THE EFFECT OF SUBSOILING ON PLANT NUTRITION AND PASTURE PRODUCTION

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An eighteen month field trial was conducted to determine the effect of soil loosening on plant nutrition and pasture production.

The field trial was conducted on an established (8 year old) mixed sward pasture. The soil type was a Templeton silt loam (yellow-grey earth) of low to medium fertility. Two layers were identified as likely to be restrictive to root growth (22-27 cm and 40-60 cm).

The statistical design was a randomised block consisting of thirty-six plots (8 m x 8 m) in four replicates. The three cultivation treatments of nil cultivation, aeration (to 27 cm) and subsoiling (to 47 cm) were carried out on the 10-Nov-90 and 10-Oct-90 respectively. On 22-Dec-90 three fertiliser treatments were applied: nil fertiliser, phosphate only (30 kg P ha^{-1}) and phosphate (as above) plus sulphate fertiliser (30 kg S ha^{-1}).

The pasture was harvested when plant height reached approximately 8-10 cm. Pasture production and macronutrient concentration were determined for each pasture harvest. From 1-Aug-91 root length measurements were made at monthly intervals. Soil water content was measured at weekly intervals at six depths (20, 30, 35, 40, 50 and 70 cm) using Time-Domain-Reflectrometry. Soil bulk density and hydraulic conductivity were measured at two dates during the period of the trial.

Although root pruning by the loosening implements was suspected to have slightly reduced pasture production from 7-Nov-90 to 22-Apr-91, soil loosening led to a significant ($P<0.10$) increase in pasture production of approximately 1,300 kg DM ha^{-1} over the second season (1991/1992) of the trial.

Loosening by cultivation of the compacted soil layers significantly ($P<0.10$) reduced bulk density (11% reduction) and significantly ($P<0.10$) increased porosity.

Through the creation of soil physical conditions which were more favourable for root growth, soil loosening allowed the earlier onset of spring root growth, and root growth rates were 0.06 mm cm^{-2} d^{-1} higher than in the nil cultivation treatment. Subsoil loosening created a more extensive pasture root system compared to the nil cultivation treatment. By 18-Jan-92 the subsoil loosened treatment had a significantly ($P<0.10$) larger root length (44% higher) at the 30-60 cm depth than the nil cultivation treatment.

The subsoiled treatment had a significantly ($P<0.10$) drier soil profile (0-70 cm) over the 1991/1992 season. This was considered to be due to higher soil drainage rates in late winter/early spring and a small increase in water use by the pasture.

Soil loosening was found to result in a significant ($P<0.10$) increase (5 kg S ha^{-1}) in sulphur uptake by the pasture plants. The Templeton silt loam of the trial site was found to be deficient in sulphur, with particularly low concentrations (<3 μg SO_4^{2-} g^{-1}) occurring in the top soil. The sulphate concentration was higher (10 μg SO_4^{2-} g^{-1}) in the lower soil depths (30-50 cm). The more extensive pasture root system at this depth in the loosened treatments therefore had greater access to this sulphur, and resulted in increased pasture uptake of sulphur and increased pasture production on the loosened treatments.

Pasture grown on the loosened treatments tended to have higher concentrations of several macronutrients (S, Ca, Mg and Na) particularly during spring and mid-summer. The concentration of these four macronutrients in this Templeton silt loam were also found to increase below a depth of approximately 30 cm. The greater root lengths below 30 cm in the loosened treatments allowed the pasture roots greater access and consequently higher uptakes of these nutrients.

In August 1991 a microplot trial was established in an attempt to establish accurately the nutrient uptake potential of roots present in the trial plots. Radioactive tracers (^{32}P and ^{35}S) were injected to three depths (25, 40, and 55 cm) in the soil profile. The 80 cm diameter microplots were harvested when pasture height reached approximately 8 cm. The pasture samples were then dissected, dried, ground and the tracer activity determined. The subsoiled treatment was found to have a higher cumulative ^{35}S percent recovery from the 55 cm injection depth, confirming the results of the main trial.

To Aaron

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1.0 INTRODUCTION.

Reports from research workers in New Zealand and overseas have shown that substantial increases in crop yields can be achieved by subsoil loosening of previously compacted soil horizons eg. Coventry *et al.* (1987), Ide *et al.* (1987b) and Greenwood (1989).

Soil physical properties affect the rate roots grow through soil,for example soil aeration, mechanical impedance, and the size and continuity of soil pores. This is because roots are unable to move through soil layers that have a high mechanical impedance and that contain a low percentage of continuous pores (Vepraskas and Miner, 1986; Chapman and Allbrook, 1987). Such a reduction in root growth will lead to plant growth retardation and yield suppression (Ide *et al.*, 1984).

Compacted soil horizons may occur naturally in the soil as fragipans or duripans from soil forming processes or they may result from livestock trampling or the use of heavy machinery (Chapman and Allbrook, 1987). A breakdown of these compacted soil layers by subsoil loosening can reduce the mechanical impedance and increase the porosity of these layers resulting in an enlargement of the rooting zone (Ide *et al.*, 1984; Greenwood, 1989).

Most yield responses due to subsoil loosening have been attributed to reductions in plant water stress following the increased rate of root growth. However, improved root growth will obviously also improve the uptake of soil nutrients (Bowen, 1986).

It was apparent from a review of the literature that little attention has been given to the effect of subsoil loosening on plant nutrition. Those researchers that have studied plant nutrition following subsoil loosening have reported increased nutrient concentrations in crops (Ide *et al.*, 1984; Bennie and Botha, 1986; Bowden and Delroy, 1986; Reeves and Trouchton, 1986; Coventry *et al.*, 1987b; Stone, 1988).

However, there appears to be no reported research on the effects of subsoil loosening on plant nutrition in New Zealand. As subsoil loosening has been shown to be effective at increasing the depth and density of plant roots it therefore should improve nutrient uptake (indigenous or fertiliser), thus increasing pasture yield. Any increased pasture production and fertiliser use efficiency would have clear economic benefits.

A study to provide scientific knowledge on the effect of subsoil loosening on plant nutrient uptake and pasture production would be of benefit to the agricultural sector of New Zealand.

This study was undertaken with the overall objective to assess the influence of subsoil loosening on plant nutrient uptake and pasture production. This was to be achieved by:

(i) Assessing the effect of subsoil loosening on plant root development and pasture production,

(ii) Assessing the effect of subsoil loosening on plant recovery of indigenous soil nutrients by labelling techniques using carrier free isotopes (^{32}P and ^{35}S),

(iii) Assessing the effect of subsoil loosening on recovery of surface applied P and S fertilisers,

(iv) Assessing the effect of subsoil loosening on selected soil physical properties.

2.0 LITERATURE REVIEW.

2.1 Introduction.

There have been numerous scientific reports and literature reviews on the causes of soil compaction and the associated agronomic problems. The alleviation of soil compaction by the use of controlled traffic or the use of deep tillage has also received a great deal of attention in the published literature.

In New Zealand research on the topics of soil compaction and it's control is limited. Therefore most of the literature reviewed originates from research in European and North American countries.

In Europe soil compaction has always been a problem due to the continuous and intensive cultivation of large areas of land for food production over many years. Methods to alleviate soil compaction are varied with many terms being used, including deep tillage, ripping, soil loosening and subsoiling, to describe the cultivation practices aimed at reducing soil compaction.

The aim of this chapter is to review the principles and reported effects of subsoiling. In order to consider those effects, a prior understanding of soil compaction is necessary. Consequently the principles and effects of soil compaction are also reviewed. Because of the numerous reports relating to the many aspects of soil compaction and subsoiling this review is not exhaustive. Only recent publications, where possible, have been selected to illustrate the subject.

2.2 Soil compaction.

The processes involved in soil compaction and the properties of compacted soils have been extensively reviewed by Soane (1975), Boone (1988), Hakansson *et al.* (1988), Marshall and Holmes (1988) and Greenwood (1989). The purpose of this literature review is to provide a summary of recent publications.

2.2.1 Causes of soil compaction.

2.2.1.1 Cultivation and traffic.

Agricultural vehicle traffic is considered to be the principal factor causing compaction of the surface and sub-surface soil horizons under field conditions (Hakansson *et al.*, 1987; Okhitin *al.*, 1991).

The character and extent of soil compaction depends upon the physical properties of both the vehicle and the soil. Vertical forces (wheel load) and horizontal forces (wheel slip) are transmitted by the vehicle to the soil (Soane *et al.*, 1981). Traffic damage results in a lower porosity, lower infiltration rate and lower aeration status of the soil (Figure 2.1) (Ross and Cox, 1981; Henderson, 1985; Okhitin *et al.*, 1991; Slowinska-Jurkiewicz and Domzal, 1991).

Dry bulk density, kg/m^3

Figure 2.1: Increasing bulk density with depth following the single passage of a tyre for three values of load and inflation pressure (Soane *et al.*, 1981).

It is common experience with many soils to find a compacted layer under the cultivation layer. It has been observed that ploughing leaves behind a loosened surface layer and a dense subsoil where aggregates have been compressed.

These high bulk density and low porosity layers are termed 'plough pans' and are a result of the combined effects of the action of the plough and the tractor wheel running in the base of the furrow (McLaren and Cameron, 1990).

The extent and depth of damage depends on the initial looseness of the soil and the initial soil moisture content (Hillel, 1988; McLaren and Cameron, 1990; Okhitin *et al.*, 1991). Maximum compaction occurs at moisture contents approaching the plastic limit of the soil. This moisture content is often close to the optimum moisture content for tillage (Hillel, 1988).

2.2.1.2 Animals.

Cattle and sheep hooves exert large pressures on the soil (Mulholland and Fullen, 1991). Static pressures of sheep and cattle hooves have been estimated to be between 80 to 400 KPa, with the actual pressure exerted by a moving animal being much greater (Climo and Richardson, 1984). The resultant compaction is linked to the frequency and location of animal treading. Soil structure and moisture content interact strongly with animal trampling. When the soil moisture content is at, or above, the lower plastic limit then trampling results in soil compaction (Climo and Richardson, 1984).

Compaction produced by animal treading destroys macropores (Figure 2.2) and has been found to decrease total porosity values to as low as ten percent (Davies *et al.*, 1989).

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Figure 2.2: Sketches from thin sections of noncompacted and hoof compacted soil (Mulholland and Fullen, 1991).

Increases in bulk density can occur up to depths of 20 cm (Climo and Richardson, 1984; Ferrero, 1991; Mulholland and Fullen, 1991). The increase in bulk density and the decrease in macroporosity which occurs can restrict root development, inhibit air and water movement and thus decrease plant growth (Climo and Richardson, 1984; Naeth *et al.*, 1990; Mulholland and Fullen, 1991).

2.2.1.3 Natural soil compaction.

High bulk density layers may occur naturally in the soil profile, for example fragipans, iron pans, clay pans and dense textural B-horizons (Parfitt and Milne, 1984; Chapman and Allbrook, 1987; Molloy, 1988; Ide and Hofman, 1990; McLaren and Cameron, 1990). Because these layers are usually below the depth of normal cultivation and intense biological activity, any increase in bulk density due to traffic will not be alleviated. This may lead to impeded root growth and poor drainage (Gibbs, 1980; Parfitt and Milne, 1984; McLaren and Cameron, 1990).

Different zones of high mechanical impedance may be identified in many soils. Figure 2.3 represents a hypothetical soil profile that includes all the possible zones of high mechanical impedance (Bennie, 1991).

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Figure 2.3: Schematic illustration of the position of different zones of a soil profile with a high mechanical impedance (Bennie, 1991).

2.2.2 Physical properties of compacted soils.

2.2.2.1 Soil strength.

Soil compaction causes increased packing density of aggregates and primary soil particles, thus increasing soil strength (Smith, 1987; Hakansson *et al.*, 1988; Holloway and Dexter, 1991). Soil mechanical strength consists of two components - cohesive strength and frictional strength (Bowen, 1981).

Soil strength is inversely related to soil water content because water reduces internal cohesion (Climo and Richardson, 1984). At any given bulk density the soil strength decreases with increasing water content (Figure 2.4) (Bennie, 1991).

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Figure 2.4: Effect of water content on the tensile strength of a soil compressed when moist to a bulk density of 1.7 g cm^{-3} (Marshall and Holmes, 1988).

It has been suggested that a penetrometer resistance of 2 to 3 MPa (but up to 5 MPa) measured at field capacity would generally restrict crop and root growth (Holloway and Dexter, 1991).

2.2.2.2 Bulk density.

Bulk density increases with the degree of compaction and tends to increase with depth. This is because of increasing overburden and decreasing disturbance at depth (Marshall and Holmes, 1988). The bulk density state produced as a result of compaction depends on the soil particle size distribution and its water content (Soane *et al.*, 1981;Marshall and Holmes, 1988; Batey, 1990). Domzal and Hodara (1991) found that the bulk density of loosened arable topsoils generally did not exceed 1.2 g cm^{-3}, however, after compaction by vehicle wheels the soil bulk density increased to 1.3-1.4 g cm^{-3}.

2.2.2.3 Porosity.

Increased soil bulk density due to compaction causes a decrease in soil porosity and a change in the pore size distribution of the soil (Russell, 1977; Logsdon *et al.*, 1992).

The proportion of large diameter pores (macropores) is reduced with compaction, there is also usually an increase in the proportion of smaller diameter pores (Figure 2.5).

