhata exhibit the lowest strength.

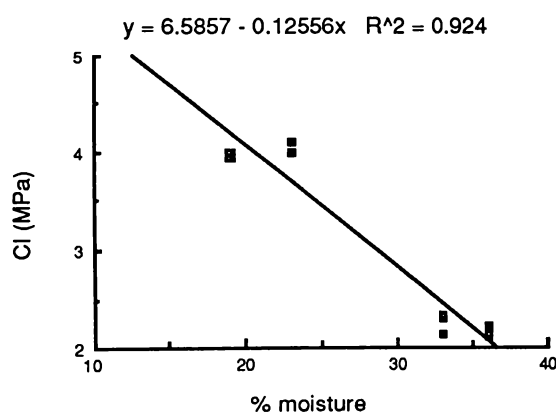


Figure 7.3.6(a) Relationship between % moisture and CI for Hamilton soil.

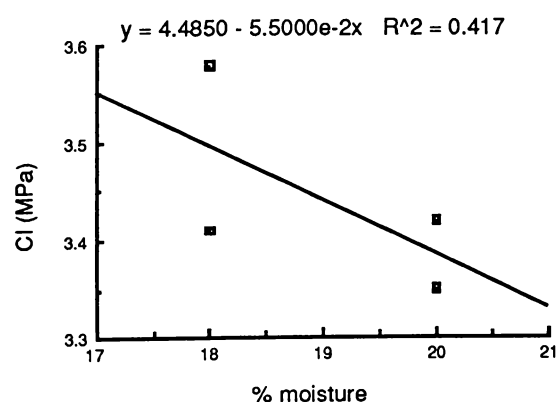


Figure 7.3.6(b) Relationship between % moisture and CI for Horotiu soil.

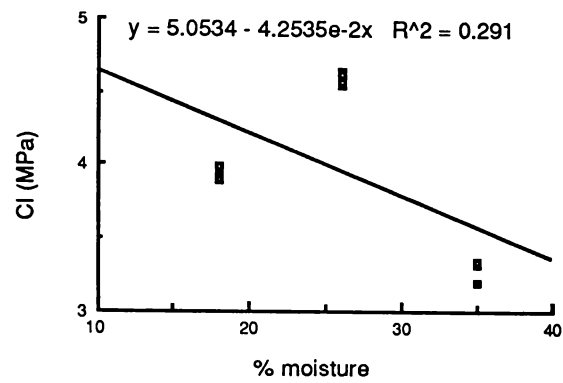


Figure 7.3.6(c) Relationship between % moisture and CI for Rugby Park soil.

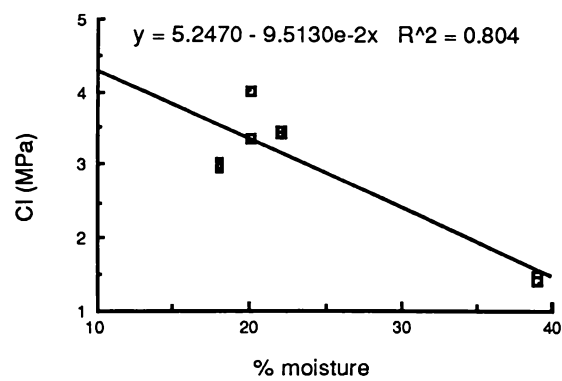


Figure 7.3.6(d) Relationship between % moisture and CI for Te Kowhai soil.

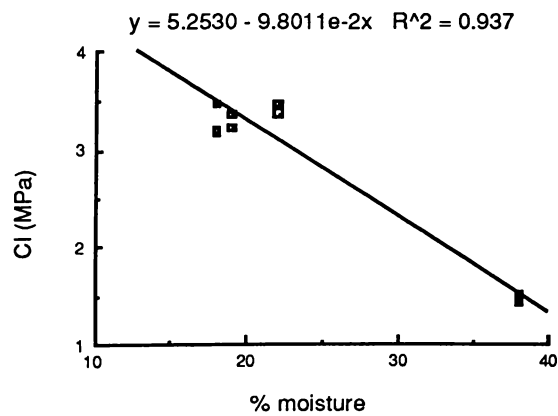


Figure 7.3.6(e) Relationship between % moisture and CI for Whatawhata soil.

Table 7.3.3 Soil strength *in situ* (penetrometer) mean profile values (MPa)

(a) Hamilton clay loam

Months following
subsoiling in

July	% soil moisture	Distance from subsoiled slot (cm)					
		Slot	10	20	30	40	Nonsubsoiled
0	33	0.86	0.98	1.52	2.40	2.14	2.31
5	23	1.14	2.05	3.10	3.73	4.00	4.11
12	36	1.44	1.46	1.77	2.13	2.20	2.12
17	19	2.14	2.52	3.57	3.84	3.93	4.00
24	38	1.66					2.03
29	24	2.70					3.77

(b) Horotiu sandy loam

December

0	18	0.68	1.88	2.69	2.92	3.41	3.58
11	20	1.42	2.68	2.96	2.99	3.35	3.42

(c) Rugby Park soil

October

0	26	1.00	2.27	2.82	3.30	4.63	4.56
2	18	2.50	2.48	3.12	3.87	3.91	3.98
8	35	1.22	2.25	2.37	2.46	3.19	3.33

(d) Te Kowhai silt loam

December

0	20	1.10	1.35	1.99	2.90	3.35	4.02
7	39	1.12	1.23	1.15	1.07	1.49	1.41
12	18	1.40	1.44	3.01	3.02	2.94	3.05
24	22	1.51	2.46	3.14	3.32	3.40	3.48

(e) Whatawhata clay loam

December

0	18	1.00	1.40	2.10	2.80	3.19	3.47
7	38	1.47	1.56	1.63	1.33	1.43	1.51
12	19	1.32	2.02	2.73	2.88	3.22	3.36
23	22	1.63	1.81	3.10	3.12	3.37	3.46

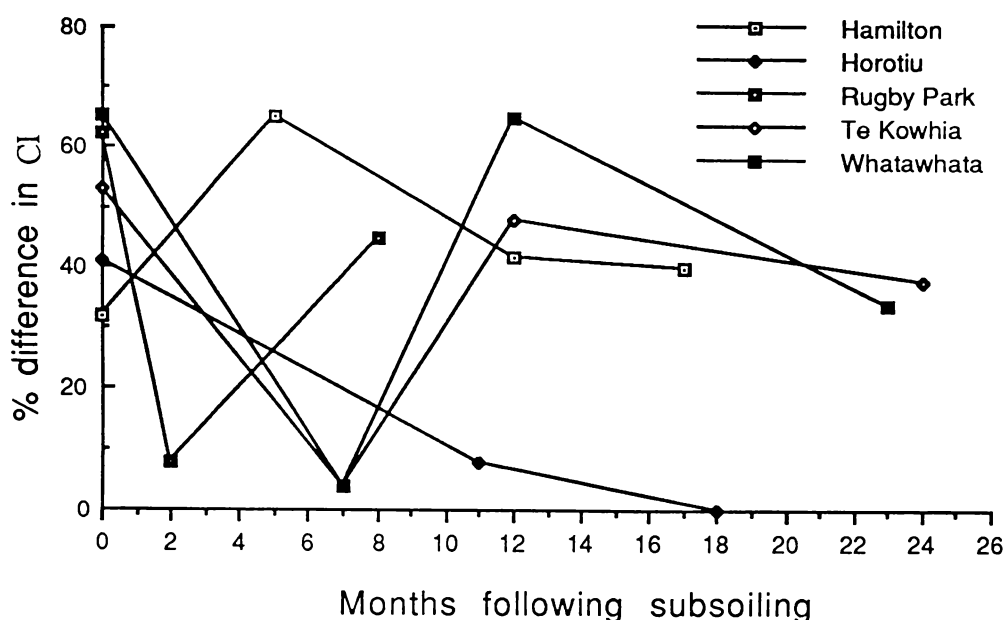


Figure 7.3.5 Percentage reduction in soil strength (CI) at 21 cm depth for 20 cm distance from slot for subsoiled in comparison with non-subsoiled.

Measuring the effects of subsoiling on soil strength by a penetrometer is therefore significantly affected by soil moisture. In this study the effect at Whatawhata was not measureable at 38% soil moisture (Table 7.3.3). Conversely under drier soil conditions as shown in Table 4.1.1b resistance to penetration in the non-subsoiled plots resulted in overload at the 24.5 cm depth.

However because of the penetrometers greater sensitivity to soil physical changes compared with SDG determinations it was useful for precise measurements of soil disturbance as shown in Figures 4.7.1 - 9. The analysis of these figures showed that subsoiling below a critical depth as described by Spoor and Goodwin (1978) resulted in a steep 70° angled V shaped area of soil disturbance. This area of disturbance accounted for approximately 30% of the treatable soil volume (Figures 4.7.3 and 4.7.4). Shallower subsoiling at or near but not below the critical depth (35 - 45 cm) resulted in a lower angled (45 - 50°) V shaped area of disturbance. An understanding of the concept of critical working depth is crucial for efficient and effective subsoiling.

Penetrometer measurements also revealed a relatively insignificant area of intermittent higher strength soil contiguous to the extremities of soil disturbance. These areas of cone increase (CI) are shown for example in Figures 4.2.2a and 4.2.2b. This effect also correlates with an increase in bulk density reported in Chapter 4.1.6.1 for the Hamilton soil.

Similar changes in soil strength found in this study in response to subsoiling have been widely reported for a range of soils (Gupta *et al.*, 1982; Ehlers, *et al.*, 1983; Vepraskas and Miner, 1986; Voorhees, 1987; Busscher, *et al.*, 1988).

7.3.3 Correlation of bulk density with soil strength

Figures 7.3.7.a,b,c,d,e,f,g,h are a series of graphs of soil strength expressed as cone index (CI) plotted against bulk density, derived from data in Table 7.3.1 and Table 7.3.3. These relationships reflect the influence of soil moisture and to a lesser degree soil shrinkage. Table 7.3.3 shows large fluctuations in soil strength whereas Table 7.3.1 shows relatively small changes in bulk density values.

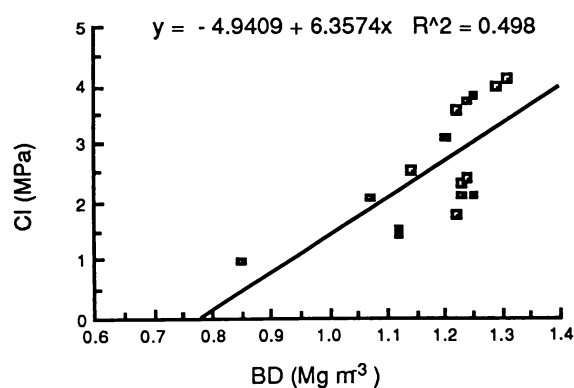


Figure 7.3.7(a) Relationship between BD and CI for Hamilton soil.

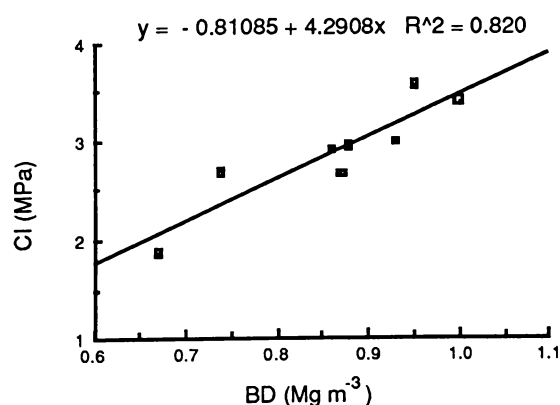


Figure 7.3.7(b) Relationship between BD and CI for Horotiu soil.

Soil moistures ranged from 19 to 36% for the Hamilton soil, 18 to 20% for Horotiu, 18 to 26% for Rugby Park, 18 to 39% for Te Kowhai and 18 to 22% for Whatawhata soil.

In Figures 7.3.7a-h strong correlations were recorded for Horotiu and Whatawhata (b,e) soils under a narrow soil moisture range, moderate for Rugby Park (c) and poor for Hamilton and Te Kowhai (a,d) where there was a wider soil moisture range.

The effect of soil moisture on soil strength has been discussed (Chapter 7.3.2), where increases in soil moisture resulted in decreased cone index (MPa) levels.

In order to compare soils under similar moisture regimes correlations were calculated for Hamilton, Rugby Park and Te Kowhai soils under soil moistures ranging from 19 to 23%, 18% and 18 to 22% respectively (Tables 7.3.1 and 7.3.3). In Figures 7.3.7f,g and h data for higher soil moistures (26 to 39%) were not included. This had the effect of normalising data which could thus be used to compare differing soil types at specific levels of soil strength and bulk density.

Figures 7.3.7 f, g and h show that bulk density and soil strength were strongly correlated under constant soil moisture. The new R^2 values were similar to the Horotiu and Whatawhata values (Figures 7.3.7 b and e). The effect of soil type on the relationship between bulk density and soil strength (CI) can be measured from the graphs (Figures b,e,f,g,h). It must be remembered that the data reflects changes in bulk density and soil strength which occurs in relation to varying distances from the subsoiled slot (Table 7.3.1 and 7.3.3). By graphical analysis a comparison of BD to CI at the 3 MPa level is evaluated. At this level the following bulk density values (Mg m^{-3}) were recorded for the Horotiu, Te Kowhai, Hamilton, Rugby Park and Whatawhata soils respectively 0.90, 1.13, 1.17, 1.18 and 1.27. These measurements provide a means for ranking the strength and bulk density of soils. In this study under a narrow range of soil moisture Horotiu ranks lowest followed in ascending order by Te Kowhai, Hamilton, Rugby Park and Whatawhata.

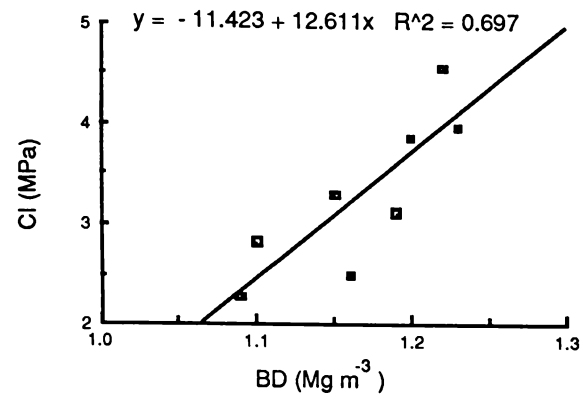


Figure 7.3.7(c) Relationship between BD and CI for Rugby Park soil.

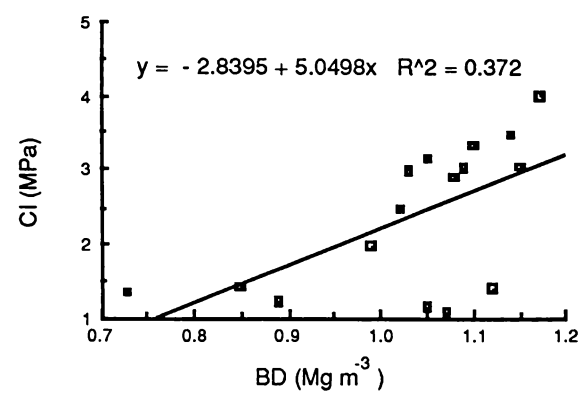


Figure 7.3.7(d) Relationship between BD and CI for Te Kowhai soil.

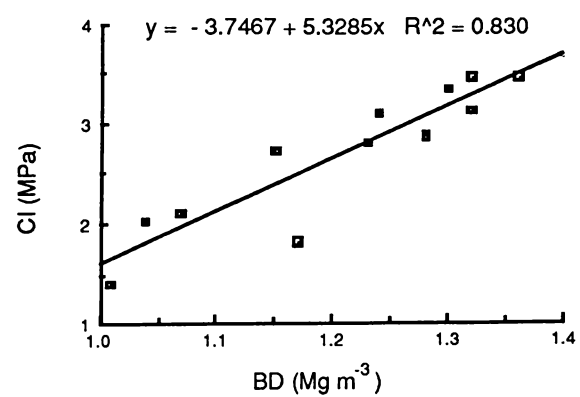


Figure 7.3.7(e) Relationship between BD and CI for Whatawhata soil.

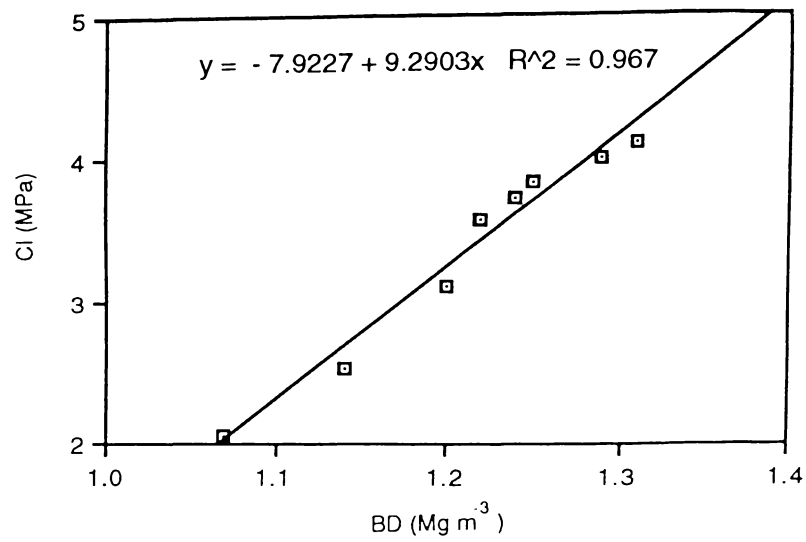


Figure 7.3.7(f) Relationship between BD and CI for Hamilton soil at constant moisture.

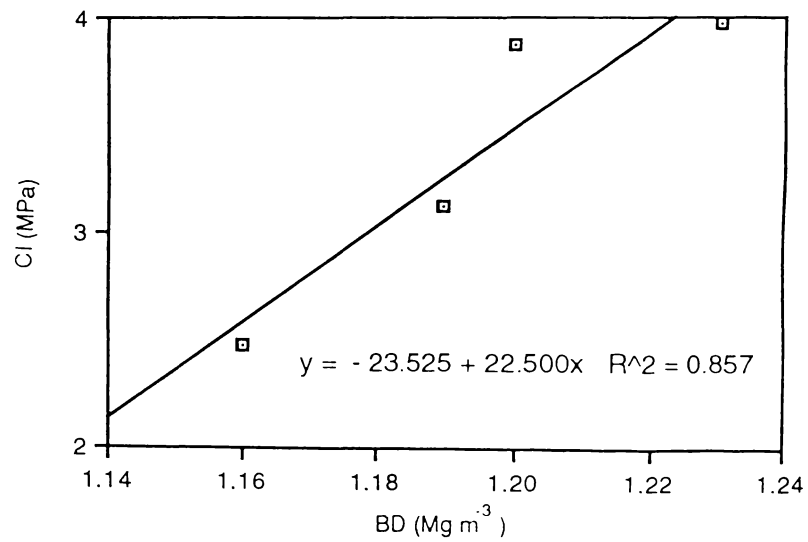


Figure 7.3.7(g) Relationship between BD and CI for Rugby Park soil at constant moisture.

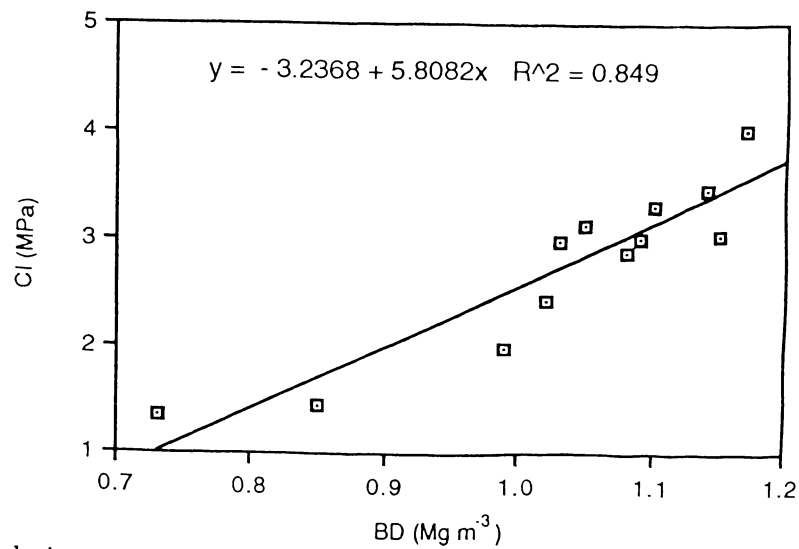


Figure 7.3.7(h) Relationship between BD and CI for Te Kowhai soil at constant moisture.

7.3.4 Soil heave

Decreases in bulk density in response to subsoiling are accompanied by increases in soil volume. These increases may cause a relatively insignificant increase in bulk density and soil strength around the extremities of disturbance as discussed in Chapter 7.3.2. However a significant increase in soil volume is measureable at the ground surface in response to subsoiling (Chapter 4.6). A heaveometer was used to measure these increases and to quantify the effect of differing tip sizes (Figure 4.6.1). A Similar instrument (profile meter) was used by Spoor and Godwin (1978) to assess soil disturbance after subsoiling with a range of rigid tines. Figure 4.6.4 shows that subsoiling below 40 cm depth resulted in reduced ground heave which further supports the critical depth concept (Spoor and Godwin, 1978).

7.3.5 Porosity

Increased soil porosity in response to subsoiling was measured by image analysis. Pores $>9.76 \mu\text{m}$ increased from 0 - 35% for the B horizon. The variability in response is related to soil type and distance from the subsoiled slot (Table 6.6.1). Figure 7.3.8 shows that porosity decreases with increases in bulk density. The inverse relationship between porosity and bulk density shown in this study has been reported previously (Gradwell, 1968; Climo and Richardson, 1984; Greenwood, 1989).

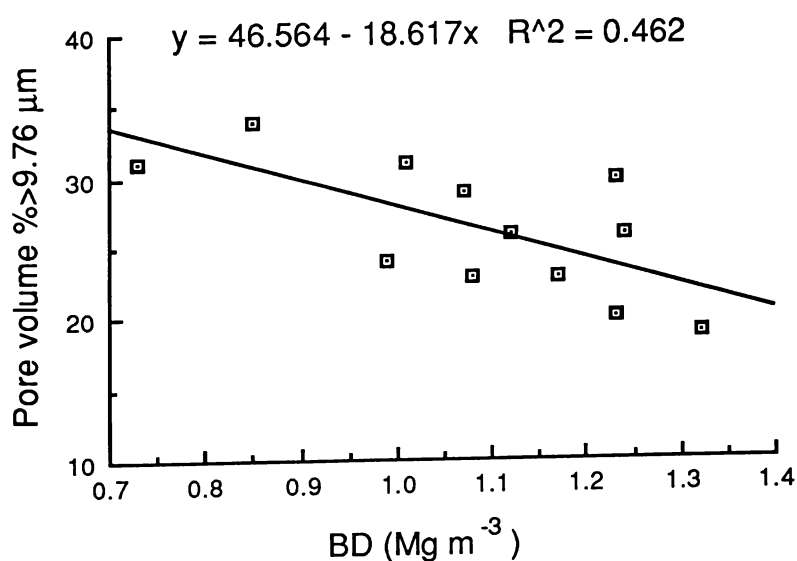


Figure 7.3.8 Relationship between bulk density and pore volume for five subsoiled soils.

7.3.6 Infiltration

Infiltration rates in and around the subsoiled slot were orders of magnitude greater following subsoiling (Figures 4.3.1 - 5) reflecting increased porosity and reduced bulk density. Figure 7.3.9 shows that infiltration rate and bulk density were moderately well correlated. Infiltration rates measured within 21 cm of the slot remained significantly higher for at least eighteen months following subsoiling.

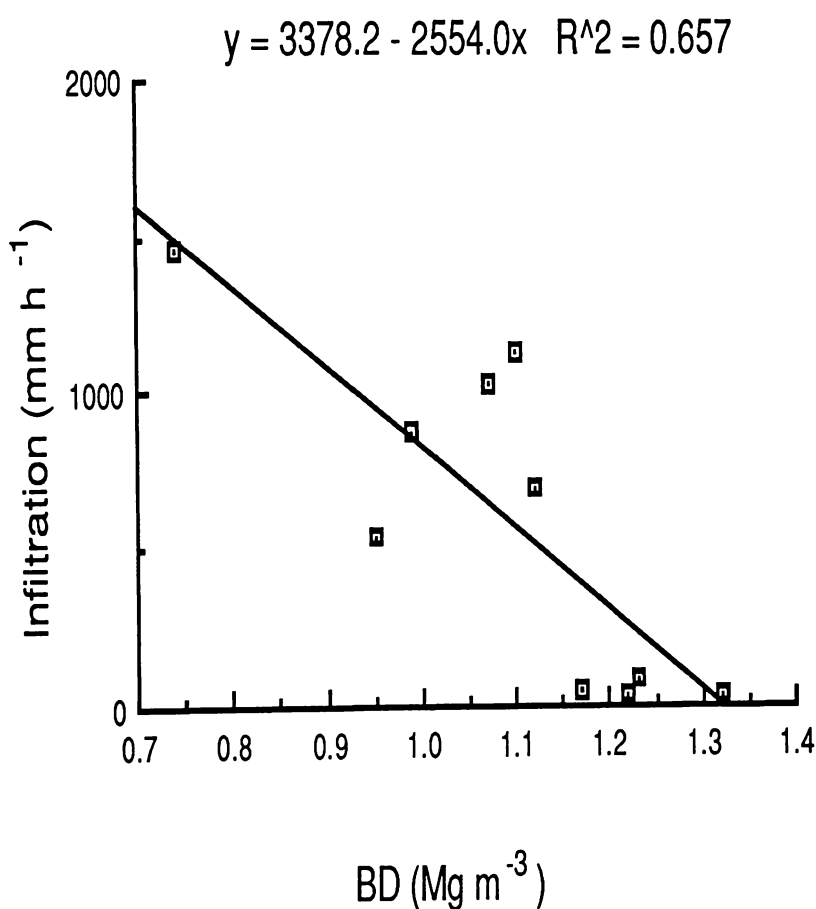


Figure 7.3.9 Relationship between bulk density and infiltration rates for five subsoiled soils.

7.3.7 Soil moisture tensions

Soil moisture tensions were lower for subsoiled plots after a summer rainstorm reflecting increased infiltration and higher in winter reflecting drier soil conditions when compared with non-subsoiled plots (Table 4.4.1).

7.3.8 Pasture root growth

Pasture root growth in response to subsoiling was assessed at the Whatawhata site. Prairie grass roots within a 10 cm band either side of the subsoiled slots were deeper than roots in the non-subsoiled plots. This suggests that the high bulk density layer identified at 20 - 40 cm depths may have been limiting for root growth (Figure 4.1.5c). Figure 7.3.10 shows that root length plotted against soil strength (CI) is strongly correlated. Similar increases in root length (Table 4.8.1) in response to subsoiling have been reported previously (Balazs, 1962; Taylor and Ratliff, 1969; Vepraskas 1986).

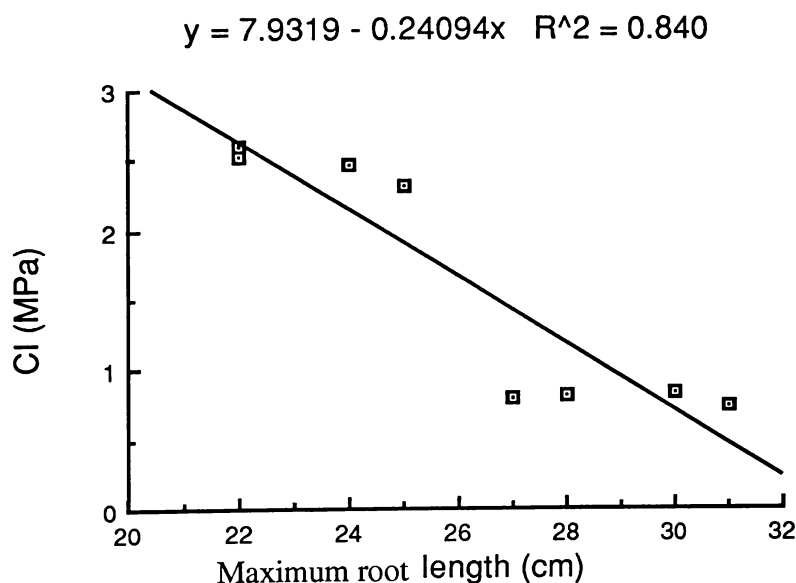


Figure 7.3.10 Relationship between soil strength and root length at the Whatawhata site.

7.3.9 Pasture production

Significant increases in pasture production (Table 4.8) are due to a number of factors, including the lowering of soil strength, reduced bulk density, increased porosity, increased infiltration of summer rains giving better moisture and better drainage implied by tensiometer measurements. Subsoiling increased the number of larger pores in the soil profile giving better aeration. Circulating air may evaporate water and remove it from the soil, resulting in the higher moisture tensions shown in Table 4.4.1 for Whatawhata site which may bring the soil nearer to the moisture content optimum for plant growth. The deeper rooting depth found in subsoiled plots at Whatawhata must also reflect increased pasture growth. Spectacular increases in crop yields in response to subsoiling have been reported previously (Taylor and Gardner, 1963; Bennie and Botha, 1986; Greenwood, 1989)

7.3.10 Soil mixing

The degree of soil mixing and soil shattering is shown by aggregate size re-distribution and small changes in soil texture and carbon percentages. Vibrating treatment resulted in greater soil mixing than non-vibrating (Figures 6.2.1 and 6.2.2). Mixing occurred within 10 cm distance of the subsoiled slot, a reflection of the shaking shank and tip. At distances further than 10 cm there was cracking and heave but no appreciable mixing. Aggregate size distribution data (Chapter 6.1) provided clear evidence for extensive shattering of large aggregates (> 8 mm) within 10 cm distance of the slot. Virtually all aggregates > 32 mm were broken down to a smaller size (Figure 6.1.2b).

The breaking up of aggregates creates more inter-aggregate pores and is therefore a major factor in ameliorating compacted soils. The mixing of A horizon and B horizon aggregates resulted in soil textural changes. Changes were greatest for Hamilton and Whatawhata soils where clay content increased for A horizons (Table 6.4.1) with consequent reductions for B horizons.

The incorporation of A horizon aggregates into lower soil levels had the effect of increasing B horizon carbon content (Figures 6.8.1 - 4).

7.3.11 The response of soils to subsoiling

Soil disturbance in this study under optimal soil conditions rarely exceeded 60% of the volume potentially treatable between subsoiler shanks (Table 4.7.1). However subsoiling with wide tips (vibrating) caused extensive soil shattering and cracking which extended upwards and outwards towards the surface, where at least 80% of near surface soil was disturbed. This is shown in heaveometer measurements (Chapter 4.6) and in the evaluation of soil disturbance patterns shown in Chapter 4.7.

The extent of soil disturbance and soil mixing and their durability was greatest for the more clayey soils, Whatawhata and Hamilton when compared with Horotiu, Rugby Park and Te Kowhai soils. The effect of soil shrinkage was discussed in Chapter 7.3.1, however this effect, in combination with the swelling characteristic of kaolinite clays, must play a key and important role in the durability of soil disturbance found in these clay rich soils. Hamilton and Whatawhata soils in summer and to a much lesser extent Te Kowhai soil exhibit pronounced blocky to prismatic structured B horizons, a reflection of drying and shrinking. It is suggested that the durability of cracks emanating from the subsoiler shanks and tips is primarily a function of swell and shrink of structural units. Although soil swelling during the wet winter months caused closure of cracks, planes of weakness remain until the following summer.

Soil structural characteristics must also play an important role in the initial response of a soil to subsoiling and its subsequent persistence. Subsoiling reduces large aggregates in and around the slot (Chapter 6.1.2). However at distances further away from the slot (20 - 40 cm) the effect of subsoiling gradually diminishes. This effect is more pronounced in the finer structured Horotiu soil when compared with the more clayey soils which maintain larger more extensive structural cracks.

Soil texture in this study has an effect on subsoiling. Sandy soils initially react significantly with large bulk density reductions but then re-compact relatively quickly, whereas more clayey soils show greater soil disturbance and the effects of subsoiling are longer lasting.

7.4 SUBSOILER DESIGN AND OPERATIONAL PROCEDURES

The Gallagher Shakaerator subsoiler for pasture use was developed from an arable subsoiler, after much testing, modification and radical redesign. Essentially the main frame of the implement was redesigned and widened to 1.6 metres to accommodate an improved shaker assembly, attachment for disc coulters (skeiths) and press rollers. Rigorous testing was undertaken under varying soil and weather conditions in order to establish standard operational guidelines. A major outcome of the testing was the recognition that subsoiling requires press rollers otherwise it could result in serious soil moisture loss and subsequent pasture wilting (Chapter 4.5).

The soil disturbance results obtained in this study suggests that the standard 1 m shank spacing is too wide. It is therefore proposed that shank spacing should be reduced to 0.8m for optimal subsoiling performance. The 1.6 m wide subsoiler frame is thus capable of carrying up to three shanks. The number of shanks selected is dependent on the area of land to be subsoiled, the tractor power required to pull the implement and the additional costs involved. In order to subsoil for maximum soil disturbance cultivation should also be carried out when soils are relatively dry. Subsoiling below the critical depth should be avoided and mid-summer subsoiling should also be avoided to prevent excessive plant root desiccation and consequent loss of pasture. Winter subsoiling when soils are wet should also be avoided as the effect on soil disturbance is somewhat limited and the risk of compaction through the use of heavy machinery (tractor with subsoiler attached) is virtually unavoidable. Autumn subsoiling is the preferred option. Soils are relatively dry at this time of year, soil moisture loss through evaporation is low when compared with summer and hence the risk of desiccation in and around the subsoiled slot is greatly reduced. Conditions in late spring may also be suitable for subsoiling, but the risk of excessive soil moisture loss, through evaporation and subsequent pasture loss through desiccation in the summer is more likely.

On hilly terrain, such as that found on the Hamilton site, subsoiling should follow the contours, thus ensuring rain interception. Contouring also reduces the risk of erosion channels forming along the subsoiled slots.

Soils having poor drainage and high water tables in winter such as the Te Kowhai and Whatawhata, can best benefit from subsoiling if a primary drainage system is installed to lower the water table below subsoiling depth.