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Figure 2.5: Effect of compaction on pore size distribution. Compaction reduced pores of diameter greater than 100 μm (Russell and Gross, 1974).

Soil compaction reduces both the volume and the continuity of pores and thus restricts water movement, aeration and root growth (Hillel, 1980; Soane *et al.*, 1981; Hodara and Slowinska-Jurkiewicz, 1982; Hakansson *et al.*, 1988; Domzal and Hodara, 1991).

The effects of soil compaction are often quantified by measures of porosity, especially macroporosity (Greenwood, 1989; Logsdon *et al.*, 1992). This is because of the large effect porosity and macroporosity have on the root growth and ultimately the yield of a crop.

2.2.2.4 Water movement and availability.

Since compaction reduces soil porosity, it therefore affects the water storage and water transmission properties of the soil (Hakansson *et al.*, 1988; Greenwood, 1989; Logsdon *et al.*, 1992). These characteristics are affected most by changes in volume, size, shape and continuity of the soil pores. Compaction has the effect of decreasing water transmission (infiltration and hydraulic conductivity) and decreasing the maximum amount of water retained by the soil at saturation (Warkentin, 1971; Soane *et al*., 1981; Domzal and Slowinska-Jurkiewicz, 1987; Hakansson *et al.*, 1988). Agrawal (1991) found that even a slight increase (0.1 g cm^{-3}) in subsurface compaction increased soil moisture retention, reduced water infiltration rate and reduced the saturated hydraulic conductivity of the soil.

Compaction of the subsoil reduces the rate of drainage of the soil profile and can result in the occurrence of perched water tables, and water logging (Greenwood, 1989; Batey, 1990).

2.2.2.5 Soil aeration.

Efficient soil aeration depends on the effectiveness of large pores conducting oxygen and carbon dioxide through the soil. Compaction causes a decrease in pore size and a reduction in pore continuity. Soil aeration has therefore been found to be reduced by compaction (Soane *et al.*, 1981; Hodara and Slowinska-Jurkiewicz, 1982; Simojoki *et al.*, 1991).

In compact soils poor aeration leads to the deterioration of oxygen conditions. Low oxygen levels in the soil influence nutrient uptake by changes in nutrient availability (decreasing nutrient solubility) and by changes in the functioning and growth of the roots themselves (Glinski and Stepniewski, 1985).

Low soil oxygen levels cause root respiration rates to slow down, and therefore less energy is available to assist in transporting nutrients, thus leading to decreases in nutrient uptake (Figure 2.6) (McLaren and Cameron, 1990).

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Figure 2.6: Phosphorus content in plants as related to oxygen concentration in soil air; (1) jojoba roots, (2) snapdragon, (3) barley leaves (Glinski and Stepniewski, 1985).

2.2.2.6 Soil temperature.

The transmission of heat through soil has been found to be affected by compaction (Marshall and Holmes, 1988). Changes in soil bulk density, soil water content and transmission, and soil surface reflectivity alter the thermal properties of soil (Willis and Raney, 1971) (Figure 2.7).

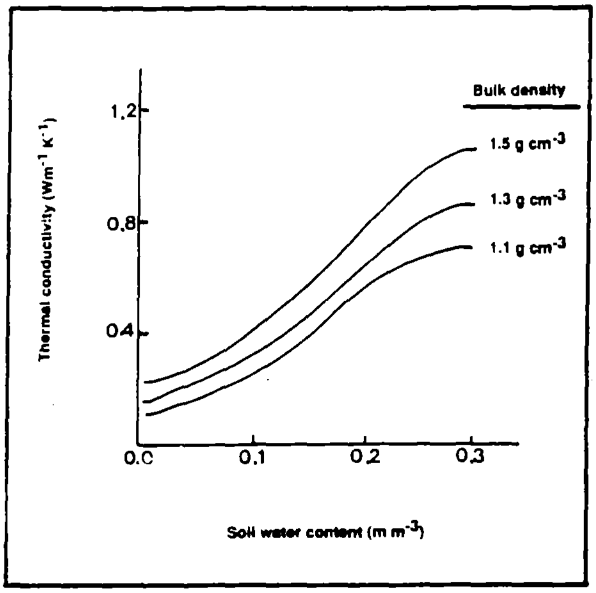

Figure 2.7: Effect of water content and bulk density on thermal conductivity of soil (McLaren and Cameron, 1990).

Increased soil bulk density results in an increase in thermal conductivity (Baver *et al.*, 1972). Compaction also increases the heat capacity and heat diffusivity of the soil. The amplitude of diurnal fluctuations of temperature at the soil surface are also smaller in compacted soil (Boone, 1988; Marshall and Holmes, 1988).

2.3 Effects of Compacted Soil on Plant Growth.

2.3.1 Plant growth and dry matter production.

Three effects of compaction on plant yield have been reported in the literature: (i) yields may increase if the soil was previously "loose" (eg. bulk density values <0.8 g cm^{-3}) (Droese *et al.*, 1975); (ii) yields may remain constant; or (iii) yields may decrease (Boone, 1988; Batey, 1990). In the majority of reports, compaction has resulted in a yield decrease, therefore, in this literature review only the negative effect of soil compaction on dry matter production will be reviewed.

There are many reports of soil compaction causing yield depressions (Table 2.1). However, because most physical, biological, and chemical soil factors are influenced to some extent by soil compaction, it is difficult to obtain direct relationships between dry matter yield and the measurable variables of soil compaction.

Crop	Compaction Quantifier	Yield Decrease (%)	Reference
pasture	1.5 g cm^{-3}	15	Chapman & Allbrook (1987)
pasture		30	Henderson (1991)
pasture	1.41 g cm^{-3}	36	Douglas *et al.* (1992)
L. perenne	1.12 g cm^{-3}	32	Ferrero (1991)
P. pratense	1.12 g cm^{-3}	47	Ferrero (1991)
cabbage	1 t ha^{-1} per 0.5 MPa<		Stone (1988)
cereal	3 MPa	15	Ide & Hofman (1990)
oats	500 KPa	28	Petelkau & Dannowski (1990)
oats	1.70 g cm^{-3}	16	Gediga (1991)

Table 2.1: Effect of soil compaction on dry matter production.

Several researchers have tried to correlate the physical factors describing soil compaction with dry matter yield. Rusanov (1991) for example found that for every 0.01 g cm^{-3} increase in bulk density in the 0-30 cm layer there was a yield reduction in wheat of 14-15 kg ha^{-1}. Stone (1988) found that increasing penetrometer resistance of the soil was related to the yield of vegetable crops with a decrease in yield of 1 t ha^{-1} for every 0.5 MPa increase in penetrometer resistance over the 0.5-2.5 MPa range (Figure 2.8).

Subsoil compaction has been shown to be negatively related to dry matter production (Gediga, 1991). Decreases in dry matter yield of up to 34% have been reported with various levels of subsoil compaction (Figure 2.8) (Stone, 1988). An increase of 0.01 g cm^{-3} in subsoil bulk density was thought to be responsible for a yield decrease in wheat of 8 kg ha^{-1} (Rusanov, 1991).

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Total dry matter production (t ha^{-1})

Figure 2.8: Relationship between subsoil (15-60 cm) penetration resistance measured at field capacity and dry matter production of four crops in two years (Stone, 1988).

There are very few quantitative measurements of the effects of soil compaction on established pasture production. Research work in New Zealand by Climo and Richardson (1984) and Chapman and Allbrook (1987) indicate that soil compaction is likely to decrease pasture production.

Dry matter yield decreases resulting from soil compaction have often been attributed to restricted root growth resulting from increased mechanical impedance (Hakansson *et al.*, 1988; Greenwood, 1989). Restricted root growth has the effect of reducing nutrient and water uptake by plants.

2.3.2 Root depth and distribution.

2.3.2.1 Mechanisms of root growth.

Roots increase in length as new cells are formed in the meristematic tissue near the root tip (Figure 2.9).

These newly formed cells increase in volume, thus pushing the root tip forward. This will only occur if growth conditions are satisfactory (Bengough and Mullins, 1990; Taylor and Brar, 1991).

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Figure 2.9: Structure of a growing root (Bengough and Mullins, 1990).

Four processes occur simultaneously for this expansion to occur and continue (Taylor and Brar, 1991). Before the cells start the process of expansion, the water potential inside the cell (Ψ_i) is equal to the water potential outside (Ψ_o). The first process is that of cell wall loosening (at this stage $\Psi_o > \Psi_i$). In the second process water flows into the cell diluting its solute concentration. This increased volume of water inside the cell causes the cell walls to expand. Finally, solutes accumulate within the cell until $\Psi_o = \Psi_i$ (Hsiao and Bradford, 1983; Dexter, 1987). If the soil constraint is severe, additional solutes may collect in the elongation zone (Figure 2.9), thus preventing Ψ_o becoming equal to Ψ_i (Dexter, 1987; Greacen, 1987; Taylor and Brar, 1991).

Some of the epidermal cells behind the meristem elongate to produce root hairs (Figure 2.9). Root hairs have a diameter of 10-20 μm. Root hairs may increase the surface area of the root system by 10 to 18 times for perennial ryegrass. The total length of root hairs per mm root length has been estimated to be 99 mm (Gregory, 1988).

The importance of distribution of roots in the soil and their relative abundance will vary according to the function carried out by the roots. Thus for the uptake of water and mobile ions (eg. nitrate) with their relative ease of movement in the soil, the number of absorbing roots may not be as significant as for the uptake of immobile phosphate ions (Williams, 1969).

2.3.2.2 Effect of soil compaction on root growth.

Depressed dry matter yields associated with soil compaction can be mainly attributed to reduced rootability, which limits water and nutrient uptake (Petelkau and Dannowski, 1990).

Roots grow more slowly in poorly aerated soils. Poor soil aeration can also reduce the rate of water and nutrient uptake by plant roots (McLaren and Cameron, 1990). With the two stresses of mechanical impedance and poor aeration interacting, the effect is greater than would be expected from each stress occurring independently (Reeves *et al.*,1984; Bengough and Mullins, 1991; Taylor and Brar, 1991).

Critical values at which root growth ceases in compact soils vary from 1< to <4 MPa depending on soil composition, plant species and pore water potential (Hamblin and Tennant, 1987). Vepraskas and Miner (1986) found relationships between root concentrations and mean penetrometer cone index values (MPa) to be negatively correlated and linear (R= $^{-}$0.79**) (Figure 2.10).

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Figure 2.10: Relationships between root concentration and mean CI (MPa) (Vepraskas and Miner, 1986).

When a root tip encounters an obstacle that resists penetration, the root cap becomes less pointed. Mechanical impedance decreases the rate of root elongation through both a decrease in the rate of cell division and a decrease in cell length rather than volume (Dexter, 1987). A decrease of 40% in the cell division rate at a penetration resistance increase of 0.34 MPa, is sufficient to decrease the root elongation rate by 70% (Bengough and Mullins, 1990). As soil strength increases, the rate of root elongation decreases and root diameter increases (Figure 2.11) (Ehlers, 1982; Barber, 1984; Linberg and Pettersson, 1985; Boone, 1988; Hatano *et al.*, 1988).

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Figure 2.11: Effects of applied pressure on the rate of elongation of seminal axes of barley plants (Tinker, 1980).

The apical meristem and zone of cell extension of impeded roots is shorter with more root hairs prevalent closer to the root tip; lateral initiation also occurs closer to the root tip (Bengough and Mullins, 1990; Taylor and Brar, 1991). The swelling of roots has been attributed to mechanical impedance. However, ethylene at very low concentrations (produced under conditions of poor aeration) is also known to inhibit root extension and induce lateral swelling (Hettiaratch, 1990; Taylor and Brar, 1991).

As the level of mechanical impedance increases, the amount of active roots per unit volume of soil decreases (Table 2.2) (Linberg and Pettersson, 1985; Stypa *et al.*, 1987; Batey, 1990; Chan and Mead, 1992). Thus limiting the uptake of water and nutrients (Petelkau and Dannowski, 1990).

Applied stress (KPa)	Soil Bulk density (g cm^{-3})	Root length (cm/core*)	Root weight (mg/core)
0	1.16	478	26.3
	1.30	424	23.3
90	1.28	275	24.5
	1.35	233	22.3
179	1.38	66	14.3
	1.40	74	15.0
269	1.47	61	12.8
	1.46	58	13.8

(*: core size = 16 cm high and 9.5 cm diameter)

Table 2.2: Effect of applied external stress and soil bulk density on pea root growth (Castillo *et al.*, 1982).

Root elongation rate is progressively decreased by increasing mechanical resistance (Figure 2.12) (Tinker, 1980; Yapa *et al.*, 1988; Bengough and Mullins, 1991; Veen and Boone, 1981).

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pore volume (%)

Figure 2.12: Relationship between the elongation rate of main root axes and the mechanical resistance (CR) of the soil (Veen and Bonne, 1981).

2.3.3 Water uptake by plant roots.

2.3.3.1 Mechanisms of water uptake.

Water moves in the liquid phase of the soil-plant system, in response to differences in the potential energy of water in the system (Gregory, 1988). For water to move from the soil into the plant, the water potential of the plant must be lower than that of the soil. The potential gradient of the plant-soil system results from water losses by transpiration at plant leaf surfaces (Unger *et al.*, 1981; Oertli, 1991). Water enters the plants through the epidermal cells of roots in contact with moist soil. The water then passes in turn through the cortical cells, endodermis, pericyclic cells and into the xylem elements which transport it to the aerial portions of the plant (Unger *et al.*, 1981). The permeability of roots to water decreases with age (Unger *et al.*, 1981; Sanderson, 1982; Barber, 1984). New absorbing surfaces are produced as roots elongate and as lateral roots are formed. The roots have to constantly elongate through the soil to exploit the available water reserves.

Water also moves through the soil by vapour diffusion. However under most conditions the volume of water moved towards plant roots by diffusion (at rates of 1 to 10 x 10^{-6} cm^2 s^{-1}) is not enough to balance transpiration rates. Therefore, for adequate amounts of water to be supplied to growing plants, the soil root zone must be large enough to supply the plant needs, and must have a physical condition such as to allow plant roots to proliferate freely (Unger *et al.*, 1981).

2.3.3.2 Effects of soil compaction on water uptake by plant roots.

Since soil compaction can limit root penetration and root proliferation it can seriously impede the ability of plants to gain access to water in the soil profile. Even when soil compaction is not too severe and roots are still able to penetrate, plant development is often reduced. This is because the reduced rate of elongation is inadequate to supply the plant with sufficient water to meet its requirements (Trouse, 1971; Gregory, 1988).

Tardieu (1988) found soil compaction (bulk density = 1.65 g cm^{-3}) reduced water uptake of maize by 50% compared to non-compacted treatments (bulk density = 1.35 g cm^{-3}), while Voorhees *et al.* (1985) found a 30% decrease in water use efficiency due to wheel traffic.

In New Zealand, Greenwood (1989) found soil compaction treatments resulted in a reduction in pea crop water use of 12-13 mm over a growing season.

Soil water contents are often higher in compacted soils due to lower hydraulic conductivity rates. Nevertheless, Tardieu (1987) and Taylor and Brar (1991) concluded that the availability of water reserves is controlled by the spatial distribution of the plant roots.

Therefore much of this extra water will be unavailable. Root respiration rates are reduced in waterlogged soils which reduces the rate of water uptake.

2.3.4 Nutrient uptake by plant roots.

2.3.4.1 Mechanisms of nutrient uptake.

Supplying plants with nutrients is one of the major functions of roots. However, less than one percent of available nutrients are obtained by root interception (Barber, 1984; Jungk, 1991). The majority of nutrients taken up by plants have moved through the soil towards the roots. The mechanisms of transport towards the root are mass flow and diffusion. These processes use water potential and nutrient concentration gradients which are set up when plant roots take up water and nutrients in their immediate vicinity (Jungk, 1991).

The total influx of nutrients (F_t) is given by:

$$F_t = F_m + F_d$$

Equation 2.1

where:

F_m = flux due to mass flow (mol m^{-2} s^{-1})
F_d = diffusive flux (mol m^{-2} s^{-1})
(Barber, 1984; Jungk, 1991).

Mass flow - Is the movement of solutes with the bulk flow of water towards the root:

$$F_m = vC_1$$

Equation 2.2

where:

v = water flux into the root (m^3 m^{-2} s^{-1})
C_1 = nutrient concentration of soil solution (mol m^{-3})

Mass flow supplies nitrate, sulphur, calcium and magnesium to plants in adequate quantities (Table 2.3) (Wild, 1988; Jungk, 1991).

Removed due to copyright

Table 2.3: Relative significance of root interception, mass flow and diffusion in supplying corn with its' nutrient requirements from a fertile Alfisol (kg ha^{-1}) (Barber, 1984).

Diffusion - Diffusion is the movement of solutes due to the random thermal motion of molecules (i.e. Brownian movement) along a concentration gradient. The distance of diffusive movement is usually only 0.1 to 15 mm (Barber, 1984).

Diffusion is generally described by Ficks Law and in plant-root-soil system, the larger the concentration gradient, the more rapid the rate of diffusion (M^c^Laren and Cameron, 1990).

$$F_d = -D_s \ (\theta) \ dc/dx$$

Equation 2.3

where:

F_d = diffusive flux (mass diffusing across a unit area per time (mol m^{-2} s^{-1})
D_s = diffusion coefficient (m^2 s^{-1})
θ = soil moisture content (m^3 m^{-3})
dc/dx = concentration gradient (mol m^{-3} m^{-1})

(Barber, 1984; Wild, 1988; M^c^Laren and Cameron, 1990; Jury *et al.*, 1991).

The influence of soil properties such as water content and tortuosity on diffusion rate are incorporated in D_s (Table 2.4) (Barber, 1984).

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Table 2.4: Diffusion coefficients (D_s) of nutrient ions in the soil ($m^2\ s^{-1}$) (Jungk, 1991).

The average movement due to diffusion (Δx) increases with time (t):

$$\Delta_x = \sqrt{2 D_s t}$$

Equation 2.4

From the values given in Table 2.4, nitrate ions would move approximately 18 mm day^{-1}, and potassium and phosphate, 0.9 mm day^{-1} and 0.13 mm day^{-1} respectively (Jungk, 1991).

Gradients of nitrate, potassium and phosphate uptake calculated from Barber (1984) using D_s values are shown in Figure 2.13.

Removed due to copyright

Figure 2.13: Calculated concentration gradients around a plant root in soil where NO_3, P and K are supplied mainly by diffusion (Barber, 1984).

It is clear from Figure 2.13 that nitrate is the most mobile nutrient shown. In Figure 2.13, it can be seen that at a distance of 1 mm from the root surface the phosphate concentration is unchanged. This distance equated to the average root hair length, which indicates that root hairs function as a sink for phosphorus (Barber and Silberbush, 1982; Foshe *et al.*, 1991; Jungk, 1991).

The nutrient flux from the soil to roots by simultaneous mass flow and diffusion under radial geometry is given by the following equation (Jungk, 1991).

$$\frac{dC_1}{d_t} = \frac{1}{r}\frac{d}{dr}\left[rD_s\frac{dC_1}{dr} + \frac{V_o r_o C_1}{b}\right]$$

Eq ation 2.5

where:

C_1 = concentration of ion in soil solution (mmol m^{-3})
r = radial distance from the root axis (mm)
r_0 = root axis (mm)
D_s = effective diffusive coefficient ($m^2\ s^{-1}$)
b = buffer capacity
v_0 = rate of water uptake ($m^2\ s^{-1}$)
t = time (s).

The large differences of D_s for macronutrients (Table 2.4) originates mainly from differences in the soil reaction and the buffer capacity of the soil (Jungk, 1991). Soil water content affects diffusion because diffusion occurs in water filled pores only. Thus diffusion also depends on pore size distribution, soil texture and soil bulk density. These factors affect the impedance factor of D_s. Increasing bulk density beyond 1.3 g cm^{-3} increases the tortuosity. This is because the path of the nutrient ions becomes more tortuous as soil particles are compressed closer together. Thus D_s decreases (Figure 2.14) (Barraclough and Tinker, 1981; Barber, 1984; Jury *et al.*, 1991).

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Figure 2.14: Average influence of soil bulk density and soil moisture level (w/w) on the rate of chloride diffusion D_e (Cl) and calculated tortuosity (f_t). Values on curves are moisture contents (%) (Barber, 1984).

2.3.4.2 Effects of soil compaction on nutrient uptake by plant roots.

Soil compaction has been found to decrease the total nutrient uptake by plants (Petelkau and Dannowski, 1990). The effects of compaction on nutrient uptake is related to the effects on root growth and the anatomical and morphological changes in the root systems (Castillo *et al*., 1982; Wild, 1988).

Silberbush *et al.* (1983) found potassium uptake decreased when soil bulk density increased. The effect of soil bulk density in reducing root growth and reducing K uptake, was much greater than the effect of compaction on buffering capacity (b) and D_s which increased K influx (Figure 2.15).

Figure 2.15: Effect of changing soil bulk density on the soil K diffusion coefficient (D_S), soil buffering power of K (b) and root length (R_L) (Silberbush *et al.*, 1983).

Some reports indicate that there is a compensatory increase in nutient uptake per unit length of root as root length is decreased by increasing mechanical impedance (Figure 2.16) (Silberbush *et al.*, 1983; Barber, 1984; Cornish *et al.*, 1984; Wild, 1988).

Figure 2.16: Effect of soil bulk density on potassium uptake (U) by Williams soybeans grown for 20 days on Raub silt loam and calculated potassium influx (In) to roots when the roots were 20 days old (Silberbush *et al.*, 1983).

It has also been found that phosphorus uptake in ryegrass per unit length of root was higher from compacted soil (225 μg P m^{-1}) than from noncompacted soil (140 μg P m^{-1}) particularly at bulk densities reaching 1.5 g cm^{-3} (Shierlaw and Alston, 1984). Cornish *et al.* (1984) found that with perennial ryegrass growing in a dry soil with low phosphorus concentration (4 μg g^{-1}) that the uptake per unit length was 0.21 μg P cm^{-3} at 1.0 g cm^{-3} and rising to 1.68 μg P cm^{-3} at 1.4 g cm^{-3}. However, the total uptake (mg P pot^{-1}) decreased from 0.13 mg P pot^{-1} at 1.0 g cm^{-3} to a mere 0.02 μg P pot^{-1} at 1.4 g cm^{-3}. These large differences in total uptake were due to the less prolific root system in the high bulk density soil. This was also shown by Veen and Boone, (1981) (Figure 2.17) who attributed decreases in nutrient uptake with increasing mechanical impedance to changes in root morphology and decreases in root proliferation.

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Figure 2.17: N, K and P contents of dry shoots, 3 weeks after emergence of plants grown in soils with different mechanical resistances (CR) (Veen and Boone, 1981).

In former traffic lanes with a high bulk density (σ) of 1.80 g cm^{-3} compared to non-tracked soil (σ = 1.47 g cm^{-3}) Petelkau and Dannowski (1990) found nutrient extraction was decreased (Table 2.5).

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Table 2.5: Relative nutrient uptake by oats (total shoot) grown in former traffic lanes in comparison with plants from non-tracked soil (Petelkau and Dannowski, 1990).

Castillo *et al.* (1982) found that the application of external pressure (90 KPa) reduced Potassium and Magnesium uptake by 12%. Further pressure (179 KPa) resulted in a 29% reduction in nutrient uptake.

Subsoil compaction affects nutrient uptake also. The influence of subsoil compaction (30-35 cm) is shown in Figure 2.18.

For non-compacted subsoil, the uptake from 30-60 cm constituted 31.5% of the total uptake. At a subsoil compaction of 1.7 g cm^{-3}, the uptake amounted to only 16.3% of the total uptake (Gediga, 1991).

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Figure 2.18: Relative uptake of ^{45}Ca from the 30-35 cm depth, depending on the subsoil bulk density (Gediga, 1991).

2.4 Subsoiling.

2.4.1 Principles of subsoiling.

Natural processes such as freezing/thawing and swelling and shrinking are known to alleviate soil compaction (Bernier *et al.*, 1989). However, for compacted layers below the depth of tillage, mechanical loosening is often necessary to ameliorate soil compaction (Batey, 1988; Bernier *et al.*, 1989; Logsdon *et al.*, 1992).

The aim of subsoiling (deep tillage) is to loosen or break up a compacted soil layer without inversion or mixing (Figure 2.19) (M^c^Laren and Cameron, 1990; Holloway and Dexter, 1991).

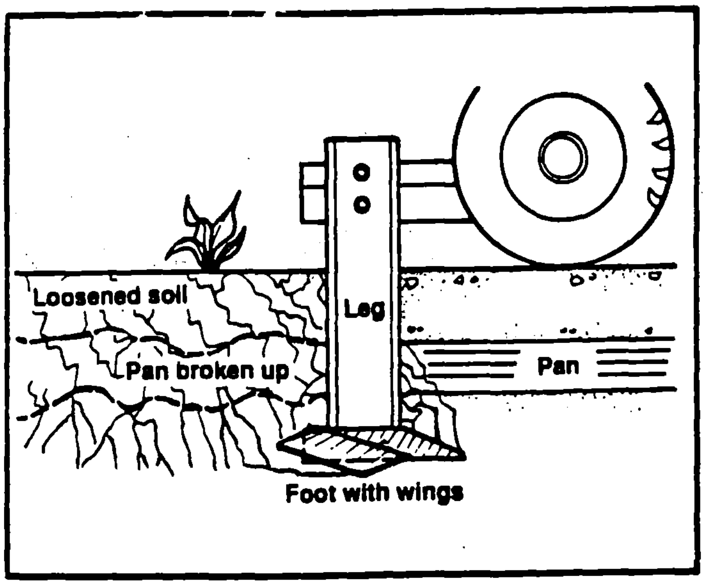

Figure 2.19: Subsoiler (aerator) design and effect on the soil (M^c^Laren and Cameron, 1990).

Subsoil loosening has been reported to increase the rate of movement of air and water in the soil and enhance root growth (Busscher and Sojka, 1987; Owen, 1988; Payne, 1988; M^c^Laren and Cameron, 1990; Greenwood and Cameron, 1990; Holloway and Dexter, 1991). However, unless there is a restricting horizon within the soil profile, no response can be expected from subsoiling (Batey, 1990; Greenwood and Cameron, 1990).

2.4.2 Subsoil loosening implements.

The basic implement consists of a large vertical or angled tine with a 'foot' at the base, some have wings for added effectiveness (Figure 2.20) (M^c^Laren and Cameron, 1990).