7.5 CONCLUSIONS

Subsoiling with the Gallagher Shakaerator significantly changed the physical condition of the five soils tested. These changes were not transitory but lasted in some soils up to two years.

Benefits from subsoiling were lower bulk densities, reduced soil strength, increased porosity, increased infiltration rates and root length and increased pasture production.

Optimal operating conditions for subsoiling are proposed after evaluation of data collected for the Hamilton and Te Kowhai soil. Under relatively dry soil conditions satisfactory soil disturbance is obtained with the machine set at 40 and 45 cm depth for the vibrating narrow and wide tips respectively. If these depths are exceeded soil disturbance is reduced. Under wetter soil conditions 35 cm depth should not be exceeded, because fracturing and consequent increase in soil volume is then only limited to a relatively small volume of soil around the lower shank and subsoiler tip. In other words energy is absorbed and contained within the soil profile, surface heave is negligible and soil volume changes are minimal. The Hamilton and Te Kowhai model would seem appropriate for the other soils, with perhaps only subtle depth changes required in order to respond to variations in soil texture and soil moisture.

Subsoiling increased the number of larger pores in the soil profile giving better aeration perhaps reflecting higher moisture tensions shown in winter which may bring the soil nearer to the moisture content optimum for plant growth.

Lower moisture tensions following a summer rainstorm are attributable to increased interception of surface rainwater into and around the subsoiled slot area, infiltration determinations carried out in the summer substantiated these findings. Rates were orders of magnitude higher for subsoiled plots immediately following subsoiling and remained significantly higher for up to eighteen months. The significant reductions in bulk density and consequent increase in porosity especially in the slot are the major reason for the considerable differences in infiltration rates.

Increased pasture production from subsoiled plots, during an early summer growth period clearly reflects the response of pasture to increased soil moisture at a time of year when moisture deficits can occur. Changes to soil physical conditions provide additional space for roots to explore and penetrate, thus increasing their length and volume, which ultimately leads to increased pasture yield.

The persistence of subsoiling effects such as structural cracks and areas of shattered soil is a function of soil type, soil structure and land use. Waterlogging, livestock treading, heavy machinery and sports use can quickly reverse the benefits of subsoiling. In this study the more clayey soils responded well to subsoiling with good sustainability. The more sandy soils re-compacted faster and therefore if deemed necessary, would have to be subsoiled at more frequent intervals than the more clayey soils. In the case of the Horotiu soils for example it may be concluded that subsoiling does nothing to improve an already well structured free draining soil. However there was a 12% yield increase in response to subsoiling this soil and therefore on this evidence subsoiling is probably justified.

7.6 SUGGESTIONS FOR FUTURE STUDY

Further work in the following areas is suggested:

The durability of soil cracks created by subsoiling under swelling and shrinking clay conditions.

Soil shrinkage of a range of soil types.

The bearing capacity of soils in relation to livestock treading.

Relation of optimum subsoiling conditions to Atterberg limits.

The effect of subsoiling on soil gaseous exchange and mineralisation.

Finally from a user point of view, which is perhaps beyond the scope of an Earth Sciences Department, an in depth cost benefit analysis of subsoiling, not only under pasture and sports turf, but also incorporating arable, horticulture and forestry enterprises would provide valuable information on the viability of such an operation.

APPENDICES

APPENDICES

APPENDIX 1.1 Gallagher Subsoiler Shakaerator



SUBSOILER SHAKAERATOR

Designed for most soil types

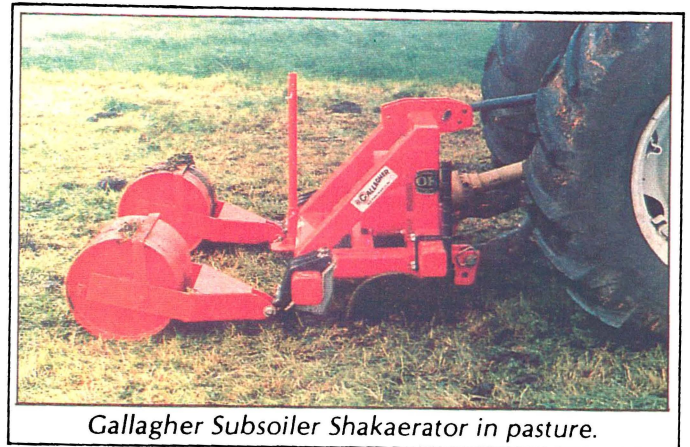


**Like a Million Earthworms —
The Gallagher Subsoiler
Shakaerator Gives Life Back To
Your Soil!**

APPENDIX 1.1 (continued)

Soil compaction

Soil compaction has been identified as a frequent cause of poor crop and pasture production. The Gallagher Subsoiler Shakaerator can correct it. Soil compaction can be caused by livestock, heavy machinery, repeated cultivation, and in some areas pans are caused by the natural processes of soil formation. Soil pans cause severe waterlogging in winter and excessive drying out in summer, inhibiting roots, which in turn restricts nutrient uptake. This is something no one can afford with today's high fertiliser prices.



Gallagher Subsoiler Shakaerator in pasture.

Improved root structure

Root growth has been shown to be severely restricted by compaction. However, trials show that the Gallagher Subsoiler Shakaerator gives greater root depth (Chapman and Ailbrook, 1987). Roots without subsoiling were at 235mm whereas the subsoiled ones went to 285mm.

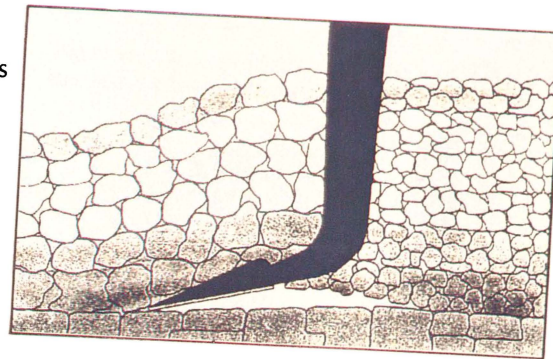
The benefits of the Gallagher Shakaerator

The unique Shakaerator, driven through the tractor p.t.o., gives a vibrating action which causes greater and deeper soil shattering, using less fuel and power than any other machine.

The heave of the tips results in vertical shatter, and the vibrating of the shanks gives horizontal shatter.

The Gallagher Subsoiler with Shakaerator allows deeper and better subsoiling without the need for bigger tractors. No other implement incorporates all these benefits.

Important feature is that the tips are leading well in front of the shanks reducing drag and opening the soil to give the 50% aeration.



*Shakaerator
Tips and
slim shanks
do not mix
subsoil
with topsoil,
but heave
and aerate
the soil.*

- Increases pore space.
- Allows life giving oxygen to the soil.
- Improves soil structure.
- Increases root depth, volume and hence produces more growth.
 - Increases organic matter and fertility.
 - Gives higher yielding pastures and crops.
 - Encourages the absorption of fertilisers.
 - Minimal damage to pastures.

• Improves the bottom line!

APPENDIX 1.1 (continued)

Frame structure

The fully welded 9mm RHS steel frame outlasts others — so some 'once bitten', now Gallagher, customers tell us. Any lighter frame won't stand up to many years of pan breaking.

Gallagher frames have the strength to work behind large tractors, penetrate most soils, and even roadways. The 1.4 metre Frame takes 1 to 3 Shanks and 2-4 metre Frame up to 5. Shanks should not be more than one metre apart.

Strong shanks — short and long

450mm Shanks are recommended for small tractors and very hard ground. 600mm Shanks are recommended for big tractors where deep penetration is essential. A combination of both may be used, in which case fit the Short Shanks in front.

The Shanks are made of molychrome steel which is one of the strongest and hardest steels, thus allowing Shanks to be slim to slip through the soil. The chrome shines up like a bumper to glide through the soil with little friction. The hardness gives long life.

TWO TIPS

There are two tip shapes, narrow ones for pasture and very hard ground, and wide ones for cultivation and soft ground.

Narrow tips should also be used for deep penetration into hard ground, and where shallow soils overlay parent rock. They can be reversed for use as a chisel plough.

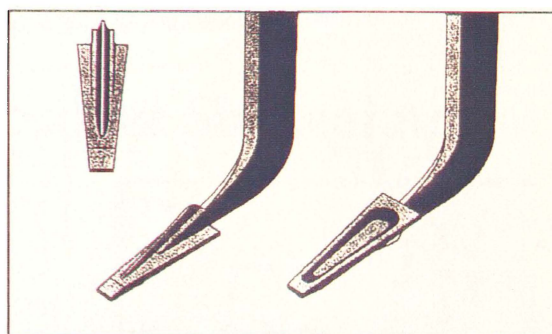
The wide tips give a greater heave and are ideal for cultivation and shallow inter-row work on arable land, or increased soil shatter in pasture.

The Gallagher slim shanks and streamlined tips don't mix the subsoil and topsoil, but heave, shatter and aerate both.

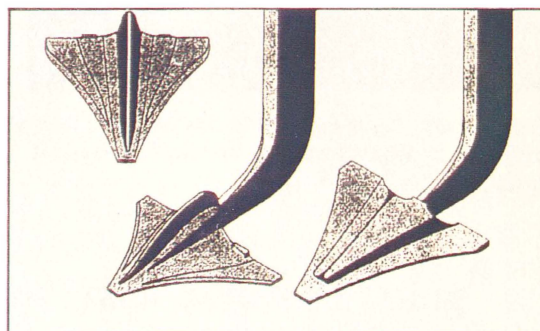
Pasture — Gallagher Subsoiler Shakaerator

The Gallagher Subsoiler Shakaerator for pasture normally consists of a 1.4 metre frame, two 600mm Shanks with the narrow tips, two disc coulters, two rollers and shakaerator.

Wide tips give greater heave and soil shatter, and are suitable at depths below 350mm. The coulters cut the turf, allowing the Shanks to penetrate without disturbing the surface. Rollers, which can be filled with water, press the cut surfaces together to minimise moisture loss. 15% increase in pasture production has been achieved in soil with pans.



Narrow Tips for deep penetration. Can be reversed for use as a chisel plough.



Wide Tips give wider heave and suitable for inter row shallow work. Can be reversed for mixing soil.



Improves Pasture.

No one ever regretted buying Gallagher Quality!

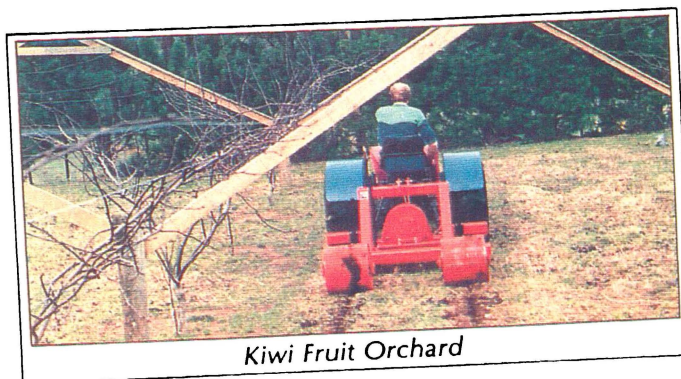
APPENDIX 1.1 (continued)

Horticultural — Gallagher Subsoiler Shakaerator

The pasture model is also recommended for orchards. Where pergolas necessitate a small tractor, short Shanks may have to be fitted because it may not be able to lift long Shanks clear of the ground.

Orchards should be well subsoiled before planting, and then between rows as required, which may be every two or three years, depending on soil type and the amount of tractor compaction caused.

Deep subsoiling adjacent to shelter belts should be done annually to cut back their roots.



Kiwi Fruit Orchard

Cultivation — Gallagher Subsoiler Shakaerator

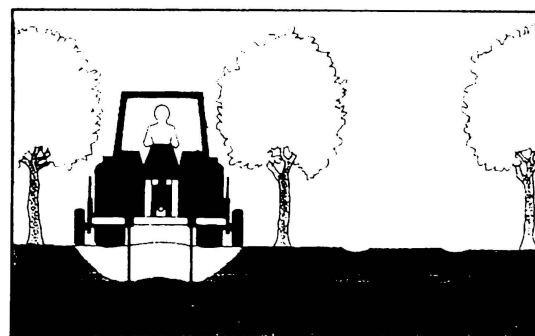
Subsoiling has increased crop yields by up to 40%.

Repeated cultivation and tractor movement cause a pan to form just below the cultivation depth.

This can be overcome economically by using the Gallagher Subsoiler Shakaerator with wide tips to do the primary cultivation, followed by a quick light cut with a Gallagher Rotodisc.

If the ground is very hard, and deep subsoiling is necessary, then use narrow tips and long Shanks.

If mixing of the soil is required, the tips should be inverted. This increases the angle and gives more lift.



Plough pans and compaction are just as big a problem with fixed crop cultivation for example in vineyards, orchards and soft fruit crops.

Other areas of use

*Golf Courses • Parks • Playing Fields • Farm Track Before Grading
• Mole Ploughing*

Research on subsoiling compacted soils

Gallagher Engineering and the Earth Sciences Department of the University of Waikato, under researcher Richard Chapman, are identifying the causes of soil compaction, and are monitoring the benefits of subsoiling in a number of soil types, using the Gallagher Subsoiler Shakaerator.

Site	Treatment	Kg per ha Dry matter	% increase in yield
5	subsoiled not subsoiled	2740 2447	12%
6	subsoiled not subsoiled	2330 2021	15%

Figure 1 (R. Chapman, R.F. Allbrook) — University of Waikato.
Pasture production taken at two test sites from 15 May to 7 July 1987.

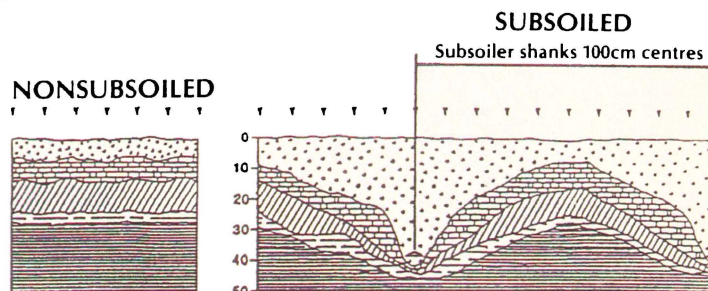


Figure 2 (R. Chapman, R.F. Allbrook) — University of Waikato.
This diagram shows the lateral effect of subsoiling to about 50cm on either side of the Shanks.

APPENDIX 1.1 (continued)

Models — Gallagher Subsoiler Shakaerator

These can include any combinations to suit your requirements.

In hard conditions the approximate power requirements are 15 kw per Short Shank and 20 kw per Long Shank.

General recommendations

Use in spring and autumn. Don't use in very wet conditions; you will achieve little. Don't use in very dry conditions; you will kill some pasture. Operate above and across existing drainage systems. Contour across slopes to intercept summer rainfall. A p.t.o. speed of 540 rpm is recommended.

Safety with your Gallagher Subsoiler Shakaerator

In the event of striking an obstacle the tractor and Shanks are protected from damage by a Shank Mounting Nut which strips off the bolt on impact.

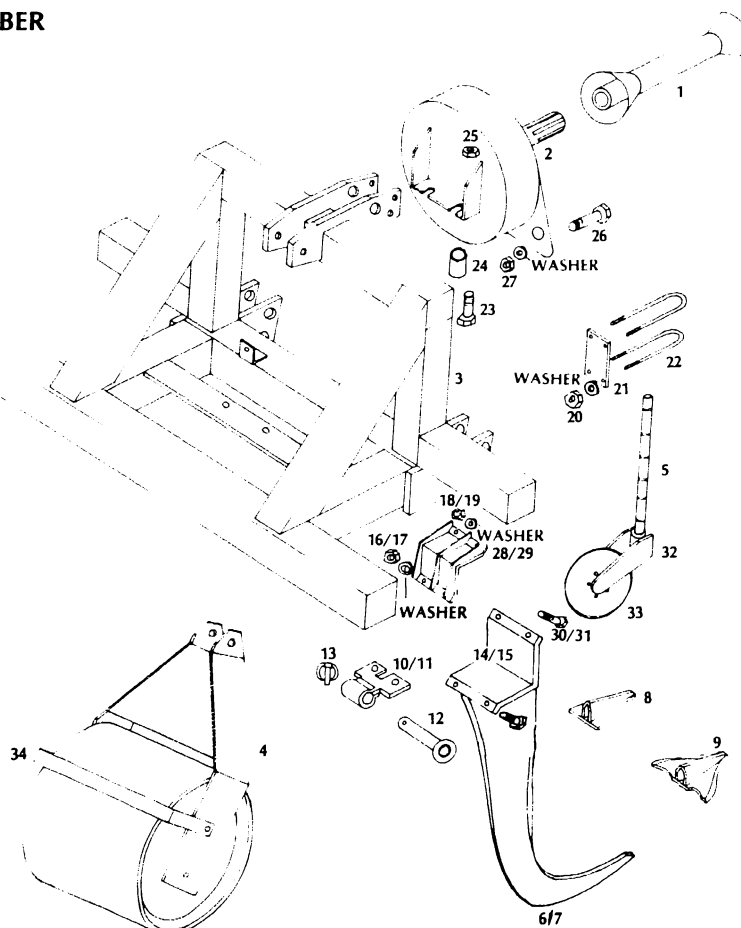
Setting Up Your Gallagher Subsoiler Shakaerator

Centralise the Subsoiler and tighten the tractor check chains, then loosen off one turn. Set the top link and levelling levers so the Frame is level both ways. Check Tractor tyre pressure to ensure good traction.