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Figure 2.20: Basic subsoiler tine shapes. (a) chisel tine; (b) conventional tine; (c) winged tine (Spoor and Goodwin, 1978).

The tines of subsoilers are widely spaced either in line or staggered on a V-shaped frame. Some have a vibrating tine which assists its movement through the subsoil (M[c]Laren and Cameron, 1990).

Figure 2.21 demonstrates the U-shaped disturbance pattern created by a wing subsoiler, which shows that it has increased the depth to the dense soil layer, in this case a plough pan.

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N.B.: No P = No pass by a tractor; One P = One pass by a tractor

Figure 2.21: Depth to a dense layer on a sandy loam with the tine axis (c) and wing position (w) superimposed to scale (Bernier *et al.*, 1989).

For subsoiling to be successful, the subsoiler shoe must lift the soil above it in such a way that the force of lifting produces a maximum number of cracks spreading out as wide as possible (Payne, 1988). Many researchers have reported the forces and types of disturbance created by subsoilers and their movement (Spoor and Goodwin, 1978; Bowen, 1981; Spoor, 1982; Greenwood, 1989; Spoor, 1990).

2.4.2.1 Effect of tine spacing and depth on soil loosening.
The most effective tine depth and spacing can be chosen only after examination of the soil to locate precisely the depth and thickness of the compacted zone (Batey, 1990).

As the operating depth increases, soil resistance to upward movement also increases until a depth (the 'critical depth') is reached where the resistance to lateral flow is smaller than that of upward flow. The soil then flows forwards and sideways only ('lateral failure') resulting in little overall disturbance and possible recompaction. Wings generally increase the critical depth (Figure 2.22) (Spoor and Goodwin, 1978; Greenwood, 1989; Batey, 1990).

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Figure 2.22: Soil movement and patterns of disturbance resulting from subsoiling above (a) and below (b) the critical depth (Spoor and Goodwin, 1978).

At close tine spacings loosening occurs to a more uniform depth and a smooth soil surface is produced. For complete loosening, maximum tine spacings depend on the particular disturbance pattern of the tines (Table 2.6).

Type of Subsoiler	Spacing in terms of working depth (d) of deep tine
Conventional	1.0-1.5d
Winged	1.5-2.0d
Winged & shallow leading tines	2.0-2.5d

Table 2.6: Recommended tine spacings for complete soil disturbance (Spoor, 1990).

2.4.2.2 Effect of soil type and moisture content.

The draft, efficiency and effectiveness of the subsoiling operation can be affected by operating characteristics such as soil type and soil moisture content (Owen, 1988).

Soil type usually defines the soil texture and thus soil consistency at specific moisture contents. Subsoiling is best conducted when the soil consistence is friable - this allows brittle failure to occur and produces the maximum disturbance of the soil profile (Spoor, 1990). If the soil moisture content is above the lower plastic limit effective loosening does not occur and there is a risk of further compaction by the subsoiling operation (Constable *et al.*, 1992). In general, the best time for the subsoiling operation to occur is in autumn, however this will depend on the climate and soil properties (Stafford, 1979; Batey, 1990; M^cLaren and Cameron, 1990; Spoor, 1990).

2.4.3 Effect of subsoiling on soil physical conditions.

The effect of subsoiling on soil physical conditions has been extensively reviewed elsewhere (Swain, 1975; Ellington, 1986; Ide *et al.*, 1987; Stone, 1988; Greenwood, 1989). The purpose of this section of the thesis is to examine the more recent literature and report results which are directly relevant to the research reported subsequently.

2.4.3.1 Soil strength.

Experiments have shown subsoiling significantly reduces mechanical impedance (Figure 2.23) (Greenwood, 1989; Ide and Hofman, 1990; M^c^Cray *et al.*, 1991; Reeves *et al.*, 1992).

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Figure 2.23: Variation in cone index (penetration resistance) with depth on a Whatawhata clay loam (Chapman and Allbrook, 1987).

Reduction in penetration resistance usually occurs to the depth of subsoiling (Figure 2.23) (Chapman and Allbrook, 1987; Steed *et al.*, 1987; Barbosa *et al.*, 1989; Greenwood, 1989; Reeves *et al.*, 1992). Barbosa *et al.* (1989) found subsoiling substantially reduced penetration resistance in the 30-40 cm layer from 2.0 MPa to 1.2 MPa.

Reported reductions in mechanical impedance are most pronounced in soil profile regions which have initially high penetration resistances (Greenwood, 1989; M^c^Cray *et al.*, 1991; Reeves *et al.*, 1992). Ide and Hofman (1990) found on subsoiled plots that peak penetration resistances (4 to 5 MPa) had been significantly reduced to 1 to 2 MPa (Figure 2.24).

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Figure 2.24: Penetration resistance in the soil profile of the two fields two and a half years after subsoiling (⊢ standard deviation) (Ide and Hofman, 1990).

2.4.3.2 Bulk density and porosity.

Soil structural units have been found to be smaller and less closely packed after subsoiling, and this has resulted in lower bulk densities (Figure 2.25) (Rowse and Stone, 1981; Ellington, 1986; Holloway and Dexter, 1991).

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Figure 2.25: The effect of subsoiled (○) and undisturbed (●) treatments on bulk density of soils.
(Horizontal bar indicate L.S.D at P = 0.05) (Henderson, 1991).

Barbosa *et al.* (1989) found that subsoiling significantly (P<0.01) lowered the bulk density of a compacted horizon (15-20 cm) from 1.73 g cm^{-3} to 1.55 g cm^{-3}.

Increases in total porosity due to subsoiling have been widely reported (Ross, 1988; Ide *et al.*, 1984; Greenwood, 1989). Typical results are given in Table 2.7.

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Table 2.7: Increase in total porosity on pasture resulting from subsoiling (45 cm) (Chapman and Allbrook, 1987).

Subsoiling has been reported to cause a large increase in the volume of larger pores (<60 μm) (Barbosa *et al.*, 1989; Greenwood, 1989). Johnston *et al.* (1989) reported a doubling in the volume of pores greater than 150 μm, and an increase in root growth, drainage rate and aeration.

Changes in pore geometry (described by pore number, volume, tortuosity and continuity) are probably more important than changes in pore volume *per se.*, since pore geometry can control rates of water, nutrient and air transmission (Greenwood, 1989).

2.4.3.3 Water availability and transmission.

Although subsoiling is unlikely to improve the waterholding capacity of a soil, water use efficiency is improved (Holloway and Dexter, 1991). For example, a pea crop after subsoiling was able to extract 45% more water over a growing season than a pea crop without subsoiling (Figure 2.26) (Greenwood and Cameron, 1990).

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Figure 2.26: Cumulative water use by a Pea crop in subsoiled (SS) and non-subsoiled (NS) treatments:
NS & non-irrigated, ○ - - ○ SS & non-irrigated, ▲ - - ▲
NS & irrigated, ●——● SS & irrigated ▲——▲
(Greenwood, 1989).

When soil drainage rates are slow, changes in subsoil water content are mainly due to water uptake by plant roots. Subsoiled areas with increased root densities at depth frequently show more pronounced changes in subsoil water content due to improved efficiency of water uptake compared with non-subsoiled control plots (Figure 2.27) (Rowse and Stone, 1981; Ide *et al.*, 1987; Steed *et al.*, 1987; Bernier *et al.*, 1989; Ide and Hofman, 1990).

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Figure 2.27: Change in water content (w/w, %) at various depths in the three plots of the experimental field, (Ide *et al.*, 1987).

Conventionally tilled soils are often drier in the top soil (15-25 cm) compared with subsoiled treatments (Barbosa *et al.*, 1989). Below these depths, the conventionally tilled soil often has a higher moisture content due to limited water uptake from depth. In contrast, the deeper rooting zone of subsoiled areas result in a more uniform moisture depletion with depth (Barbosa *et al.*, 1989).

Barber and Diaz (1992) found Soya yield response to subsoiling to be strongly related to increases in soil moisture availability (R^2=97%). This emphasises the effect of subsoiling in increasing the supply of available water due to the removal of compacted soil horizons (Oussible and Crookston, 1987; Greenwood, 1989; Barber and Diaz, 1992).

Subsoiling also increases the infiltration rate (Unger, *et al.*, 1981; Greenwood, 1989). Increases in soil infiltration rates have been attributed to rapid flow of water into a continuous surface connected system of macropores. However, increased infiltration rates may only be apparent until the macropores created by the subsoiling operation have become water filled (Greenwood, 1989).

Subsoiling results in an increase in soil hydraulic conductivity to the depth of effective disturbance. This effect has been attributed to increases in the volume of continuous macropores (Greenwood, 1989).

Subsoil cultivation affects soil water characteristics and water use efficiency which in turn affect the use and yield of pastures in New Zealand. The very limited research in this subject area prevents efficient use of subsoil cultivation, to increase pasture yield and lessen the environmental impacts of agricultural farming.

2.4.3.4 Soil aeration.

By fragmenting the soil into smaller units and the creation of airfilled macropores, subsoiling reduces oxygen deficiency and improves conditions in the primary aeration pathway.

Imperfectly drained soils, excessive irrigation rates or heavy rains can reduce crop yields through the effects of water logging. Subsoiling has been used to reduce the occurrence of water logging in the root zone. Yield increases in these circumstances are due to improved aeration and better root development (Greenwood and Cameron, 1990).

Air porosity (ϵ_a) values of 0.10 $m^3\ m^{-3}$ are frequently cited as the level below which aeration is inadequate for plant growth (M^c^Laren and Cameron, 1990). Subsoiling has been found to produce air porosity values above this critical level (Johnston *et al.*, 1989).

2.4.4 <u>Effect of subsoiling on plant production.</u>

Many previous studies have shown that subsoiling can increase yields in a range of crops (Table 2.8). There are however only a few limited studies of the effect of subsoiling on pasture production.

Crop	Subsoiled depth (cm)	Year subsoiled	Year measured	Yield Increase (%)	Reference
Pasture	45	1986		12	Chapman & Allbrook (1987)
Pasture	45	1986		15	Chapman & Allbrook (1987)
Pasture	15	1984		120	Davies et al. (1989)
Barley	45	1981		17	Marks & Soane (1987)
Barley	50	1985	1986	20	Greenwood (1989)
Cereals	60	1982		5-10	Ide et al. (1987)
Corn	40	1983	1983	19	Reeves & Touchton (1986)
Cabbage	90	1975		28	Stone (1988)
Leek	90	1975		18	Stone (1988)
Lupins	50	1985		20	Henderson (1991)
Maize	40	1982		30	Bennie & Botha (1986)
Peas	40	1985	1988	13*	Greenwood (1989)
Peas	40	1985	1988	6#	Greenwood (1989)
Peas	50	1985		60	Henderson (1991)
Soya	40			23	Barbosa et al. (1989)
Wheat	60	1981	1981	26	Coventry et al. (1987)
			1982	41@	
			1983	11	
			1984	16	
			1985	17	
Wheat	45	1980		197	Cassel & Edwards (1985)
Wheat	45	1980		277	Cassel & Edwards (1985)
Wheat	80	1982	1983	8	Ide & Hofman (1990)
Wheat	35			15*	Box & Langdale (1984)

N.B. *= Dry Conditions.
#= Irrigated.
@= Drought Conditions.

Table 2.8: Effects of subsoiling on plant yields.

Crop yield increases resulting from subsoiling have been attributed to three main effects:
(i) The result of reduced water stress during dry conditions, improving root proliferation to a greater depth in the soil profile which enables greater water extraction (Greenwood, 1989; Batey, 1990; Ide and Hofman, 1990; Holloway and Dexter, 1991).

(ii) Reductions in water logging and improved aeration where these conditions reduce root growth, root activity and cause plant health problems (Greenwood, 1989; Batey, 1990; Greenwood and Cameron, 1990; Barber and Diaz, 1992).

(iii) Increased yields have also been attributed to increased nutrient uptake. Subsoiling allows deeper and denser root proliferation in the soil profile and thus a greater opportunity for nutrient uptake (Delroy and Bowden, 1986; Batey, 1990; Ide and Hofman, 1990; Holloway and Dexter, 1991). (This will be discussed in more detail in Section 2.4.6).

Yield increases due to subsoiling depend on the ability of the subsoiling treatment to improve root growth and function (Greenwood, 1989).

A nil or negative response to subsoiling can occur if the supply of water and nutrients is adequate. This can be the case even if roots are restricted by a severely compacted layer (Greenwood, 1989). In Figure 2.28 it can be seen that as the amount of rainfall approaches adequate levels, the response to subsoiling decreases (Barber and Diaz, 1992).

Figure 2.28: Relationship between soya yield response to annual subsoiling and seasonal rainfall 1985 to 1989 (Barber and Diaz, 1992).

2.4.5 Effects of subsoiling on root growth.

The effect of subsoil compaction on different aspects of plant growth is directly related to the intensity with which soil mechanical resistance impedes root proliferation. Subsoiling is an effective way of relieving subsoil compaction, thus improving root density and increasing maximum rooting depth. This is achieved by subsoiling causing a decrease in soil penetration resistance, an increase in macroporosity and an increase in aeration. These more favourable root conditions lead to an increase in soil water uptake and nutrient uptake by plants, thus increasing yield (Ide *et al.*, 1984; Bennie and Botha, 1986; Hipps and Hodgson, 1988; Greenwood, 1989; McCray *et al.*, 1991).