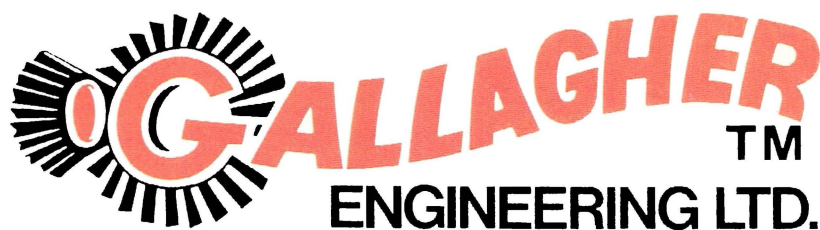
Gallagher Subsoiler Shakaerator Parts Schedule.

SUBSOILER PART NUMBER

1 Driveshaft	823018
2 Shakaerator	105003
3 Frame (1.4m)	105016
4 Roller Assembly	105018
5 Coulter	105025
6 Shank (Long)	712571
7 Shank (Short)	712570
8 Tip (Narrow)	712580
9 Tip (Wide)	712581
10 Hinge Bracket Short Shank	105021
11 Hinge Bracket Long Shank	105020
12 Hinge Pin	105023
13 Lynch Pin	839002
14 Bolt $\frac{5}{8}$ " U.N.F. x 3"	831108
15 Bolt $\frac{3}{4}$ " U.N.F. x 3"	831109
16 Nut $\frac{5}{8}$ " Nyloc U.N.F.	834158
17 Nut $\frac{3}{4}$ " Nyloc U.N.F.	834134
18 Shear Nut $\frac{5}{8}$ " U.N.F. Short Shank	834058
19 Shear Nut $\frac{3}{4}$ " U.N.F. Long Shank	834034
20 Nut M10	834110
21 Clamping Plate	105031
22 'U' Bolts	105030
23 Bolt M16	832504
24 Shakerbox Rear Spacer	105032
25 Nut M16	834116
26 Bolt M16	832501
27 Nut M16	834116
28 Shank Clamp Bracket (Short)	712572
29 Shank Clamp Bracket (Long)	712552
30 Bolt $\frac{5}{8}$ " U.N.F. x 3"	831108
31 Bolt $\frac{3}{4}$ " U.N.F. x 3"	831109
32 Coulter Support Arm Assembly	105026
33 Coulter Disc 14"	829003
34 Roller Scraper	105024

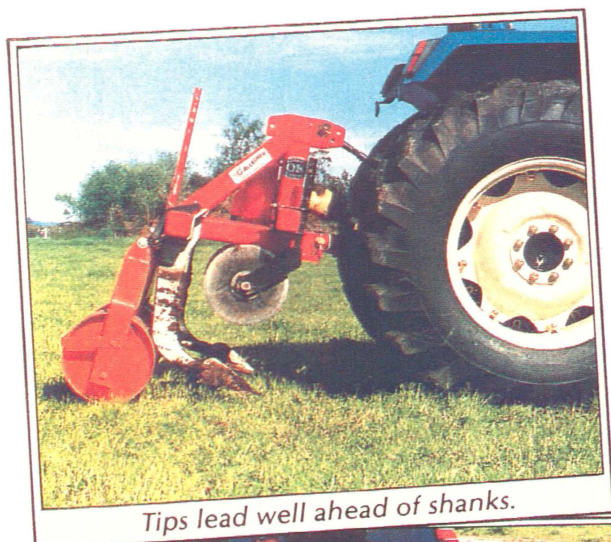


APPENDIX 1.1 (continued)



SUBSOILER SHAKAERATOR

The Versatility, Increased Production and Greater Profitability Justify the Purchase of a Gallagher Subsoiler Shakaerator.



Tips lead well ahead of shanks.



Minimum Pasture Damage.



AWARDS WON

Prince Phillip Prize for Australian Design.

New Zealand National Fielddays Award of Merit.



Rollers press the cut surfaces together.



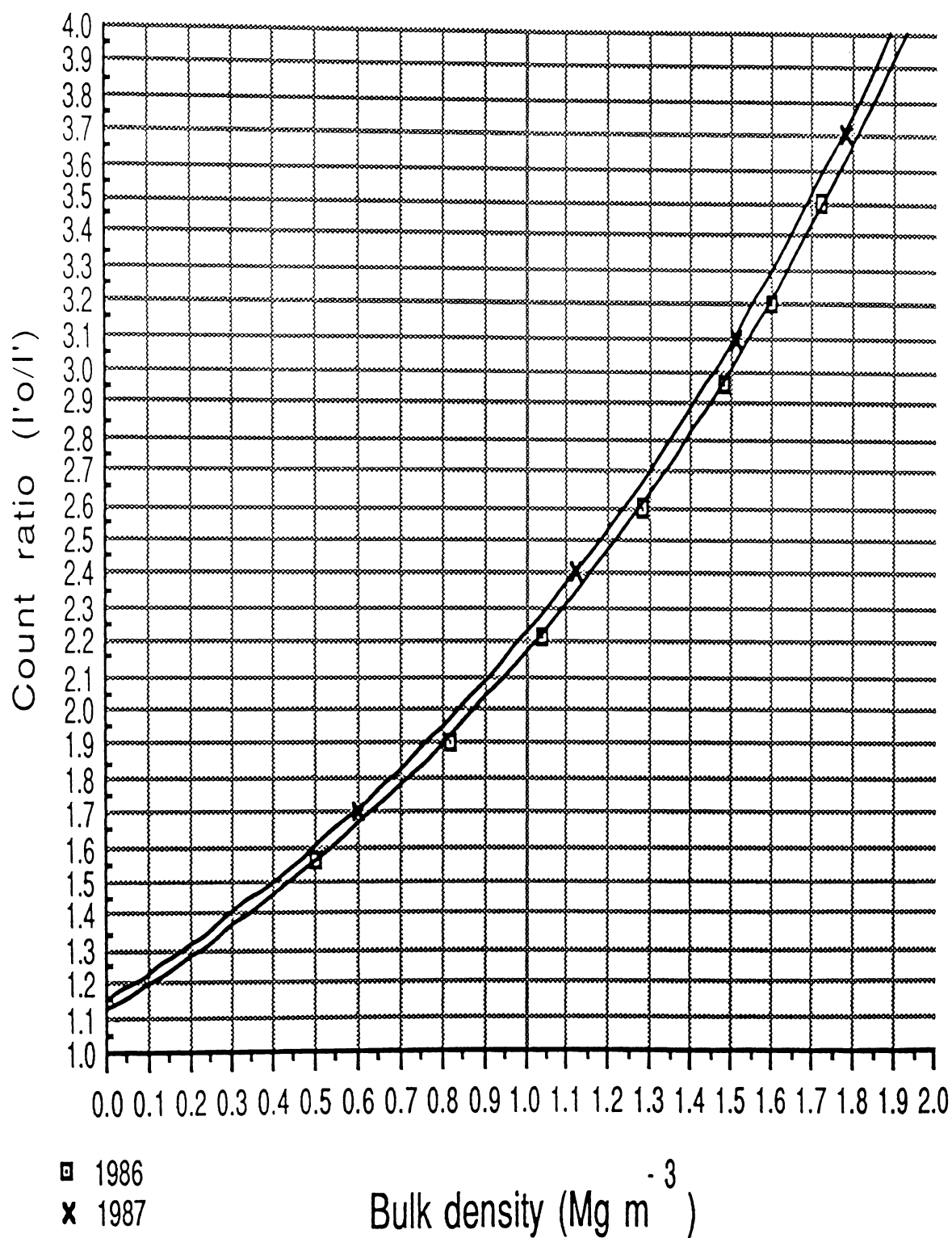
**HARVESTING & CULTIVATION
EQUIPMENT**

Your Local Dealer

Gallagher Engineering Ltd,
Private Bag, Hamilton, New Zealand.
Telephone: (071) 389-800, Fax: (071) 389-801, Telex: NZ21798.
Kahikatea Drive, Melville, Hamilton, New Zealand.

REF 6K-5873 11/87

APPENDIX 2.1 Calibration curves for Ronly subsurface transmission density gauge



APPENDIX 3.1 Penetrometer Data

* significantly different from non-subsoiled ($P < 0.05$) OL = penetrometer overload
Moisture determination for 0 - 10 cm depth

Penetrometer readings (MPa) on a transect across subsoiled and non subsoiled plots.

Hamilton clay loam

(a) 13/7/87, 33% moisture

Depth cm	Distance from slot					
	Slot	10 cm	20 cm	30 cm	40 cm	Nonsubsoiled
3.5	0.37*	0.37*	0.67*	1.20	1.12	1.27
7.0	0.90*	1.12	1.05	1.60	1.05	1.35
10.5	1.35	1.20	0.97*	1.57	1.50	1.42
14.0	1.20	0.90*	0.97*	1.72	1.50	1.50
17.5	1.05*	0.75*	1.35*	2.62	2.17	2.10
21.0	0.90*	0.67*	1.42*	2.62	2.17	2.10
24.5	0.60*	0.67*	1.35*	3.00	2.62	2.85
28.0	0.67*	0.60*	1.72*	2.77	2.62	2.85
31.5	0.52*	0.67*	2.32	3.00	2.92	2.62
35.0	0.90*	1.20*	2.02*	3.00	2.62	2.92
38.5	0.90*	1.80*	2.10*	2.85	2.35	3.00
42.0	0.90*	1.50*	2.02*	2.62	2.62	3.00
45.5	0.97*	1.35*	1.80*	2.47	2.62	3.00
49.0	2.05*	2.50	2.77	2.77	2.32	2.92

(b) 9/12/87, 22% moisture

Depth cm	Distance from slot					
	Slot	10 cm	20 cm	30 cm	40 cm	Nonsubsoiled
3.5	0.90*	1.20	1.20	1.27	1.27	1.20
7.0	0.90*	0.90*	1.35	1.50	1.50	1.50
10.5	1.12*	1.35*	1.50*	2.10	1.95	2.10
14.0	1.12*	1.35*	1.50*	1.80*	2.62*	3.75
17.5	1.35*	1.42*	1.80*	1.95*	4.57	5.00
21.0	1.35*	1.57*	1.95*	4.92	5.10	OL
24.5	1.50*	1.50*	2.10*	OL	OL	
28.0	1.80*	1.85*	3.75*			
31.5	1.85*	1.85*	5.10			
35.0	1.80*	2.02*	OL			
38.5	2.10*	2.92*				
42.0	3.37*	3.75*				
45.5	OL	OL				
49.0						

APPENDIX 3.1 (continued)

(c) 5/7/88, 36% moisture

Depth cm	Distance from slot					
	Slot	10 cm	20 cm	30 cm	40 cm	Nonsubsoiled
3.5	0.67*	0.90	0.90	0.90	0.97	1.12
7.0	0.97*	0.90*	0.97*	1.12	1.20	1.35
10.5	1.35	1.35	1.42	1.42	1.50	1.35
14.0	1.42	1.35	1.42	1.50	1.35	1.42
17.5	1.50	1.80	1.50	1.72	1.87	1.80
21.0	1.35*	1.10*	1.50*	1.87*	2.10	2.62
24.5	1.20*	1.20*	1.72*	2.77	2.40	2.62
28.0	1.20*	1.50*	1.72*	2.62	2.50	2.40
31.5	1.72*	1.50*	2.02	2.85	2.92	2.40
35.0	1.50*	1.80*	2.10	2.77	2.40	2.62
38.5	1.50*	1.72*	2.40	2.47	2.62	2.50
42.0	1.80*	1.80*	2.50	2.85	2.50	2.62
45.5	2.62	2.10	2.85	2.85	2.85	2.85
49.0	2.47	2.62	2.85	2.85	3.00	2.85

(d) 13/12/88; 19% moisture

Depth cm	Distance from slot					
	Slot	10 cm	20 cm	30 cm	40 cm	Nonsubsoiled
3.5	0.82*	1.20	1.27	1.35	1.30	1.30
7.0	1.12*	1.12*	1.50	1.20	1.12*	1.50
10.5	1.12*	1.35	1.50	1.50	1.50	1.35
14.0	1.20*	1.35*	1.85*	2.10*	2.62	3.37
17.5	1.20*	1.50*	1.95*	3.75	4.50	4.57
21.0	1.35*	2.02*	3.45*	OL	OL	OL
24.5	1.35*	2.10*	OL			
28.0	1.65*	1.85*				
31.5	1.65*	1.85*				
35.0	2.62*	3.37*				
38.5	3.75*	OL				
42.0	OL					
45.5						
49.0						

APPENDIX 3.1 (continued)

(e) 6.7.89, 38% moisture

Depth cm	Slot	Nonsubsoiled
3.5	0.90	0.97
7.0	1.12	1.12
10.5	1.20	1.12
14.0	1.35	1.20
17.5	1.35	1.35
21.0	1.42*	2.10
24.5	1.20*	2.50
28.0	1.50*	2.42
31.5	1.80*	2.85
35.0	1.92*	2.85
38.5	2.50	2.85
42.0	2.62	2.62
45.5	2.92	2.85

(f) 10/12/89, 24% moisture

Depth cm	Slot	Nonsubsoiled
3.5	1.12	1.20
7.0	1.12	1.35
10.5	1.36	1.50
14.0	1.87	3.50
17.5	1.80*	3.00
21.0	2.50*	4.57
24.5	2.50*	OL
28.0	2.85	
31.5	2.40	
35.0	2.62	
38.5	OL	
42.0		
45.0		
49.0		

APPENDIX 3.1 (continued)

Horotiu Sandy loam

(a) 15/12/86, 18% moisture

Depth cm	Distance from slot					
	Slot	10 cm	20 cm	30 cm	40 cm	Non-subsoiled
3.5	0*	1.50	1.50	1.87	1.87	1.50
7.0	0.37*	1.50*	3.00	3.75	3.50	3.00
10.5	0.75*	1.50*	2.62	3.00	3.12	3.37
14.0	0.53*	0.90*	2.25*	2.85	3.50	3.37
17.5	0.37*	0.75*	2.25*	3.00	3.87	3.97
21.0	0.37*	1.87*	2.62*	3.00*	4.12	4.50
24.5	0.37*	2.10*	2.85*	3.00*	4.37	4.40
28.0	0.37*	2.25*	2.85	2.62	3.37	3.00
31.5	1.20*	2.85*	2.85*	2.25*	3.62	4.87
35.0	1.20*	2.25*	3.43	3.37	3.10	3.75
38.5	1.12*	2.62*	3.45	3.75	3.10	3.75
42.0	0.75*	2.25*	3.45	3.00	3.62	3.75
45.5	1.50*	2.10*	1.87*	2.62	3.25	3.37
49.0	3.50	3.87	3.87	3.75	3.00	3.37

(b) 30/11/87, 20% moisture

Depth cm	Distance from slot					
	Slot	10 cm	20 cm	30 cm	40 cm	Nonsubsoiled
3.5	0.90	1.05	0.90	0.90	0.90	1.12
7.0	0.90*	1.87*	1.87*	1.95*	2.85	2.62
10.5	1.12*	1.87*	2.10*	1.87*	2.85	2.85
14.0	1.12*	2.10*	2.50*	2.62	3.15	3.00
17.5	1.12*	2.25*	2.40*	2.85	3.15	3.00
21.0	1.50*	3.00	3.15	3.15	3.15	3.45
24.5	1.50*	3.15*	3.50*	3.50*	4.12	4.87
28.0	1.65*	3.15*	3.97*	3.37	4.50	4.87
31.5	1.65*	3.75	4.12	3.97	3.97	4.12
35.0	1.87*	3.00	3.50	3.50	3.97	3.37
38.5	1.87*	3.15	3.37	3.50	3.75	3.37
42.0	2.10*	3.15	3.60	3.75	3.50	3.97
45.5	2.85	3.37	3.60	3.97	3.75	3.97
49.0	3.97	4.12	4.12	3.87	3.75	3.97

APPENDIX 3.1 (continued)

Rugby Park Soil

(a) 7/10/86, 26% moisture

Depth cm	Distance from slot					
	Slot	10 cm	20 cm	30 cm	40 cm	Nonsubsoiled
3.5	0*	0.75	0.67	0.75	0.82	0.75
7.0	0*	0.75*	0.75*	1.20*	4.92	4.57
10.5	0*	1.87*	1.61*	1.61*	4.87	4.92
14.0	0.67*	2.10*	1.87*	1.68*	5.40	OL
17.5	0.90*	1.87*	2.10*	2.25*	OL	
21.0	0.90*	1.65*	2.10*	3.75		
24.5	0.90*	2.10*	2.10*	5.10		
28.0	1.20*	2.50*	4.92	OL		
31.5	1.20*	2.77*	OL			
35.0	2.62*	3.75*				
38.5	2.62*	4.94				
42.0	OL	OL				
45.5						
49.0						