Subsoiling has been reported to increase the maximum rooting depth of plants (Figure 2.29) (Bennie and Botha, 1986; Delroy and Bowden, 1986; M[c]Cray *et al.*, 1991).

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Figure 2.29: Effect of subsoiling on increasing maximum root depth (Bennie and Botha, 1986).

Subsoiling was found to significantly (P=0.05) increase root depth from 23.5 cm to 28.5 cm in a New Zealand permanent pasture (Chapman and Allbrook, 1987). Rooting depth was thought to have increased because of decreased penetration resistance and increased macroporosity of pores >60 μm and >300 μm in diameter.

Some evidence suggests that on occasions, root density is not well correlated to either water uptake or transpiration rate, for example when some parts of the deeper profile have a plentiful supply of water, and small lengths of roots in these layers are able to supply the crop adequately (Hamblin and Tennant, 1987).

Hamblin and Tennant (1987) calculated water loss over the growing season from the full depth of the rooted soil profile as:

$$WL = ((S_1 + p) - S_2))$$

Equation 2.6

where:

WL = water loss (mm)
p = precipitation (mm)
S = soil water storage for the maximum rooting depth at sowing time (S_1) and harvest (S_2) (mm).

Correlations between water loss and maximum depth of roots and between water loss and total root length per unit ground area were tested. The maximum depth of roots was significantly ($P<0.001$) related whilst total root length was non-significantly related. This was taken to indicate that sometimes maximum rooting depth, not total root length, is the root morphological characteristic most responsible for efficiency of water uptake in drought-stressed environments (Hamblin and Tennant, 1987; Ide *et al.*, 1987; Ide and Hofman, 1990; Holloway and Dexter, 1991).

Delroy and Bowden (1986) found that subsoiling to 30 cm depth increased the rate of root extension, and that this resulted in a more efficient use of nitrogen fertilizer. The root growth rate in the subsoiled plots (22 mm day^{-1}) was significantly higher than that of the non-subsoiled plots (11.8 mm day^{-1}). The result of subsoiling being that there was a larger volume of soil utilised.

Subsoiling results in an increase in rooting density, especially in the previously compacted zone, or just beneath this zone (Stone, 1982; Ide *et al.*, 1987; Davies *et al.*, 1989; Ide and Hofman, 1990). For example, after the removal of a compact layer (>3 MPa) at the 20-30 cm depth by subsoiling, there was a significant increase in the root density of wheat at and below this zone (Table 2.9).

Table 2.9: Effect of subsoiling on the root density of Wheat (Ide *et al.*, 1987).

Vepraskas and Miner (1986) reported that subsoiling significantly increased the number and proportion of tobacco roots below the plough pan. However, relatively few roots were found below the plough pan on the non-subsoiled plots (>2.5 MPa) (Figure 2.30).

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Figure 2.30: Root distributions afte· 6· days following the transplanting of Tobacco Seedlings (Vepraskas and Miner, 1986).

Subsoiling has been found to reduce or eliminate thickening and contortion of roots, and to permit the roots to penetrate deep into the profile (Table 2.10) (Ellington, 1986; Coventry *et al.*, 1987).

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Table 2.10: Effect of subsoiling on increasing root mass and reducing root thickening (Ellington, 1986).

Oussible and Crookston (1987) found finer, longer roots in subsoiled treatments. The roots in the subsoi·· layers were 54% longer per unit weight. This is important since fine long roots are more efficient at water absorption and nutrient uptake (Oussible and Crookston, 1987).

Little is known about roots in pastoral systems, and this component is seldom considered in management decisions. Yet, the roots of the soil environment exert an overriding effect on pasture production (Davidson, 1969). There are only two previous studies carried out in New Zealand on the effect of subsoiling on pasture root growth patterns and activity.

2.4.6 Effect of subsoiling on uptake of native and surface applied nutrients.

Subsoiling has often been reported to increase the uptake of surface applied fertilisers (Chaney and Kamprath, 1982; Johnston and M[c]Ewen, 1984; Delroy and Bowden, 1986; Davies *et al.*, 1989). Davies *et al.* (1989) observed that the net uptake of nitrogen on fertilised (336 Kg N ha^{-1}) non-subsoiled pasture plots (260 kg N ha^{-1} yr^{-1}) was well below the amount taken up on subsoiled plots (500 kg N ha^{-1} yr^{-1}). The greater rooting depth of plants grown in subsoiled ground was suggested as the reason for increased nitrogen uptake efficiency.

Improved nitrogen uptake efficiency leads to increased dry matter production in subsoiled areas (Delroy and Bowden, 1986) (Figure 2.31).

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Figure 2.31: The relationship of wheat-tops at maturity and soil nitrogen status; ■ non-subsoiled; □ subsoiled (Delroy and Bowden, 1986).

An indication of better exploitation of the soil profile by roots in subsoiled plots can often be deduced from changes in nutrient concentrations in the different soil depths as a function of time. For example, Ide *et al.* (1987) reported a more rapid change in subsoil nitrate concentration with wheat grown in subsoiled plots compared with those in control plots (Figure 2.32).

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Figure 2.32: Change in amount of nitrate nitrogen at different soil depths under winter wheat (Ide *et al.*, 1987).

Chaney and Kamprath (1982) attributed increased yields of corn to increased moisture and nitrogen utilisation following subsoiling. Subsoiling disrupted a tillage pan and allowed root access to nitrogen that had been leached to depth in the previous season.

Increased nitrogen uptake with subsoiling has been reported in a number of studies and can be attributed to soil loosening allowing an increase in root mass and rooting depth (Figure 2.33) (M^{c}Ewen and Johnston, 1979; Chaney and Kamprath, 1982; Coventry *et al.*, 1987b).

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Figure 2.33: **Nitrogen uptake of wheat-tops at 127 days from sowing**
□ ripped, ■ non-ripped (Delroy and Bowden, 1986).

The effect of subsoiling on nutrient uptake differs depending on the particular nutrient and on the way in which the nutrient is absorbed by the roots. For example, the absorption of phosphate and potassium being mainly reliant on transport by diffusion, is strongly influenced by the development of the root system. As a result of a better and deeper developed root system on subsoiled plots, the concentration of phosphate and potassium can increase significantly in the dry matter (Table 2.11) (Ide *et al.*, 1984; Barbosa *et al.*, 1989; De Nobili *et al.*, 1990).

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Table 2.11: Effects of tillage methods on dry matter, concentration and total amounts of some nutrients in the roots of Soya bean (Barbosa *et al.*, 1989).

The concentration of nutrients in the roots may increase with subsoiling, although the concentration of nutrients in the above ground dry matter may not necessarily increase (Ide *et al.*, 1984; Barbosa *et al.*, 1989). However, with the increased dry matter yield, the total nutrient uptake does increase with subsoiling (Table 2.11) (M[c]Ewen and Johnston, 1979).

It is often stated that subsoiling increases nutrient uptake by crop plants. Only one study (Davies *et al.*,1989) has so far approached the subject of nutrient uptake of pasture following subsoiling. New Zealand spends $450m per year on pasture fertiliser. Any farming practice that increases the use of indigenous soil nutrients and increases applied fertiliser use efficiency, by pasture plants is worthy of study.

2.5 Conclusions.

This literature review has shown that subsoiling can alleviate the problems caused by compaction of soil. The beneficial changes in soil physical properties result in increases in plant root density and maximum rooting depth.

A combination of soil physical properties and root growth patterns control the ability for water and nutrient uptake by plants, thus increasing or decreasing yield and economic returns of crop and pasture plants. The effects of subsoil cultivation on these controlling factors is relatively well researched in respect in high input and high economic return crops eg. wheat and vegetables. However, there is only one study (Chapman and Albrook, 1987) on the effect of subsoiling on pasture growth in New Zealand.

More research is **necessary** to assess the effect of subsoiling on pasture root growth patterns, and nutrient and water uptake.

The deficiency in research on these topics has arisen at least in part because of the difficulty in accurately assessing pasture plant root depth and distribution, as well as pasture nutrient uptake from specified depths within field soils.

3.0 METHODS AND MATERIALS.

3.1 Site and Soil Characteristics.

The trial was located in Canterbury, New Zealand, on paddock R_{21} of the Lincoln University Research Farm (Figure 3.1).

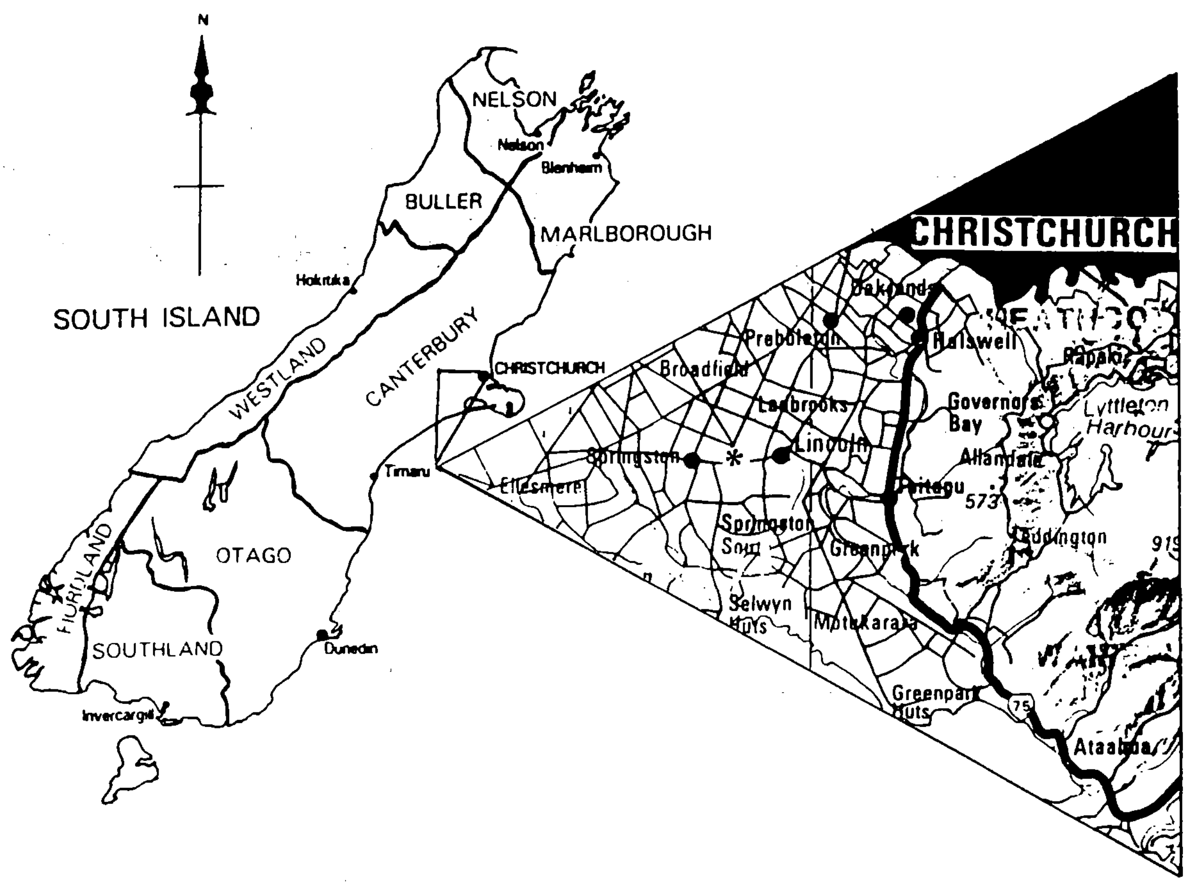

Figure 3.1: Location of trial site.

3.1.1 Soil type.

The soil was a Templeton silt loam (Appendix 3.1). Initial measurements showed the soil at the site to have two layers of high bulk density. These layers were at 22-27 cm (bulk density = 1.4 g cm^{-3}) and 40-60 cm (bulk density = 1.6 g cm^{-3}).

The soil was formed on fine greywacke alluvium of the Intermediate Waimakariri Terraces (Kear *et al.*, 1967; Molloy, 1988). It is a yellow-grey earth (Kear *et al.*, 1967) (Ustrocrept). For this soil to develop there is usually a period of moisture deficiency for plant growth of one to three months annually (Gibbs, 1980). The top soil is between 20-35 cm deep, but can vary markedly (Karageorgis, 1980). A characteristic of the Templeton silt loam is the yellowish brown compacted subsoil - a fragipan which is very hard when dry (bulk density >1.4 g cm^{-3}) (Gibbs, 1980). The Templeton series is often mapped as a complex. The Templeton soils are used intensively for cropping and pastoral farming on the Canterbury plains (Gibbs, 1980; Molloy, 1988).

Recently three other studies have been conducted on the Templeton soil series. These studies have looked at the effect of subsoil compaction on plant behaviour (Reid *et al.*, 1987; Greenwood, 1989; Fraser, 1992).

3.1.2 Soil grid survey.

The wide variations in texture of the Templeton silt loam may significantly influence the effect of subsoiling on soil physical conditions, root growth and pasture yield (Greenwood, 1989). A texturally uniform trial site was therefore required.

A soil survey of Paddock R_{21} was undertaken to locate an area of sufficient uniformity. A 10 m x 10 m grid spacing was used, at each grid intersect point soil samples were collected, using a Screw Auger, at every 100 mm depth increment, and the texture determined by hand.

Five soil profile classes were identified, by modifying the soil profile classification used by Greenwood (1989) (Appendix 3.2) (Figure 3.2).

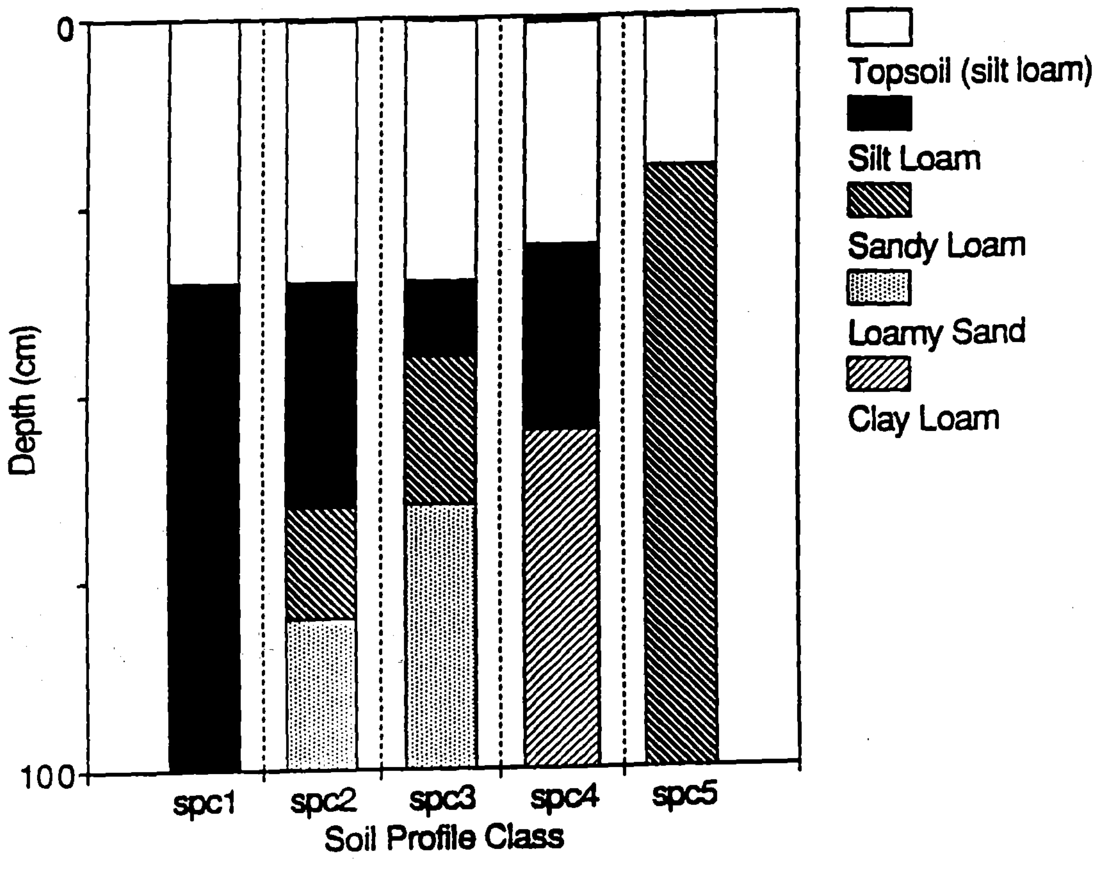

Figure 3.2: The five soil profile classes (spc) used.

The topsoil horizon was consistently a silt loam between 20-35 cm in depth. By grouping soil profile classes 2 and 3 together, a suitable site was found.

3.1.3 Pasture history.

The paddock history (Table 3.1) shows that since 1984 the area (1.2 ha) has been grazed by sheep and cattle, with strip grazing being used in the winter. No other seeding or cultivation has occurred since 1984.

Year	
1980	Ploughed, sown in barley (yield = 4 t ha^{-1})
1981	" " " "
1982	" " " "
1983	Direct drilled 'Tama'
1984	Cultivated. Sown with ryegrass/white clover
1985	Grazed
1986	Grazed
1987	Grazed
1988	Grazed; Irrigated Nov. to Mar.
1989	Grazed; Irrigated Nov. to Mar.

Table 3.1: Paddock R_{21} history.

3.1.4 Soil fertility and Ministry of Agriculture and Fisheries Quick Tests.

Since 1980 there has been only two applications of fertiliser: (i) 1984 - 250 kg ha^{-1} Superphosphate and (ii) 1989 - 40 kg ha^{-1} Urea and 125 kg ha^{-1} Superphosphate.

M.A.F. Quick Tests were carried out on soil samples collected on 11-Oct-90 (Table 3.2). The results indicated that the soil was of 'medium to low' fertility.

Depth (cm)	pH	Ca	P	K	S	Mg	Na
0-7.5	6.1	11	9	7	3	27	9
0-20	5.6	10	6	7	8	19	10
20-40	5.8	7	11	2	10	35	10
40-60	6.0	9	10	2	11	79	16
60-80	6.1	10	9	2	7	95	24
80-100	6.3	10	10	2	8	100	37

Table 3.2: The results of the M.A.F. Quick Tests conducted on 11-Oct-90.

3.2 Treatments and Experimental Design.

3.2.1 Plots and their positioning.

The statistical design was a randomised block with four replicates (nine plots per replicate i.e. thirty-six plots). The plots were 8 m x 8 m. The treatment allocation was random. The plots were arranged as shown in Figure 3.3 to allow vehicle access, for cultivation, thus preventing the recompaction of cultivated plots.

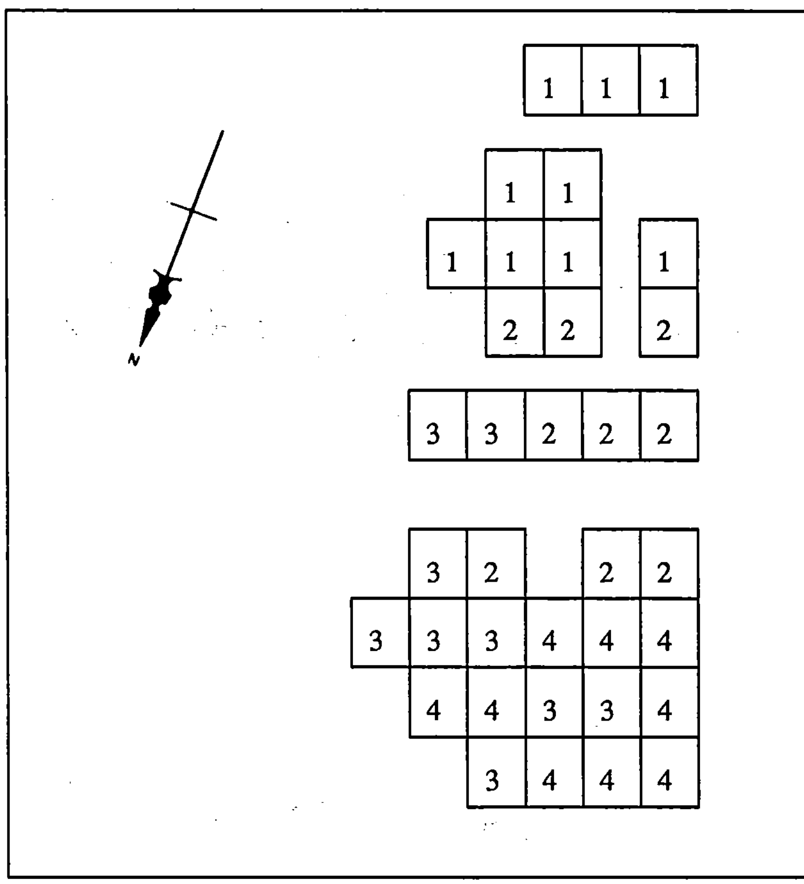

Figure 3.3: Replicates and plot design.
1= Replicate 1
2= Replicate 2
3= Replicate 3
4= Replicate 4.

3.2.2 Cultivation treatments.

Three cultivation treatments were used (Table 3.3):

1. Nil (i.e. control)
2. Aeration - mechanical loosening to 27 cm (Plate 3.1)
3. Subsoiling - mechanical loosening to 47 cm.

Plate 3.1: The Clough Panaerator used to aerate the profile to an average depth of 27 cm.

Cultivation	Date	Average Depth (cm)	Tine Spacing (cm)	Cultivator
Nil	-	-	-	-
Aeration	10-Nov-90	27	60	Clough Panaerator
Subsoiling	10-Oct-90	47	80	Talbot ('Maru') Subsoiler

Table 3.3: Cultivation treatments.

The allocation of cultivation treatments to mainplots can be seen in Figure 3.4. On both cultivation implements the tines were staggered in a triangle arrangement, and the leg angled in such a way to give 20° of lift with a winged foot at the base (Appendix 3.3) (Figure 3.5).

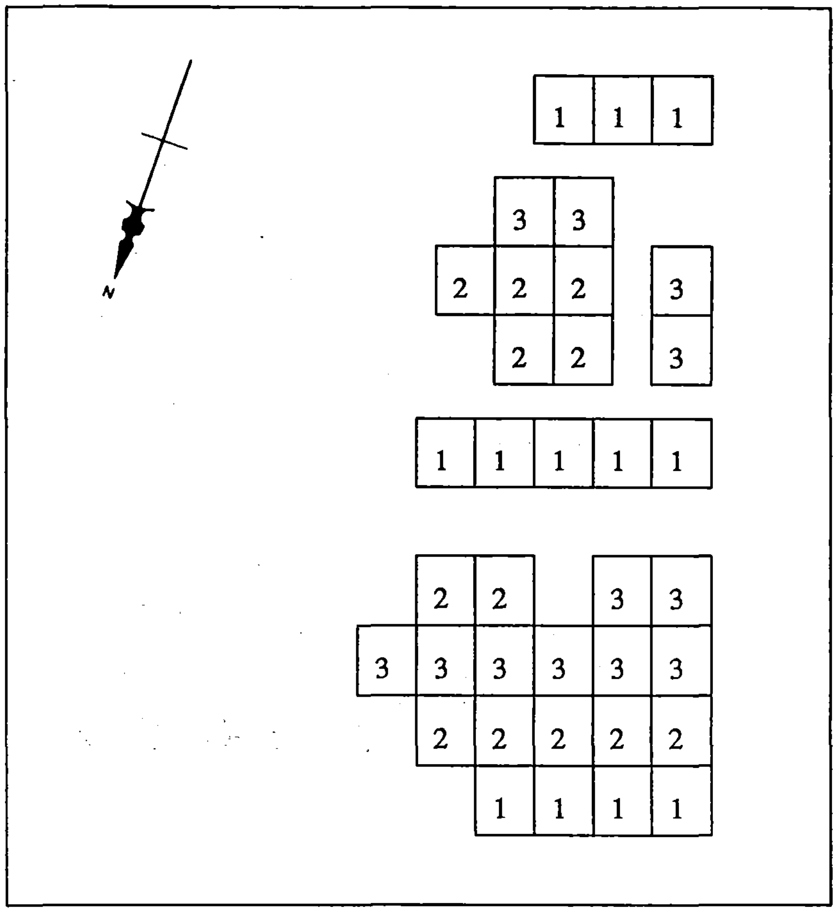

Figure 3.4: Allocation of cultivation treatments to plots.
1= Nil cultivation
2= Aeration (average depth of 27 cm)
3= Subsoiled (average depth of 47 cm).

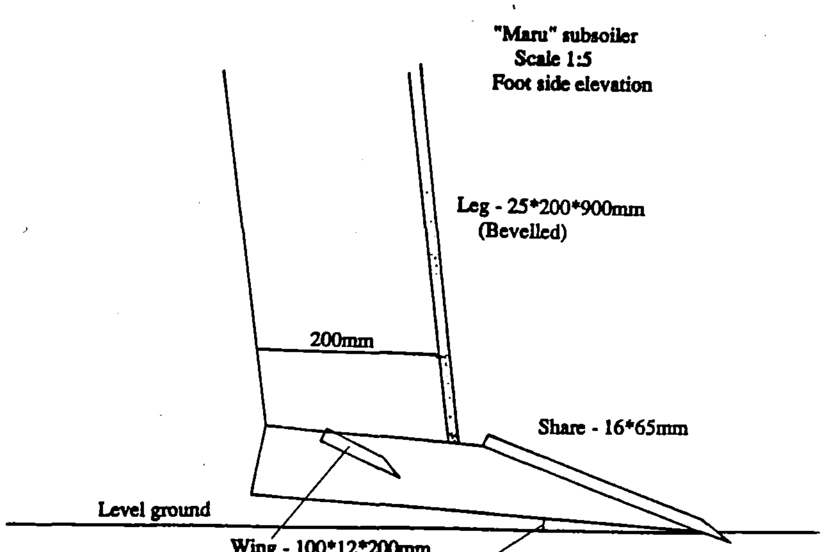

Figure 3.5: 'Maru' subsoiler foot.

On the foot of the subsoiler there was a leading tine that acted as a turf cutter, whilst the aerator had a disc, going before each tine to cut the turf and limit disturbance to the pasture (Plate 3.2).