(b) 15/12/86, 18% moisture

Depth cm	Distance from slot					
	Slot	10 cm	20 cm	30 cm	40 cm	Nonsubsoiled
3.5	0.75	0.67	0.82	0.75	0.75	0.75
7.0	1.20*	1.20*	0.90*	2.10*	1.87*	4.92
10.5	1.20*	0.90*	1.20*	3.50*	3.45	3.75
14.0	1.50*	1.50*	2.10*	3.75*	3.45	3.50
17.5	2.10*	1.87*	3.50	3.75	3.75	3.45
21.0	2.50*	2.10*	3.45	3.45	4.87	3.75
24.5	3.50	3.45	3.75	4.94	4.87	3.75
28.0	3.50*	3.45	3.75	4.94	5.10	4.94
31.5	3.75*	3.37*	4.87	5.40	OL	OL
35.0	3.45*	3.85*	OL	OL		
38.5	4.12	OL				
42.0	OL					

APPENDIX 3.1 (continued)

(c) 2/6/87, 35% moisture

Depth cm	Distance from slot)					
	Slot	10 cm	20 cm	30 cm	40 cm	Nonsubsoiled
3.5	0.37*	0.90	0.82	0.90	0.90	1.05
7.0	0.37*	1.50*	1.20*	1.50*	1.68	2.10
10.5	0.90*	2.10*	1.50*	1.50*	2.77	3.50
14.0	0.90*	1.87*	1.50*	1.61*	2.10	2.25
17.5	0.90*	2.10*	1.87*	1.61*	3.45	3.75
21.0	0.82*	2.10*	1.87*	1.82*	3.45	3.45
24.5	0.90*	1.50*	2.50*	2.10*	3.75	3.50
28.0	1.35*	2.10*	2.50*	2.50*	3.50	3.50
31.5	1.87*	2.50*	2.50*	2.62	3.15	3.50
35.0	2.10*	3.37	2.62*	3.45	3.75	3.75
38.5	2.10*	3.45	4.57	4.92	4.87	4.57
42.0	2.10*	3.50*	OL	OL	OL	OL
45.5	OL	OL				

Te Kowhai silt loam

(a) 3/12/86, 20% moisture

Depth cm	Distance from slot					
	Slot	10 cm	20 cm	30 cm	40 cm	Nonsubsoiled
3.5	0.45*	0.97	0.82	1.27	0.97	1.05
7.0	0.45*	1.35	1.25	1.25	1.20	1.12
10.5	0.45*	0.75*	1.10	1.62	2.25	2.42
14.0	0.37*	0.90*	1.95	2.77	2.62	2.77
17.5	0.45*	0.90*	2.15	2.62	2.02	OL
21.0	0.52*	1.05*	2.62*	2.02*	2.17*	
24.5	0.67*	0.75*	2.17*	1.95*	2.10*	
28.0	1.35*	0.82*	2.02*	2.17*	5.25	
31.5	1.35*	1.42*	2.02*	2.10	OL	
35.0	1.35*	1.50*	2.02*	OL		
38.5	1.12*	1.35*	1.42*			
42.0	0.97*	1.27*	1.80*			
45.5	4.87	4.50	4.57			
49.0	OL	OL	OL			

APPENDIX 3.1 (continued)

(b) 6/7/87, 39% moisture

Depth cm	Distance from slot					
	Slot	10 cm	20 cm	30 cm	40 cm	Nonsubsoiled
3.5	0.22*	0.67	0.53*	0.82	0.75	0.75
7.0	0.45*	0.67	0.67	0.67	0.75	0.75
10.5	0.97*	0.75*	0.75*	0.67*	0.82*	1.35
14.0	1.35	1.12*	0.90*	0.75*	1.20	1.65
17.5	1.42	1.35	0.90*	0.82*	1.50	1.65
21.0	1.42	1.42	1.35	0.90*	1.50	1.42
24.5	1.12	1.35	1.35	0.90	1.57	1.12
28.0	1.20	1.27	1.42	1.42	1.57	1.42
31.5	1.57	1.35	1.42	1.50	1.95	1.50
35.0	1.57	1.42	1.42	1.42	1.80	1.57
38.5	1.27	1.57	1.35	1.57	1.80	1.57
42.0	1.05*	1.57	1.42	1.57	2.10	1.57
45.5	1.05*	1.50	1.50	1.72	2.10	1.95
49.0	1.05*	1.35*	1.57*	2.10	2.85	3.00

(c) 11/12/76, 18% moisture

Depth cm	Distance from slot					
	Slot	10 cm	20 cm	30 cm	40 cm	Nonsubsoiled
3.5	0.67*	0.82*	1.27	1.05	1.05	1.12
7.0	0.67*	0.90*	0.90*	0.75*	1.50	1.35
10.5	0.75*	0.90*	1.12	1.50	1.50	1.35
14.0	1.05*	0.75*	1.12	1.35	1.35	1.35
17.5	1.12*	1.05*	1.35	1.50	1.78	1.42
21.0	1.12*	1.05*	1.35*	1.50*	2.50	OL
24.5	1.12*	1.12*	2.17	2.10	2.62	
28.0	1.50*	1.35*	4.92	4.57	3.50	
31.5	1.67*	1.80*	OL	OL	OL	
35.0	1.35*	1.50*				
38.5	1.35*	1.50*				
42.0	2.17*	2.10*				
45.5	3.75*	3.90*				
49.0	OL	OL				

APPENDIX 3.1 (continued)

(d) 15/12/88, 22% moisture

Depth cm	Distance from slot					
	Slot	10 cm	20 cm	30 cm	40 cm	Nonsubsoiled
3.5	0.82*	0.97	0.97	0.90	1.05	1.12
7.0	0.97	0.90*	1.12	1.12	1.20	1.20
10.5	0.97*	1.20	1.20	1.12	1.35	1.35
14.0	1.12	1.20	1.33	1.35	1.65	1.35
17.5	1.20*	1.35*	1.42*	1.50	1.65	2.18
21.0	1.35*	1.20*	1.78*	3.90	3.95	OL
24.5	1.50*	1.85*	4.92	OL	5.00	
28.0	1.35*	2.10*	OL		OL	
31.5	1.42*	3.75*				
35.0	1.57*	OL				
38.5	1.33*					
42.0	4.57					
45.5	OL					
49.0						

Whatawhata clay loam

(a) 15/12/86, 18% moisture

Depth cm	Distance from slot					
	Slot	10 cm	20 cm	30 cm	40 cm	Nonsubsoiled
3.5	0*	0.67*	0.75	0.82	0.98	0.90
7.0	0*	0.75*	0.75*	0.82*	0.90*	1.20
10.5	0.37*	0.67*	0.75*	0.82*	0.90*	1.82
14.0	0.53*	0.75*	0.82*	1.35	1.50	1.75
17.5	0.60*	0.82*	0.82*	1.35*	1.87	2.10
21.0	0.67*	0.82*	1.20*	1.20*	1.87*	3.45
24.5	0.75*	1.12*	1.35*	1.68*	3.45	3.75
28.0	0.75*	1.20*	1.61*	3.75*	4.92	5.23
31.5	0.82*	1.35*	1.61*	4.94	5.14	OL
35.0	0.90*	1.50*	3.45*	5.31	OL	
38.5	1.87*	2.10*	3.78*	OL		
42.0	2.10*	2.62*	4.87			
45.5	3.75*	3.75*	5.62			
49.0	4.87	4.90	OL			

APPENDIX 3.1 (continued)

(b) 7/7/87, 38% moisture

Depth cm	Distance from slot					
	Slot	10 cm	20 cm	30 cm	40 cm	Nonsubsoiled
3.5	0.23*	0.67	0.53	0.67	0.60	0.67
7.0	0.53*	1.28	1.28	0.90	0.90	0.97
10.5	1.35	1.80	1.50	1.50	0.97	0.90
14.0	1.50	1.87	1.72	1.65	1.65	1.50
17.5	2.10	1.72	2.10	2.10	2.02	1.65
21.0	2.25	1.65	2.18	2.18	1.72	1.65
24.5	2.18	1.72	1.80	1.35	1.35	1.65
28.0	1.80	1.65	1.65	1.65	1.50	1.50
31.5	1.35	1.72	1.65	1.65	1.95	1.35
35.0	1.58	1.65	1.72	1.58	2.25	1.95
38.5	1.50	1.65	1.72	1.72	1.65	1.95
42.0	1.28*	1.65	1.65	1.43*	1.20*	2.10
45.5	1.43	1.35	1.65	1.65	0.90	1.80
49.0	1.50*	1.43*	1.43*	1.80	2.25	2.25
52.5	1.35*	1.43*	1.50	2.77	2.77	2.18

(c) 14/12/87, 19% moisture

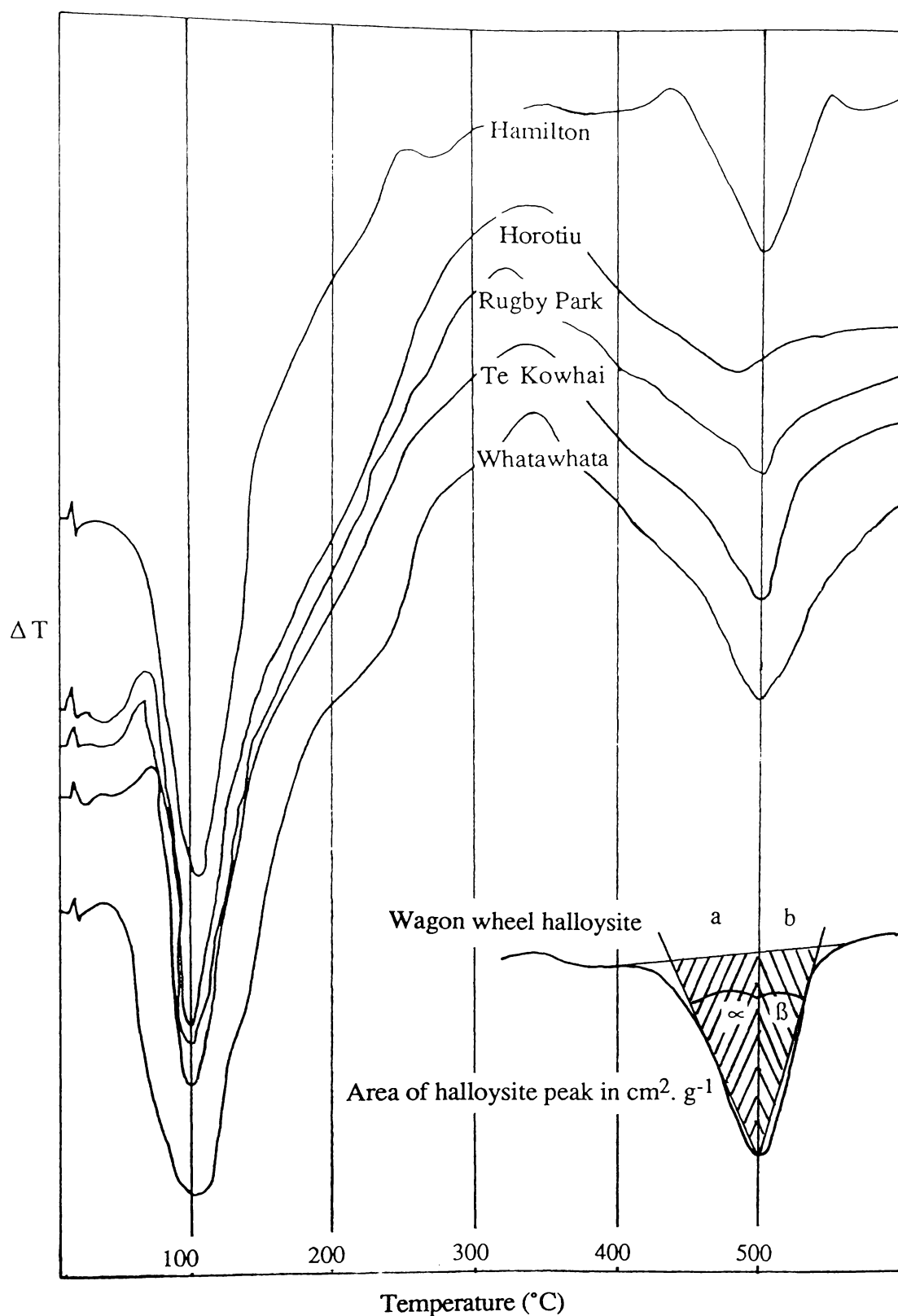
Depth cm	Distance from slot					
	Slot	10 cm	20 cm	30 cm	40 cm	Nonsubsoiled
3.5	0.37*	0.53*	0.67	0.67	0.82	0.82
7.0	0.53*	0.53*	0.67*	0.82	0.82	0.90
10.5	0.82	0.82	0.67	0.82	0.90	0.90
14.0	0.82*	0.82*	0.90*	1.20	1.20	1.35
17.5	0.90*	1.20	1.20	1.35	1.35	1.35
21.0	0.90*	1.20*	1.20*	1.35*	2.62	3.45
24.5	0.90*	1.20*	2.62*	2.25*	3.75	4.50
28.0	0.82*	1.87*	2.62*	3.75*	5.40	5.40
31.5	0.90*	2.10*	4.92	5.23	OL	OL
35.0	1.20*	2.10*	OL	OL		
38.5	2.10*	3.75*				
42.0	2.10*	5.23				
45.5	4.87	OL				
49.0	OL					
52.5						

APPENDIX 3.1 (continued)

(d) 16/11/88, 22% moisture

Depth cm	Distance from slot					
	Slot	10 cm	20 cm	30 cm	40 cm	Nonsubsoiled
3.5	0.67*	0.67*	0.75	0.75	0.82	0.90
7.0	0.67*	0.82*	0.90*	0.82*	0.90	1.20
10.5	0.90*	0.82*	0.90*	0.82*	1.35	1.35
14.0	1.20	1.50	1.28	1.50	1.95	1.35
17.5	1.20*	1.50*	1.65*	1.65*	1.95	2.77
21.0	1.20*	1.50*	1.65*	2.10	2.25	2.50
24.5	1.20*	1.35*	2.62*	2.50*	4.57	5.00
28.0	1.35*	1.35*	5.10	5.40	OL	OL
31.5	1.20*	1.87*	OL	OL		
35.0	1.50*	1.87*				
38.5	2.62*	2.62*				
42.0	2.62*	2.40*				
45.5	4.92	5.25				
49.0	OL	OL				

APPENDIX 4.1 Selected DTA thermograms



Curves indicated the following minerals: halloysite, allophane and kaolin for Hamilton, Horotiu and Whatawhata samples respectively
 Halloysite standard (after Bramao *et al.*, 1952)

APPENDIX 4.2 Selected XRD traces



Traces show allophane (XRD amorphous) dominates the Horotiu sample and Halloysite (10 Å) predominates in the Hamilton, Rugby Park and Te Kowhai samples and Kaolin (7.2 Å) dominates the Whatawhata sample.

APPENDIX 5.1 Aggregate size analysis data

Graphical method parameters (Folk and Ward, 1957)

Sieve size (mm), weight (%), x (mean weight diameter)

Hamilton

Sieve size	A Horizon		Bg Horizon	
	Non-subsoiled Weight	Subsoiled Weight	Non-subsoiled Weight	Subsoiled Weight
48	6.00	1.00	2.50	5.00
24	25.00	15.50	15.00	10.00
12	37.50	30.00	30.00	16.00
6	8.50	21.00	25.50	28.50
3	9.50	14.50	10.50	15.50
1.5	5.00	6.00	4.00	7.50
0.75	3.50	5.00	5.50	6.50
0.375	1.50	2.00	5.50	6.00
0.125	3.50	5.00	3.50	5.00
Classification	Poorly sorted, strongly fine skewed leptokurtic $x = 13.00$	Poorly sorted strongly fine skewed, leptokurtic $x = 8.57$	Poorly sorted strongly fine skewed, leptokurtic $x = 8.22$	Very poorly sorted, fine skewed, leptokurtic $x = 6.06$