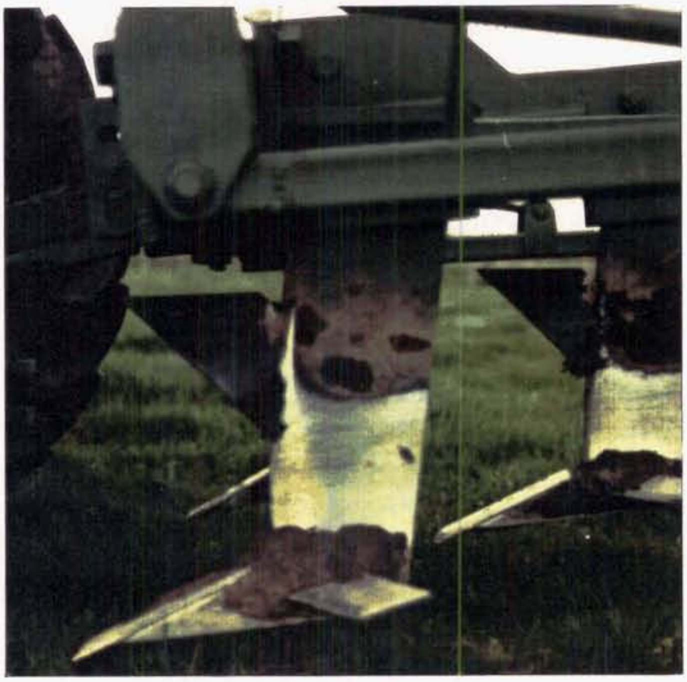

Plate 3.2: 'Maru' subsoiler showing the presence of a turf cutter.

Before the subsoiling operation, the trial site was irrigated and allowed to drain for 2 days to allow the soil to reach field capacity. The soil water content before the aeration operation was also at field capacity, due to natural rainfall (33%, v/v).

3.2.3 Fertiliser treatments.

The three fertilizer treatments were:

1. Nil (control)
2. Phosphate only (30 kg P ha^{-1}) applied as sodium dihydrogen orthophosphate ($Na_2H_2PO_4.2H_2O$)
3. Phosphate (as above) and sulphur (30 kg S ha^{-1}) applied as sodium sulphate (Na_2SO_4).

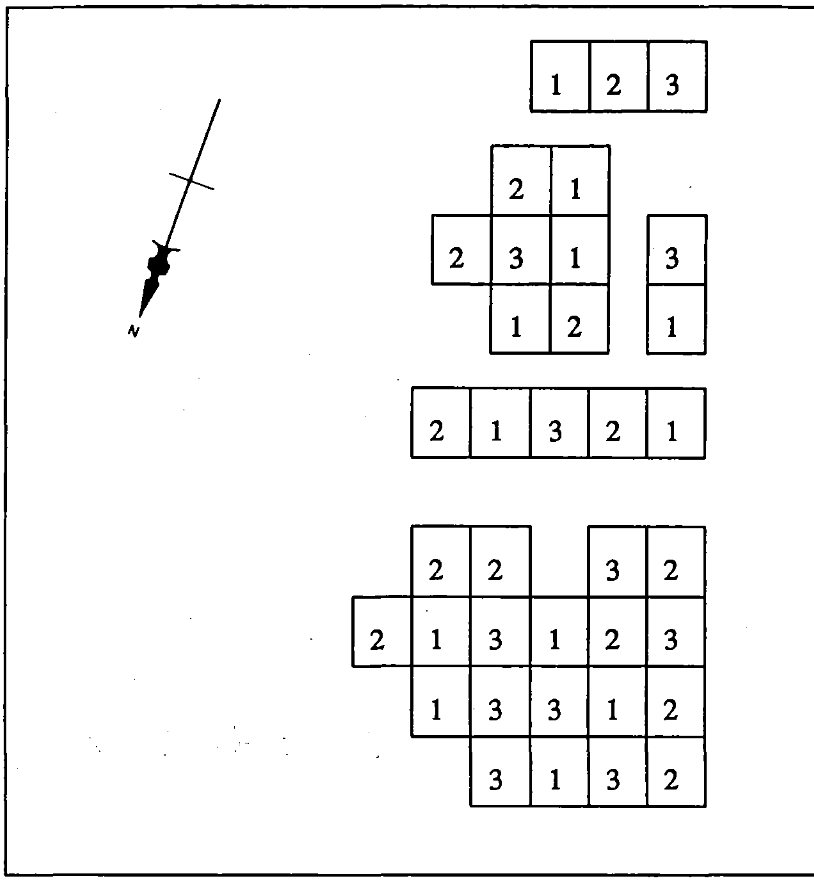

Figure 3.6: Allocation of fertiliser treatments to plots.
1= Nil fertiliser
2= Phosphate only
3= Phosphate and Sulphate.

Allocation of fertiliser treatment to main plots can be seen in Figure 3.6. The fertiliser was broadcast by hand on 22-Dec-90, twenty hours prior to light rain.

The phosphate and sulphate rates were chosen to simulate farmer practice of the Ellesmere district. A one meter strip at the South facing edge of each plot was left unfertilised.

3.2.4 Radioactive tracer microplot trial.

To study in detail the uptake of native nutrients from various depths in the soil profile, carrier free radioactive isotopes (^{32}P and ^{35}S) were injected into the soil during August 1991, at three depths (25, 40 and 55 cm). The experiment was carried out on 80 cm diameter microplots. The microplots were positioned, with the shear plane centrally located, within the unfertilised 1 m strip of the main plots (Section 3.2.3). Full details of the Microplot Trial are given in Section 5.0.

3.3 Trial Management and Regular Measurements.

3.3.1 Soil water content.

Time-Domain-Reflectrometry (TDR) was used to measure soil water contents at regular intervals over the duration of the trial. A 'Trase System 1' TDR (Model 6050X1) provided an instantaneous measurement of soil volumetric water content at selected depth intervals (Plate 3.3).

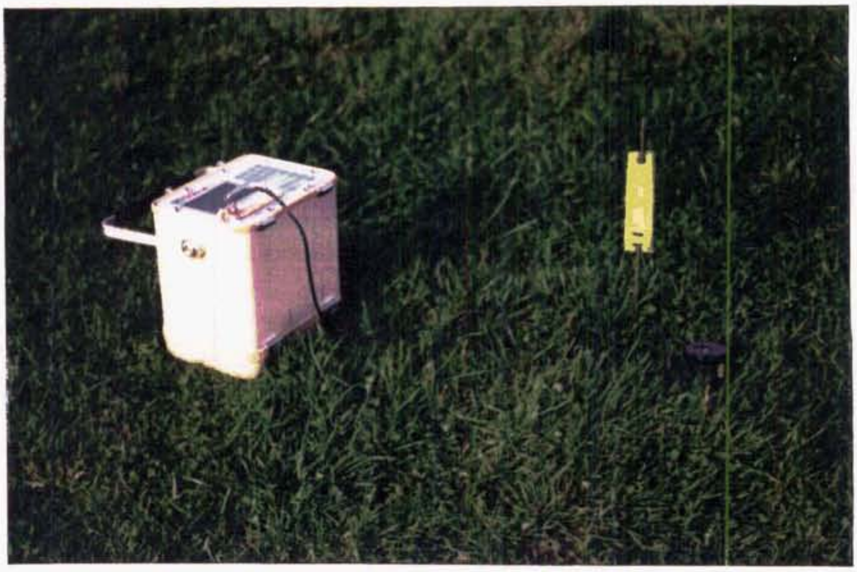

Plate 3.3: The TDR-soil moisture measuring device.

3.3.1.1 Installation of Time-Domain-Reflectrometry wave guides.

Wave guides (Stainless steel rods: 6.5 mm diameter) were installed on 26-Oct-90. The wave guides were installed parallel to the shear plane, in the unfertilised area of twelve mainplots. The wave guides were placed at a distance of 15 cm and 20 cm from the aerated and subsoiled shear planes respectively, similar to the locations used for moisture measurements in previous studies (Greenwood, 1989).

Six lengths of wave guides were used: 20, 30, 35, 40, 50 and 70 cm. These six depths allowed for soil water measurements to be made over the range of disturbance patterns created by the three cultivation treatments (Figure 3.7).

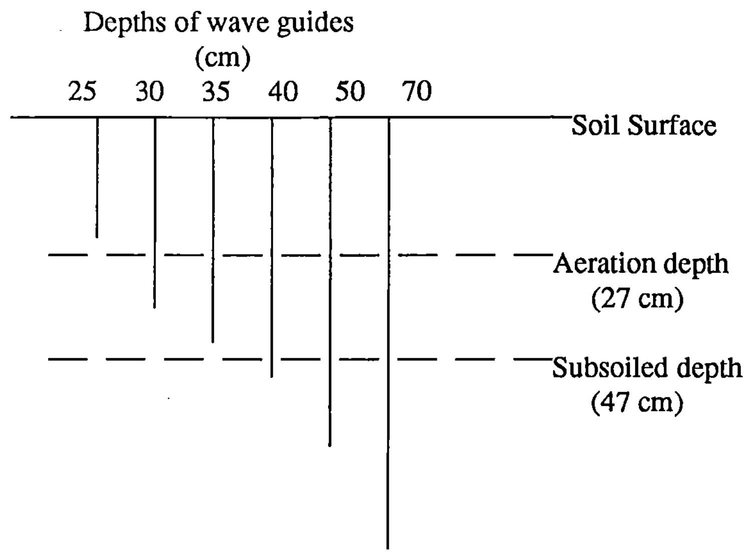

Figure 3.7: Depths of the T.D.R. wave guides to measure volumetric water content.

3.3.1.2 Soil water measurements.

The volumetric water content of the soil was measured every two weeks until the beginning of the radioactive tracer study (August 1991), from when measurements were made weekly.

3.3.2 Pasture management.

No irrigation was applied over the duration of the trial. This was to allow the simulation of a dryland pastoral farming situation.

Grass grub was noticed to be a problem affecting pasture yield in June 1991. On 21-Jun-91 Miral 10G granules (Ciba-Geigy Agriculture) were broadcast by hand at 20 kg ha^{-1}.

3.3.3 Pasture measurement.

Pasture was harvested when pasture height reached approximately 8-10 cm. Therefore cutting intensity increased during periods of rapid growth (eg. Spring and Autumn) (Table 3.4).

Harvest Dates	Dissection Dates	Micronutrient Analysis
7.11.90	7.11.90	7.11.90
5.12.90		5.12.90
15.1.91		
25.2.91		
22.4.91	22.4.91	
1.8.91		1.8.91
5.9.91		
26.9.91		
11.10.91		
24.10.91		
28.11.91		
28.1_.91		
16 1.92		
12.2.92	12.2.92	12.2.92

Table 3.4: Pasture harvest dates for main trial.

Before and after each mowing event, a 0.125 m^2 quadrat was cut to ground level. The quadrat was cut using the hand piece of a battery powered shearing unit. After washing and drying, the pre- and post-cut drymatter was determined, and pasture growth rate calculated (kg ha^{-1} and kg ha^{-1} d^{-1}).

From subsamples taken at each pasture harvest macronutrient (N, P, S, K, Ca, Mg and Na) concentrations were determined. Micronutrient (Mn, Zn, Cu, Fe and Co) concentrations were determined only for the four dates shown (Table 3.4).

Botanical dissections were carried out on the three dates shown in Table 3.4. These were done by taking ten cuts per mainplot using hand held shears (≈ 5x10 cm). These samples were bulked for each mainplot and then dissected into grasses, clover, weeds and dead material.

The whole of the trial area was cut to a height of 4-5 cm at each harvest date (Table 3.4) and the grass clippings returned to each plot.

3.3.4 Root length measurements.

Regular measurements of root length were made to follow root growth over a growing season (August 1991 to January 1992) (Table 3.5).

Date	Number of Plots
27.2.91	3
5.8.91	9
5.9.91	9
3.10.91	9
30.10.91	9
29.11.91	9
18.12.91	9
18.1.92	18

Table 3.5: Dates of root length measurements.

The *in situ.* profile wall method was used (Bohm, 1976; Greenwood, 1989) to estimate root length per unit area and maximum rooting depth (Plate 3.4).

Plate 3.4: The *in situ* profile wall method used to estimate root length (cm cm^{-2}).

Measurements were made in replicates one, two and four only. Replicate three was excluded to reduce the time taken and because of the variable soil type present in that replicate. The 80 cm x 100 cm grid was placed at right angles to the direction of cultivation and centrally positioned on the shear plane. The number of 5 mm lengths of living root per 5 cm x 5 cm grid section were recorded (Greenwood, 1989).

3.3.5 Root length/root density calibration.

Many researchers, when studying plant roots, use root density (cm cm^{-3}) measurements to compare treatments. We therefore tried to devise a method of relating root length (cm cm^{-2}) to root density (cm cm^{-3}).

On 18-Jan-92, immediately after root length counting, a 100 mm x 100 mm metal sample box was pushed 100 mm in to the profile wall, samples were collected over the area of the 800 mm x 1000 mm grid. The roots and soil were separated by washing. The root length per unit volume, hence density, was determined by the grid intersect method of Tennant (1975).

Regression analysis was used to examine and describe the relationship between root length and density for each of the three cultivation treatments.

3.4 Measurement of Soil Physical Characteristics.

3.4.1 Bulk density.

In March 1991 bulk density measurements were made using the soil core method (Blake and Hartage, 1986; Greenwood, 1989). The variability of the data (Appendix 3.4) was such that an alternative method was sought.