Te Kowhai Soil

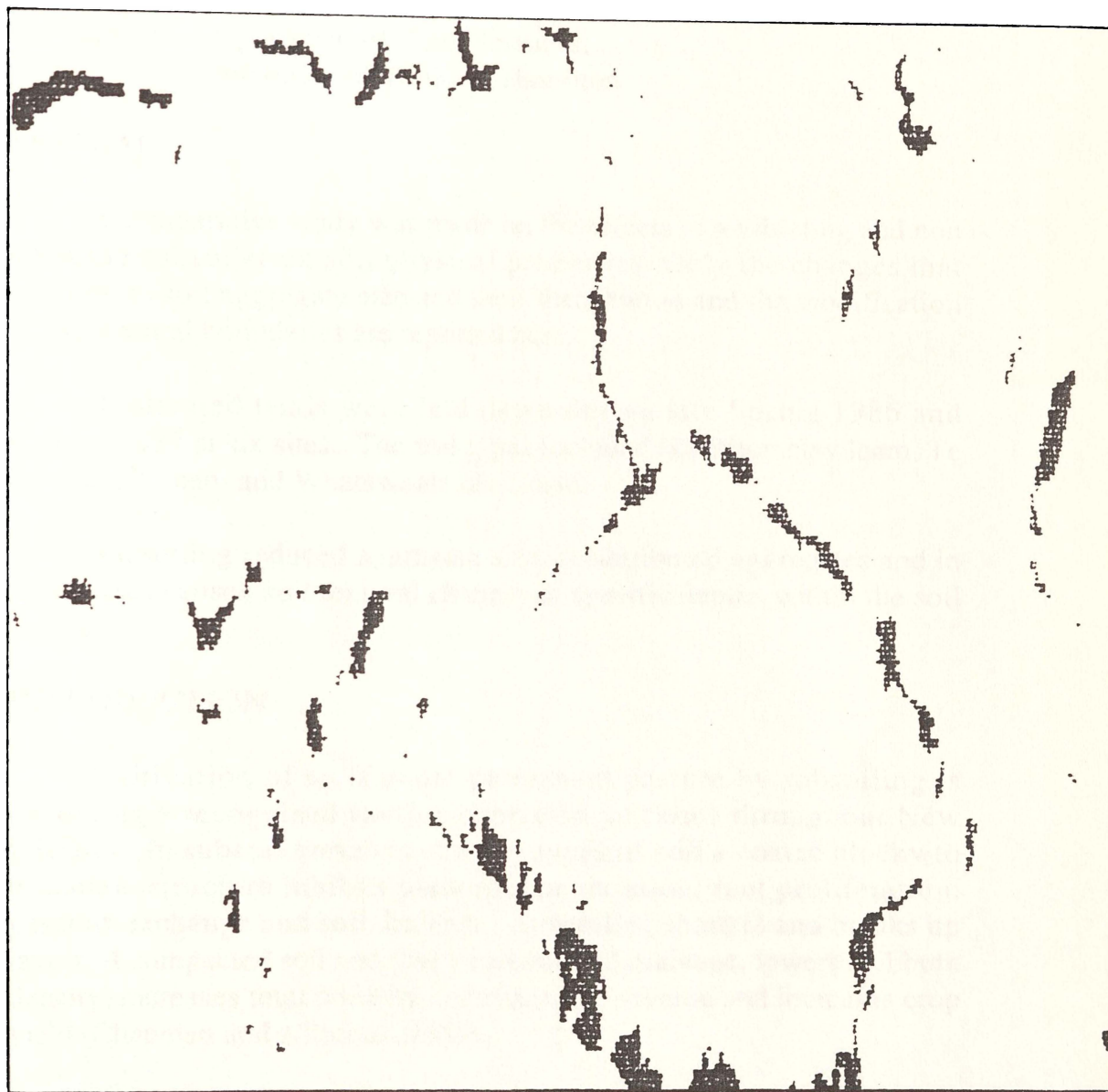
Sieve size	A Horizon		Bg Horizon	
	Non-subsoiled Weight	Subsoiled Weight	Non-subsoiled Weight	Subsoiled Weight
48	7.50	5.00	29.50	2.00
24	25.00	20.00	19.00	17.46
12	35.00	26.00	24.00	44.64
6	16.00	29.50	11.00	19.95
3	5.50	8.00	7.00	6.48
1.15	3.75	4.00	4.00	2.49
0.75	2.25	2.50	1.75	2.49
0.375	2.00	2.25	1.75	2.00
0.125	3.00	2.75	2.00	2.49
Classification	poorly sorted, strongly fine skewed leptokurtic $x = 15.35$	Poorly sorted, fine skewed, leptokurtic $x = 12.13$	Poorly sorted, strongly fine skewed, mesokurtic $x = 18.50$	Poorly sorted, strongly fine skewed very leptokurtic $x = 13.55$

Whatawhata Soil

Sieve size	A Horizon		Bg Horizon	
	Non-subsoiled Weight	Subsoiled Weight	Non-subsoiled Weight	Subsoiled Weight
48	9.50	7.50	0.00	0.00
24	42.50	31.40	42.00	13.00
12	4.00	3.00	6.50	13.00
6	12.00	10.50	12.00	18.00
3	11.50	23.50	19.00	21.00
1.5	2.50	5.00	3.50	4.50
0.75	13.00	14.00	10.50	17.00
0.375	2.50	2.50	4.50	7.50
0.125	2.50	2.60	2.00	6.00
Classification	Very poorly sorted, strongly fine skewed, platykurtic x = 11.31	Very poorly sorted, near symmetrical, platykurtic x = 7.11	Very poorly sorted, strongly fine skewed, platykurtic x = 8.28	Very poorly sorted, fine skewed platykurtic x = 4.38

* All subsoiled samples taken from within 10 cm of the subsoiled slot.

APPENDIX 6.1 Image analysis



Fractional area (4.01%) represents pores $> 9.76 \mu\text{m}$ for a scanned 9.05 mm^2 section of a B horizon aggregate taken from Hamilton clay loam.

APPENDIX 7.1 Published report

**Proceedings, 5th National Land Drainage Conference,
Massey University, 1992**

CHANGES IN SOIL STRUCTURE AND TEXTURE AFTER SUBSOILING SOILS UNDER PERMANENT PASTURE.

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ABSTRACT

A comparative study was made on the effects of a vibrating and non vibrating subsoiler on soil physical properties. Only the changes that occurred to soil aggregate size and their distribution and the modification of soil textural boundaries are reported here.

Replicated trials were laid down during late Spring 1986 and Autumn 1987 at six sites. The soil types included Hamilton clay loam, Te Kowhai silt loam and Whatawhata clay loam.

Subsoiling reduced aggregate size, redistributed aggregates and in some cases caused soil textural changes at specific depths within the soil profile.

INTRODUCTION

Cultivation of soils under permanent pasture by subsoiling is becoming a recognised routine operation on farms throughout New Zealand. In subsoil horizons of many types of soil a coarse blocky to prismatic structure inhibits plant root penetration, root proliferation, gaseous exchange and soil drainage. Subsoiling shatters and breaks up layers of compacted soil and thus improves soil drainage, lowers soil bulk density, increases total porosity, increases root volume and increases crop yield (Chapman and Allbrook, 1987).

The objectives of this study are to quantify the changes in aggregate size, their distribution and horizon of origin and to record changes in soil texture as an effect of subsoiling. A Gallagher Shakaerator¹ with shank spacing set at 100 cm and operating at a depth of 45 cm, with a forward speed of 5 kph, was used in this study. It was used in both its vibrating and non vibrating mode.

¹ *Mention of trade name does not imply endorsement by Waikato University to the exclusion of other products that may be suitable.*

APPENDIX 7.1 (continued)

FIELD AND LABORATORY MEASUREMENTS

Samples for measurement of aggregate size and their redistribution were observed in situ and then recovered for laboratory analysis. Samples from subsoiled and non subsoiled plots were airdried and sieved carefully by hand with mesh sizes ranging from 0.063 to 32 mm. Aggregates with >32 mm principal axis were measured by ruler.

RESULTS

Soil textural changes

The subsoiled (vibrating) Hamilton and Whatawhata soils (Table 1) both showed a significant increase in clay size particles in the top 0 to 25 cm soil layer. The respective 11% and 12% increase resulted in a "reclassification" of the upper 0 to 25 cm layer from clay loam to clay. Conversely the Te Kowhai top soil sand fraction increased from 27 to 35%, but this increase was not sufficient to change the textural class. The Hamilton and Whatawhata soils (Table 1) had fewer clay size particles within the disturbed subsoiled deeper layers (25 - 45 cm) when compared with soils from non subsoiled plots.

Aggregate size distribution in subsoiled (vibrating) and non subsoiled plots.

The Hamilton non subsoiled soil Fig.1(a) exhibited a positive skewed unimodal aggregate size, centred around the 8 to 16 mm mean intermediate principal axis. Subsoiling normalised the fragment size by reducing this peak by 15% and increasing the 4 to 8 mm size from 9 to 23%.

A characteristic of the Whatawhata soil is its multimodal range of aggregate size Fig.2(b) both before and after subsoiling. The larger subsoil aggregates (16 to 32 cm) were fissured and broken up by subsoiling and hence the 4 to 16 mm aggregate fraction increased.

The large (32 to 64 mm) blocky structured units of the Te Kowhai subsoil Fig.3(b) were completely shattered giving an increase in 4-16 mm. However the effect on "A" horizon aggregates for this soil was not so dramatic (Fig.3(a)).

Soil Type	Horizon depth cm			Mechanical Analysis			Textural Class
				% Sand (2-0.063 mm)	% Silt (0.063-0.002 mm)	% Clay (<0.002 mm)	
Te Kowhai Silt loam	0 -	20	NS	27	51	22	Silt loam
Te Kowhai Silt loam	0 -	20	S	35	46	19	Silt loam
Te Kowhai silt loam	20 -	45	NS	30	43	27	Silt loam
Te Kowhai Silt loam	20 -	45	S	35	39	26	Silt loam
Hamilton Clay loam	0 -	25	NS	29	34	37	Clay loam
Hamilton Clay loam	0 -	25	S	26	26	48	Clay
Hamilton Clay loam	25 -	45	NS	8	21	71	Clay
Hamilton Clay loam	25 -	45	S	14	21	65	Clay
Whatawhata Clay loam	0 -	25	NS	20	32	40	Clay loam
Whatawhata Clay loam	0 -	25	S	21	28	52	Clay
Whatawhata Clay loam	25 -	45	NS	11	23	66	Clay
Whatawhata Clay loam	25 -	45	S	16	25	59	Clay

Table 1: Showing redistribution of soil particles after subsoiling. Each measurement is the average of four replicates. Subsoiled (S) Non Subsoiled (NS)

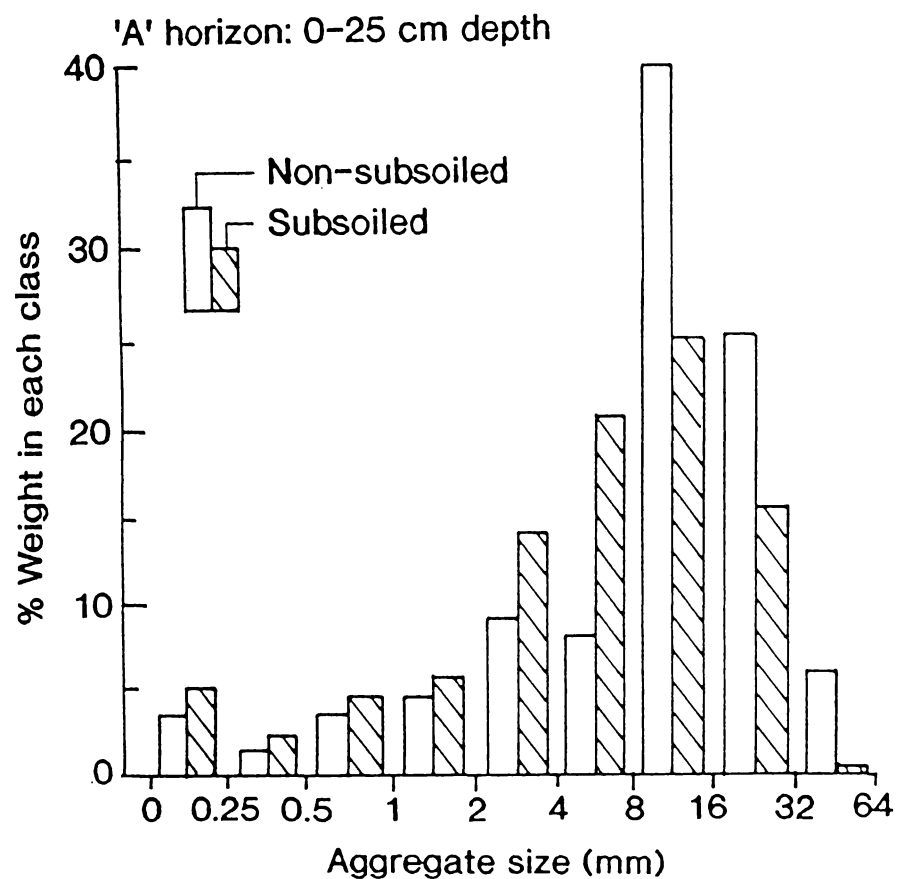


FIGURE 1(a) Hamilton clay loam (moisture 25% v/v)

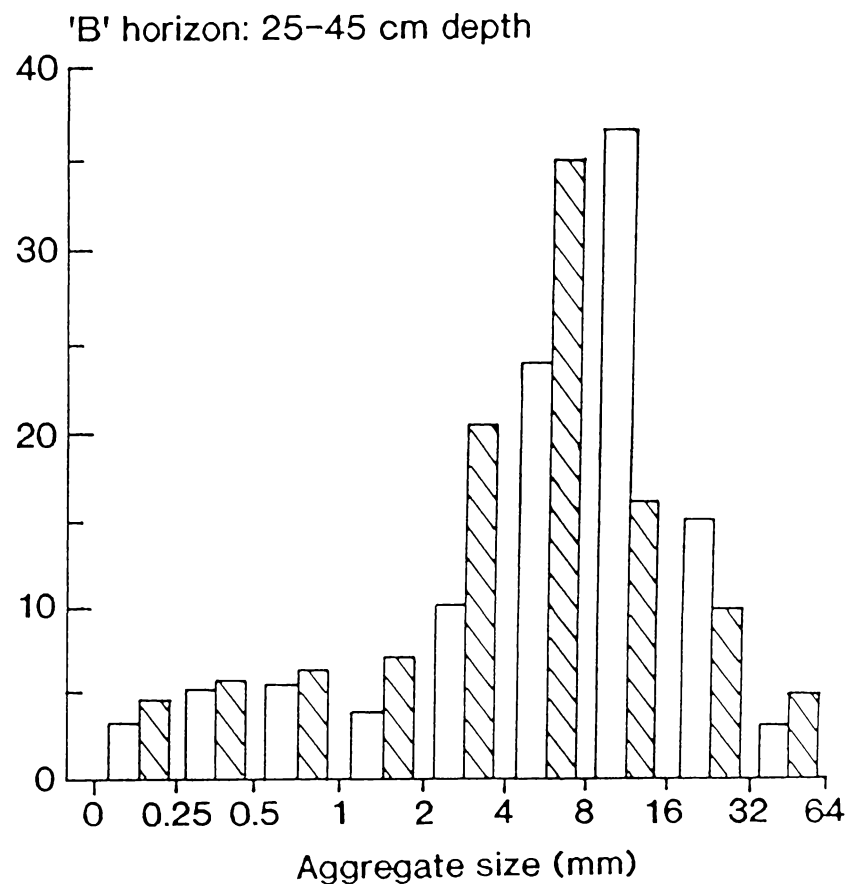


FIGURE 1(b): Hamilton clay loam (moisture 23% v/v)

Graphs show aggregate size distribution for subsoiled and non subsoiled plots.

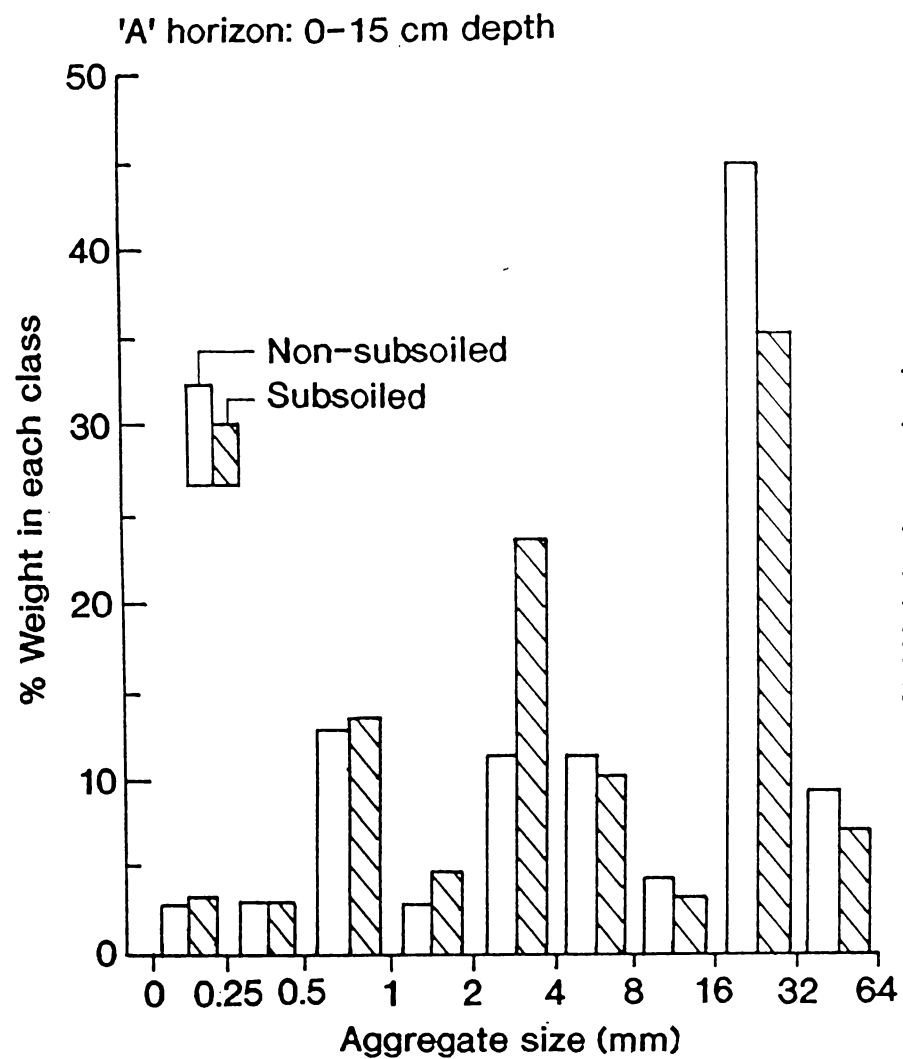


FIGURE 2(a): Whatawhata clay loam (moisture 26% v/v)

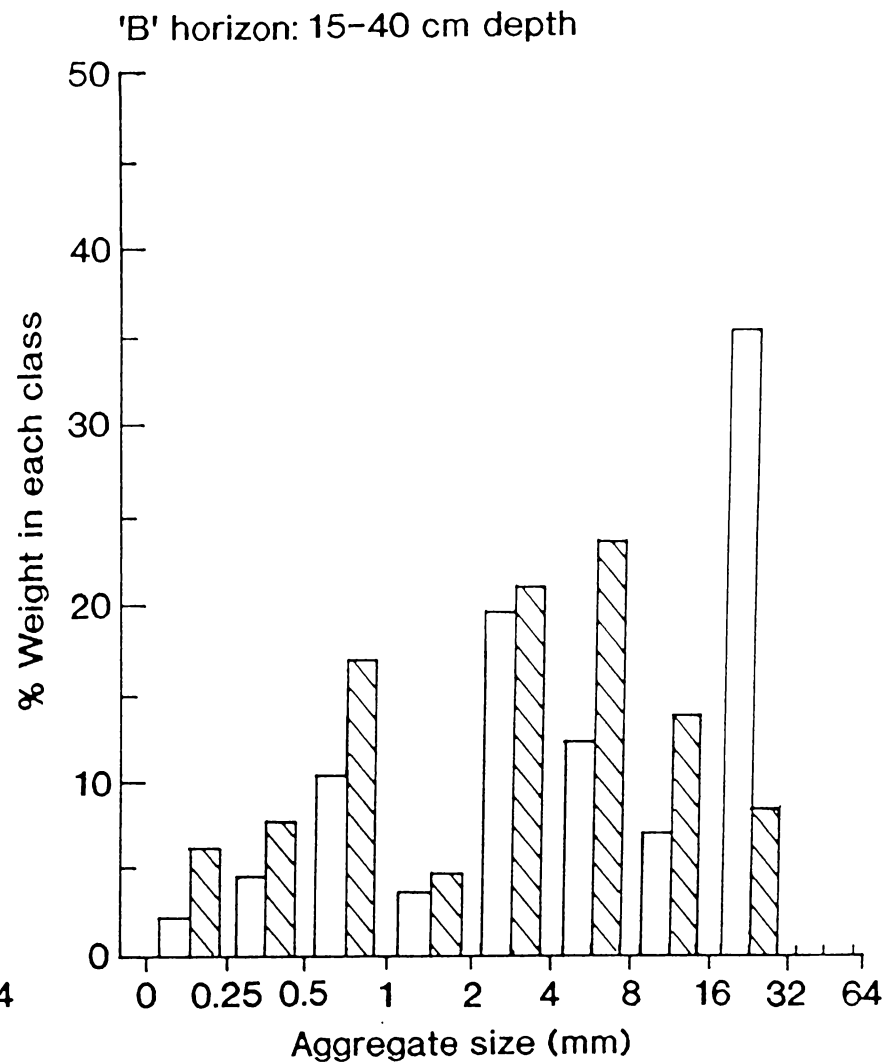


FIGURE 2(b): Whatawhata clay loam (moisture 21% v/v)

Graphs show aggregate size distribution for subsoiled and non subsoiled plots.

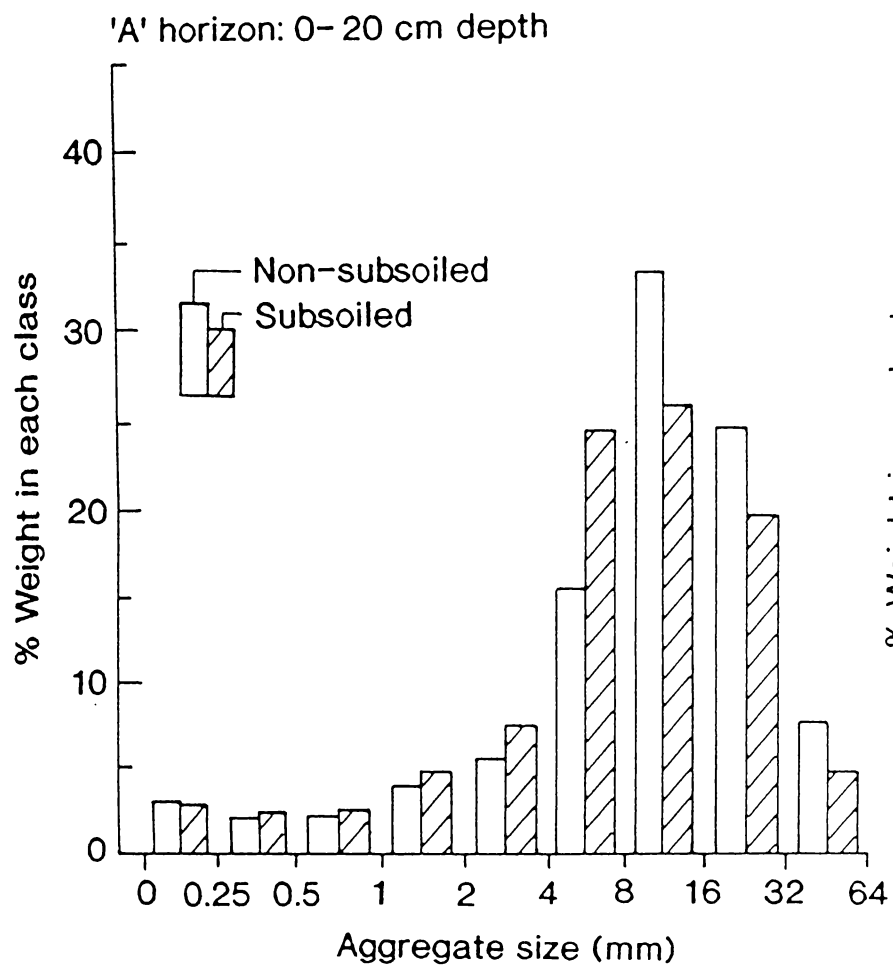


FIGURE 3(a): Te Kowhai silt loam (moisture 22% v/v)

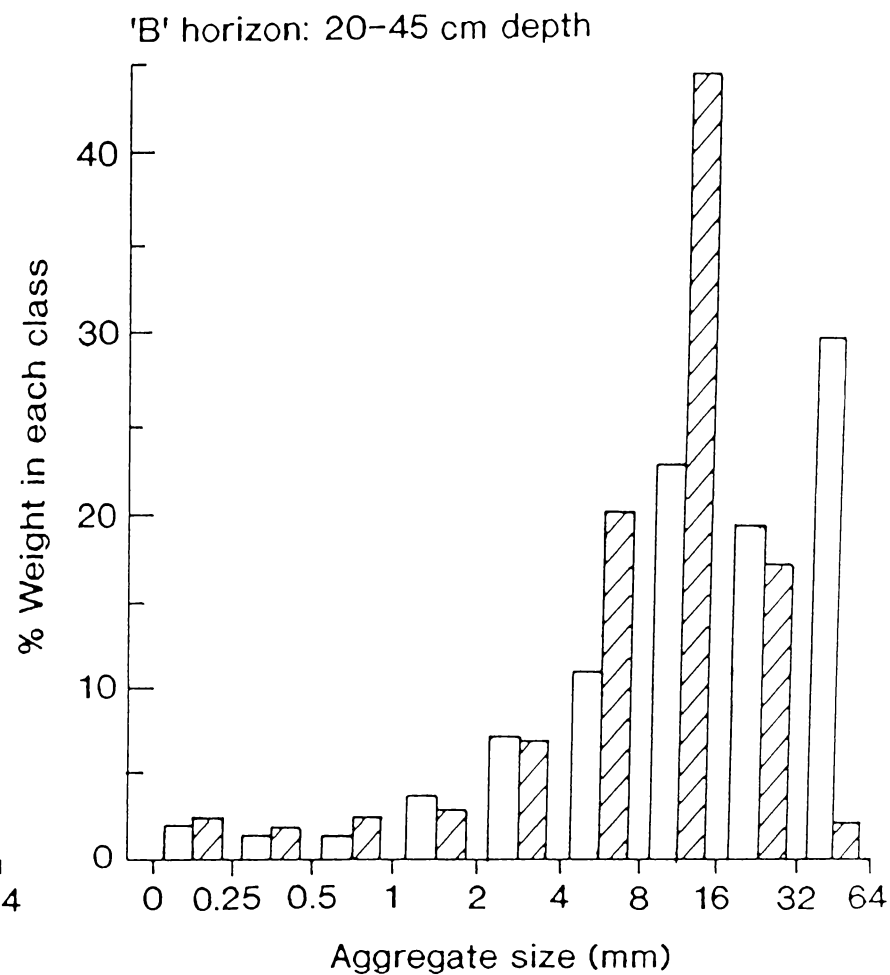


FIGURE 3(b): Te Kowhai silt loam (moisture 22% v/v)

Graphs show aggregate size distribution for subsoiled and non subsoiled plots.

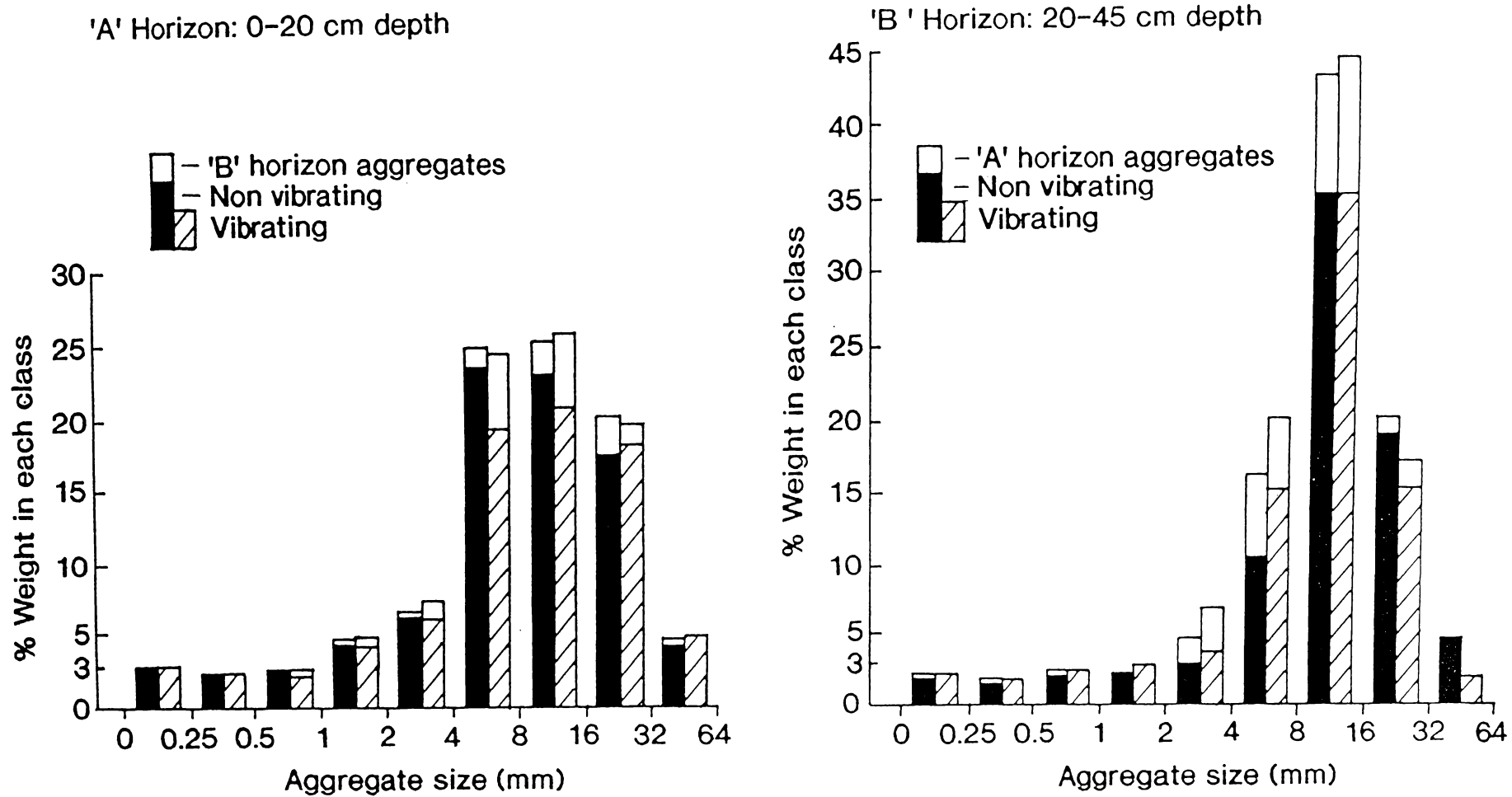


FIGURE 4: Te Kowhai silt loam (moisture 24% v/v)

Graphs show aggregate size distribution and horizon mixing after subsoiling.

APPENDIX 7.1 (continued)

Horizon of origin of soil aggregates

Examination of soil aggregates (Te Kowhai gleyed soil) within the subsoiling troughs showed that soil mixing through heave and shatter, resulted in the addition of approximately 15% "B" horizon aggregates into the top 0-20 cm layer, and a similar percentage of "A" horizon aggregates incorporated into the deeper 20-45cm subsoil layer (Fig.4). Although vibrating caused greater soil disturbance than non vibrating, it did not significantly change the redistribution percentage of soil aggregates (Fig.4).

DISCUSSION

The physical properties of all three soils showed significant changes after subsoiling (Chapman & Allbrook 1987). The soils were subsoiled in a relatively dry state, this resulted in much disturbance and soil mixing.

Soil aggregates from deeper layers were forced into upper layers by the unique design of the subsoiler shank and winged tip. This resulted in the Hamilton and Whatawhata soil becoming more clayey in the 0 to 25 cm layer and the Te Kowhai soil becoming more sandy. Subsoils of all three soils gained top soil aggregates, through them falling down behind the vibrating subsoiler shanks. This redistribution of soil aggregates and changes in textural properties may result in some negative effects, but to date none have been observed or recorded.

However changes to soil physical properties such as lowered bulk densities, raised porosities and improved drainage through subsoiling has resulted in increased root volumes with increased pasture yields on all three soils under investigation.

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APPENDIX 7.2 Published report

DRAIN AGE

AN OCCASIONAL NEWSLETTER OF THE
NEW ZEALAND LAND DRAINAGE ASSOCIATION (INC)

No. 5
December 1988

SUBSOILING FOR BETTER DRAINAGE

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Subsoiling, a form of sub-tillage, has long been recognized as an essential routine cultivation in arable farming, especially where compacted soils limit crop production.

Compacted soils inhibit free exchange of gases, restrict plant roots, lower soil porosity, increase soil bulk density and affect soil drainage.

Compacted soil layers may result from natural soil forming processes, for example hard clay pans. They may however result from man's influence, such as livestock trampling, use of heavy machinery, or in the case of sports fields, continuous use under a wide range of moisture conditions.

In conjunction with Gallagher Engineering Ltd, Hamilton, the Earth Sciences Department, University of Waikato set up a research programme in July 1986 to assess the benefits and effects of subsoiling various soil types under differing culture regimes. A Gallagher Shakaerator subsoiler was used to carry out the subsoiling.

The main thrust of the research was directed toward quantifying the changes in soil physical characteristics and crop production response.

It soon became obvious that in addition to changes in bulk density, porosity and root volume, subsoiling resulted in major effects to soil moisture and drainage.

A number of soils within the Waikato region with poor drainage benefitted from subsoiling. A replicated trial on a Whatawhata clay showed that the subsoiled plots were drier than the non-subsoiled plots during the winter. However, after a summer rain storm, the subsoiled plots were wetter than the non subsoiled plots.

These results suggest that the subsoiling created a larger proportion of macropores in the soil, which facilitate better drainage. Also, the lowered bulk density and increased porosity of the soil after subsoiling encouraged a better infiltration of summer rain, at a time when moisture stress can be a limiting factor for optimal crop production.

In addition to the soil investigation, the Gallagher Shakaerator subsoiler was also assessed for performance, and as a result the machine was redesigned to include disc coulters and rollers for pasture work. The machine is versatile and strong and the pasture model leaves a clean undisturbed surface. Its unique shaking action results in a large volume of subsurface shatter which creates space for roots to explore and increase, both in volume and depth. The effects of subsoiling soils under pasture in the Waikato resulted in a 12 - 15% increase in dry grass matter.

The research work is continuing with emphasis on long term effects of subsoiling, critical operating depths, width of shanks and changes of soil microstructure.

APPENDIX 7.3 Published report

Proceedings Agronomy Society
of New Zealand. 17 1987

THE EFFECTS OF SUBSOILING COMPACTED SOILS UNDER GRASS — A PROGRESS REPORT

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ABSTRACT

The relationship between penetrometer resistance, root growth and pasture production have not been satisfactorily defined under field conditions.

It is often difficult to identify those layers of soil which have sufficiently high mechanical impedance to limit root growth. The object of our research has been to establish a relationship between the physical properties of the soil and pasture production. The Gallagher subsoiler shattered the soil with little damage to the pasture.

Replicated trials were laid down during late Spring 1986 and Autumn 1987, at six sites. The soil types included a Whatawhata clay loam, a Te Kowhai silt loam, a Horotiu sandy loam and a Hamilton clay loam.

Subsoiling reduced the resistance of the soil to a penetrometer and decreased the bulk density and hence increased the porosity of the soil. After subsoiling a Whatawhata clay loam the root length of prairie grass plants increased. Pasture production is being monitored using a pasture probe.

Additional Key Words: bulk density, penetrometer, porosity, tillage, soil strength.

INTRODUCTION

Soil physical properties influence the growth of roots (Nye and Tinker, 1977). Soil horizons that have a high resistance to a penetrometer often have a high bulk density, and a low percentage of large continuous pores (Russell, 1977). These horizons may occur naturally in the soil as fragipans or duripans from soil forming processes, or they may result from livestock trampling, use of heavy machinery, on in the case of sports fields, heavy use at high moisture levels. Such horizons can be broken up by subsoiling – a form of deep tillage. In New Zealand subsoiling pasture land every 2-3 years, to depth of 45 cm, has not been a recognised form of sub-tillage because of the damage to pasture inflicted by traditional arable subsoilers.

The objective of this study is to monitor the effect of subsoiling on grass growth in pastoral farming and at a stadium used for sport. The machinery used in this study prevents surface scuffing. It slices through the turf in front of the subsoiler shanks and two rollers at the back of the machine partly press the uplifted soil, thus conserving soil moisture.

Location

Six sites in the Waikato where soil compaction appeared to limit pasture production were chosen but results from only three sites are reported here. Table 1 gives the location, soil types, pasture species and date of subsoiling.

Experimental design

In each trial a modified block design with four or five replicates was used. Plots varied in size from 100 – 400 m² and were either subsoiled (treated) or nonsubsoiled (control) to depths of up to 45 cm using a *Gallagher Grassland Subsoiler, with shank spacing set at 100 cm. Data was analysed using GENSTAT.

Field measurements

Soil strength was measured at ten sites within each plot using a *Bush recording cone penetrometer (Anderson, *et al.*, 1980). Readings were taken at increments of 3.5 cm, with the force applied per unit area expressed as a cone index (MPa).

Bulk density was measured at two locations per plot using a

*Ronly, hand-held gamma-ray probe. Measurements down the profile were taken at 5 cm intervals. Auger samples were taken and gravimetric measurements of soil water were made at corresponding depths.

Table 1: Location, subsoiling date, soil type and pasture type.

Location	Subsoiling Date	Soil Type	Pasture Species
Rugby Park Hamilton	7.10.86	artificially constructed	Perennial ryegrass
Ohaupo	20.11.86	Horotiu sandy loam	Perennial ryegrass
Whatawhata	5.12.86	Whatawhata clay loam	Praire grass

Table 2: Soil porosity (%) at Whatawhata

		Depth (cm)							
Treatments	Porosity	5	10	15	20	25	30	35	40
Subsoiled	total	64	63	62	62	58	57	57	62
Control	total	56	55	53	49	45	44	43	50
Subsoiled	air-filled	46	44	38	31	23	18	17	22
Control	air-filled	38	34	23	17	7	4	4	10

* Mention of trade names does not imply endorsement by Waikato University to the exclusion of other products that may be suitable.

APPENDIX 7.3 (continued)

Table 3: Maximum root depths of 40 cores taken at Whatawhata

	Subsoiled	Nonsubsoiled	SED	Signif.
Maximum root depth (cm)	28.5	23.5	6.56	***

Table 4: Pasture production at two sites from 15 May to 7 July 1987

Location	Treatment	Kg ha ⁻¹	% increase yield	SED	Signif.	n
Ohaupo	Subsoiled	2740	12	17.28	***	200
	Control	2447				
Whatawhata	Subsoiled	2330	15	14.76	***	200
	Control	2021				

Moisture tension was assessed using a *Quickdraw tensiometer at depths of 10, 30 and 45 cm. Measurements were made in July 1987 and were taken within 10 cm of the slits made by the subsoiler.

Pasture production and root depth

Pasture production was quantified using a pasture probe (*Design Electronics, Palmerston North). The instrument is a portable microprocessor controlled capacitance meter, which measures and records pasture mass as kilograms of dry matter per hectare.

Small monoliths taken from the pasture with a spade were used to measure root depth. These soil blocks were gently shaken to expose the root system.

RESULTS

Maximum penetrometer readings were obtained in the control plots at Whatawhata at 25 cm depth and at Rugby Park at 10 cm depth (Figure 1).

When plots were subsoiled at these sites penetrometer readings were reduced and maximum readings were obtained at 45 and 40 cm depth respectively. Subsoiling shattered the soil laterally 50 cm either side of the shanks (Figure 2.)

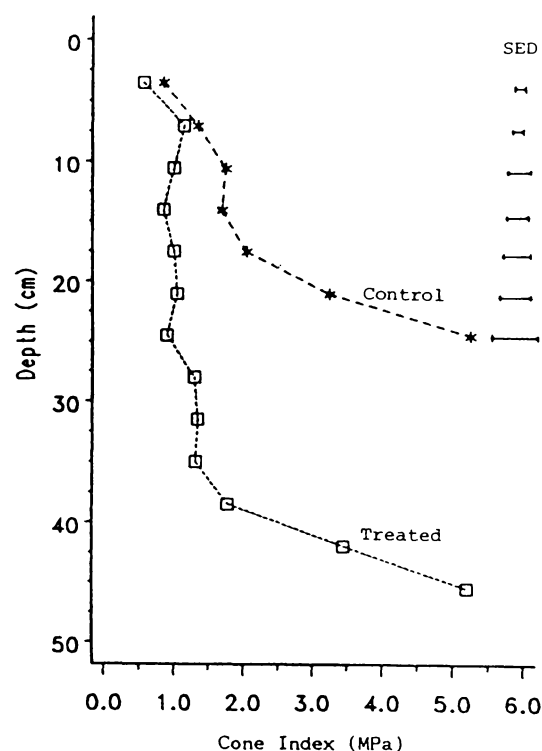


Figure 1: Variations in cone index in a soil profile from Whatawhata clay loam. Mean of 40 measurements. Significance * (10-40 cm depth)**

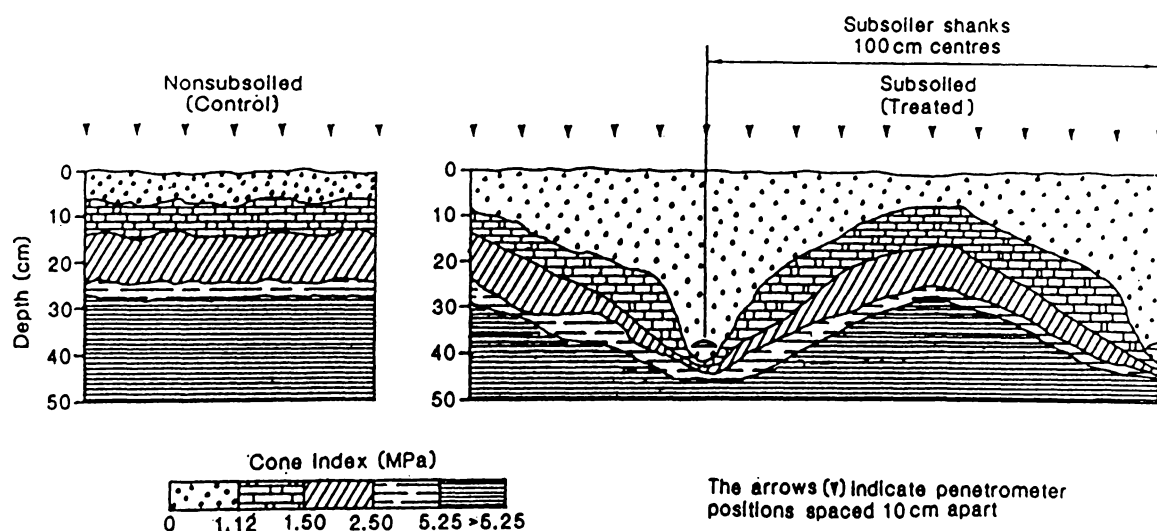


Figure 2: Variation in cone index (CI) with depth on a Whatawhata clay loam.

APPENDIX 7.3 (continued)

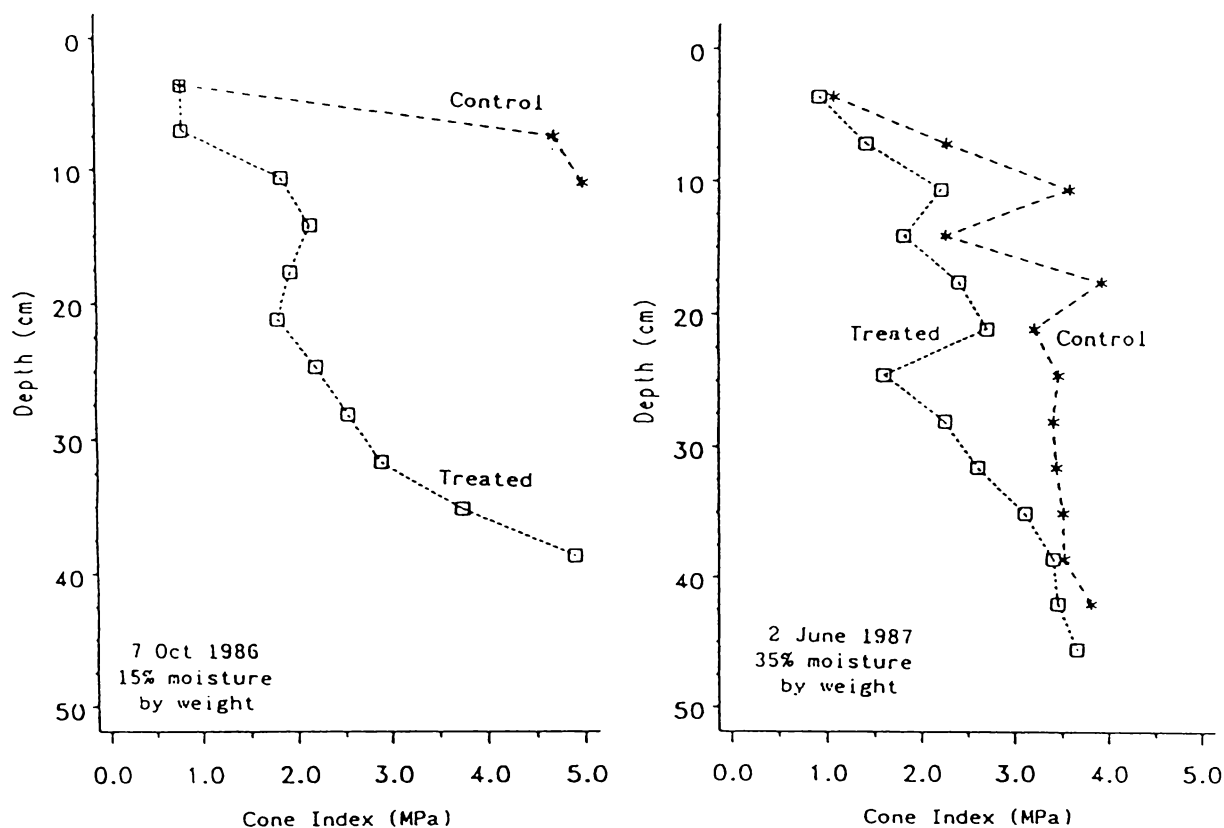


Figure 3: The influence of soil moisture on a cone index in an artificially constructed soil at Rugby Park.

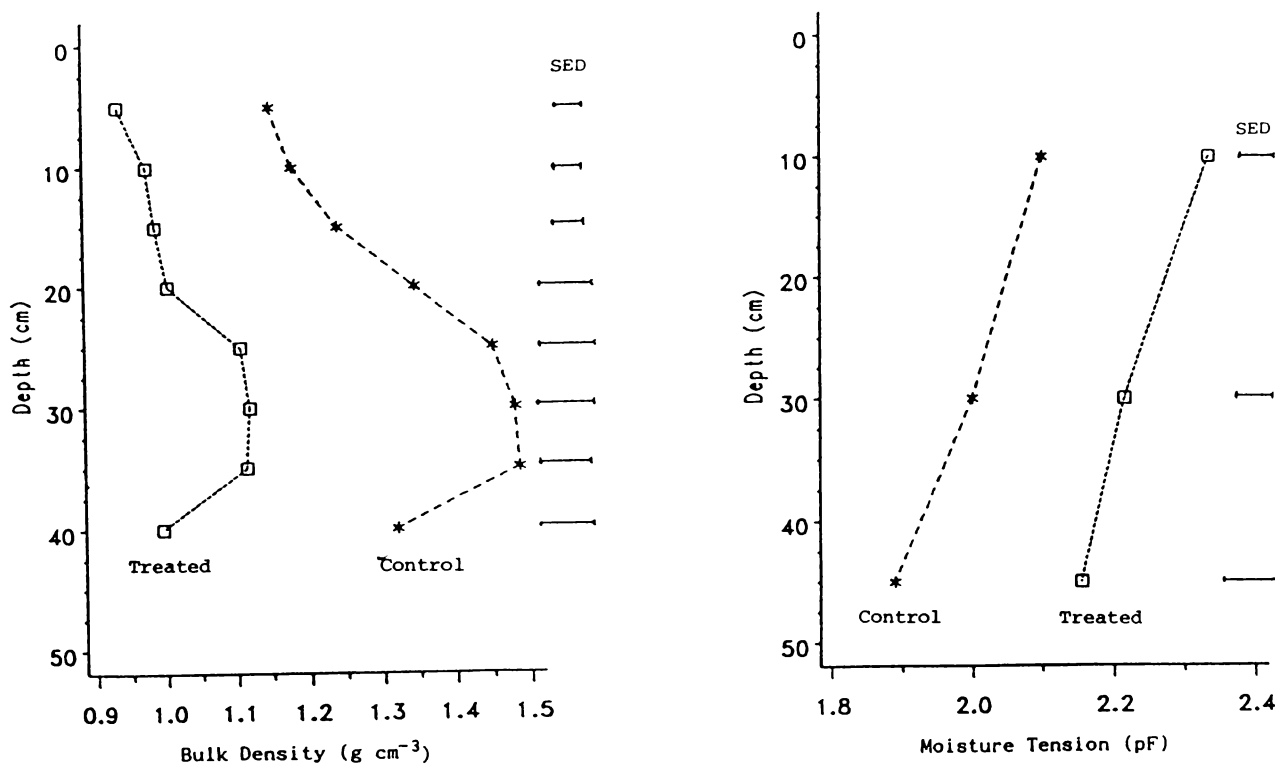


Figure 4: Bulk density within the profile of a Whatawhata clay loam.

Figure 5: Variation in soil moisture tension in the profile of a Whatawhata clay loam.

APPENDIX 7.3 (continued)

Soil strength fell significantly at moisture contents of 35% (Figure 3.).

Total porosity and air-filled porosity were calculated from bulk density and were greater in the subsoiled plots throughout the profile, even though the measurements were carried out 200 days after subsoiling occurred (Table 2).

Eight months after subsoiling, moisture tension was significantly greater in the subsoiled plots than in the control plots, which suggests that the soil in the treated plots was drier (Figure 5).

At the Whatawhata site, the depth of plant roots growing within a 10 cm band either side of the subsoiler slits were deeper than roots in the nonsubsoiled plots (Table 3).

Early winter pasture production was measured with a pasture probe and showed a significant increase in yield due to subsoiling of 12-15% (Table 4).

In some cases severe wilting occurred when pastures were subsoiled during mid-summer, due to root pruning and/or soil moisture loss. However this was not a problem at other times of the year.

DISCUSSION

At all sites significant changes to the physical condition of the soil were achieved by using the Gallagher subsoiler. These changes were not transitory but lasted for at least nine months. The destruction of a compacted layer within the soil profile lowered the bulk density and raised the porosity of the soil and reduced the penetrometer cone index readings.

Root growth has been shown to be severely restricted by high soil strength (Taylor and Ratliff, 1969). A subsoiler can modify soil structure, thus enabling grass roots to grow better (Table 3), fill a larger volume, and hence produce more leaves (Table 4).

Subsoiling increased the number of larger pores in the soil profile giving better aeration of the top 25 cm. Circulating air may evaporate water and remove it from the soil, resulting in the higher moisture tensions shown in Figure 5 which may bring the soil nearer to the moisture content optimum for plant growth.

In the control plots the number of air-filled pores in the layer of soil between 20 and 35 cm deep was very low and it is possible that plant growth could be limited by poor aeration. However in the subsoiled treatments the number of air-filled pores was satisfactory (Table 2). The increase in total porosity shown in this table may be assumed to be due to an increase in macropores, which are most affected by cultivations (Nye and Tinker, 1977) or compaction (Allbrook, 1986).

More work on root volume and root depth is required, and we hope to gain from our micromorphological studies information on why compacted soils provide unsuitable conditions for root growth and how these soils may be improved. Monitoring of soil moisture throughout the year will show whether moisture conditions near optimum for plant growth have been achieved. In the case of the sports stadium, maintenance of a freely drained soil should allow the turf to recover after its surface has been severely compacted during rugby matches in winter.

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