Previous workers have stated that they were unable to develop a technique for soil bulk density measurement that would take cores of less than 750 mm diameter without causing serious compression (Erbach, 1987). Also, it has been questioned if a cutting edge can be made on a corer which will not compress the wall of the sample (Jamison *et al*, 1950).

Bulk density measurements were therefore made using a Gamma density probe (MC-3 Portaprobe ^{R}) (Appendix 3.5). The probe operates by emitting radiation from two radioactive sources.

Gamma ray attenuation is measured using a Cesium-137 source. Radiation which passed through the soil is detected by the Geiger-Mueller detector located in the MC-3 Portaprobe.

An Americium-241:Beryllium source emits neutron radiation which is used to provide a measure of soil water content. The probe was calibrated to account for water content at the time of bulk density measurement.

Access tubes (Aluminium: 20 mm diameter) one metre in length were placed in twenty-seven mainplots near to the Time-Domain-Reflectrometry wave guides where possible. The access tubes were placed in pairs parallel to the shear plane at a distance of 15 cm and 30 cm, and 20 cm and 40 cm from the shear plane of the aerated and subsoiled cultivations respectively (Figure 3.8). The twin probes of the MC-3 Portaprobe were lowered into the access tubes, and dry bulk density measurements obtained at 2.5 cm depth increments to a total depth of 80 cm.

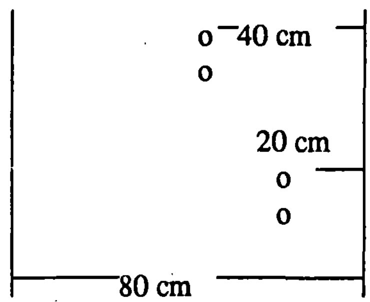

Figure 3.8: The placement of the access tubes for the measure of bulk density using gamma ray attenuation using a 80 cm tine separation.

In April 1991 manual measurements were taken at the same time as gamma ray attenuation measurements. From the results presented in Figure 3.9 and Appendix 3.4 it was shown the manual sampling gave unreliable results.

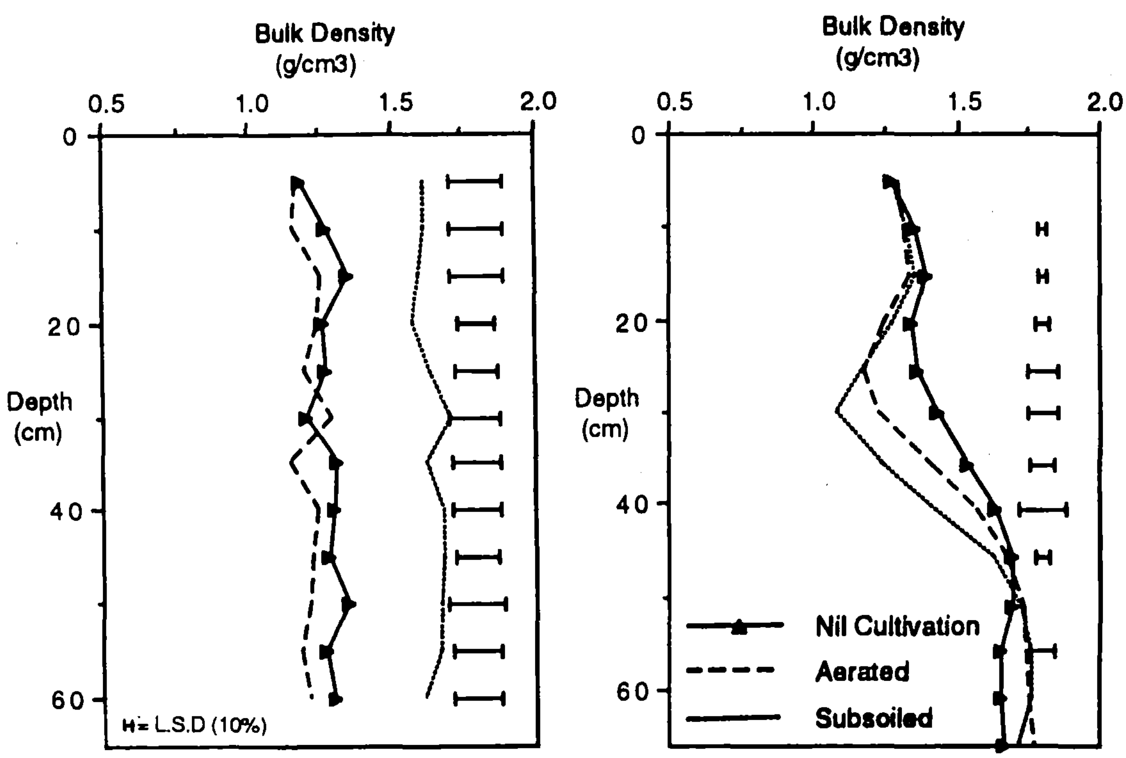

Figure 3.9: Bulk density measurements comparing manual core sampling (left) with gamma ray attenuation (right), for the 15/20 cm distance from the shear plane.

These results were in agreement with previous workers. Erbach (1987) presented a review of soil bulk density measurement practices for field soils and concluded that the core sampling method, which is often considered to be the standard method for comparative purposes, may have errors that are far greater than the gamma ray attenuation method.

3.4.2 Hydraulic conductivity.

Hydraulic conductivity measurements were made in May 1991 and January 1992.

Saturated hydraulic conductivity (K_{sat}) was measured on 200 mm diameter lysimeters, containing a 100 mm depth of soil. See Cameron *et al.* (1990) for collection method and pre-measurement treatment eg. vaseline sealing and acetate/acetone peeling.

The lysimeters were taken from three replicates of each cultivation treatment (nine plots). Two replicate lysimeters were taken of each depth per plot. The depths sampled were 10-20 cm, 20-30 cm and 30-40 cm. A further two replicates were taken (two mainplots; one control and one subsoiled), from 0-10 cm and 40-50 cm. A total of 58 lysimeters were taken.

The saturated hydraulic conductivity (K_{sat}) was measured using a constant head permeameter device (Figure 3.10). Changes in permeameter reservoir volumes were recorded using Sensym SCXO1DNC pressure transducers which were attached to a CR10 data logger.

The changes in pressure from the decreasing volume of water in the polycarbonate column were detected by the pressure transducer and stored in the Campbell Scientific CR10 data logger.

The data logger was programmed to convert this data in to measurements of K_{sat}. The measurements continued until the full column of water (1.5 litres) had drained and the 2 cm hydraulic head disappeared.

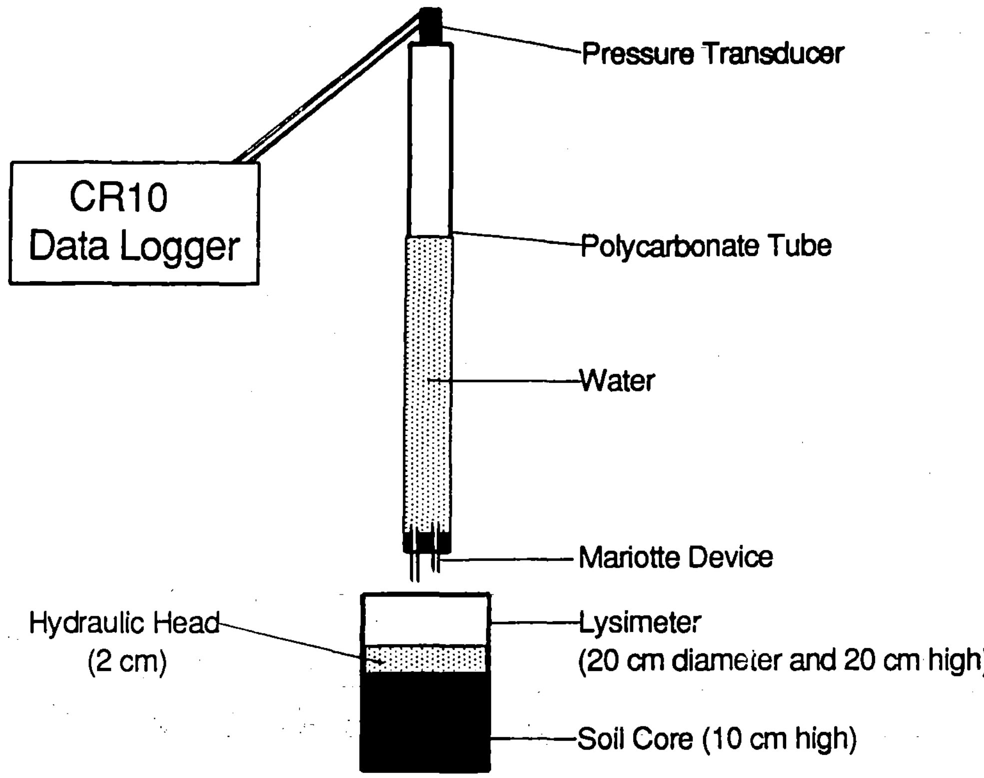

Figure 3.10: Experimental apparatus used to measure K_{sat}.

4.0 RESULTS.

The field experiment started in October 1990 and continued until February 1992. The results will be presented for the complete period of the trial and for the period 1 August 1991 to 27 February 1992, representing the second season when the most intensive monitoring took place.

4.1 Climatic Conditions.

Lincoln has a subhumid climate (Cox, 197). The summers are dry, with high temperatures and frequent northwest Föhn winds. This combination results in high evapotranspiration and drought conditions are common.

During the period of the trial meteorological data was obtained from the Lincoln University Meteorological Station (approximately 1 km from the trial site).

4.1.1 Rainfall.

4.1.1.1 Rainfall events.

From October 1990 to February 1992 860 mm of rainfall was recorded.

The 1991/1992 season (i.e. 1-Aug-91 to 27-Feb-92) was a dry cool season (Cherry, 1991, 1992). With two large rainfall events recorded of 23.8 mm and 30.6 mm respectively (Figure 4.1).

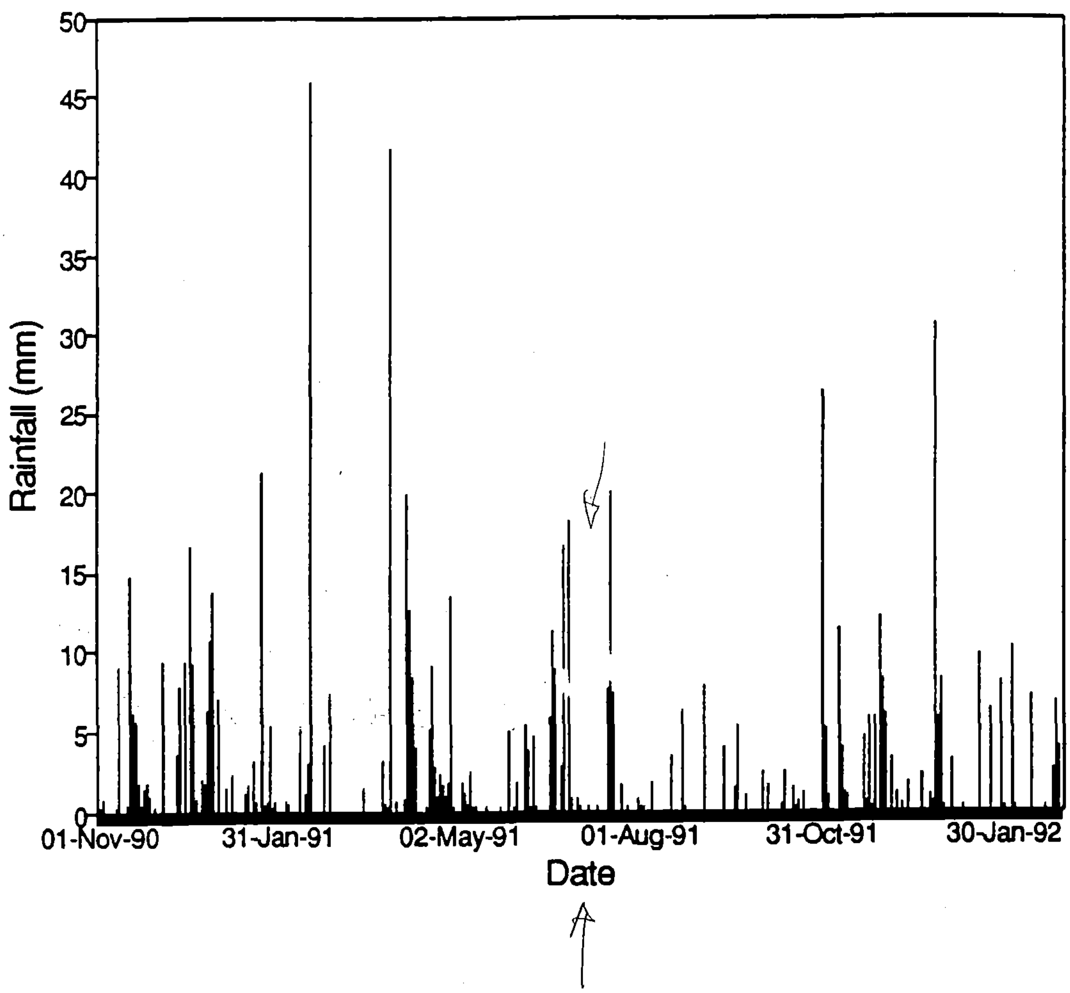

Figure 4.1: Rainfall events from 1-Nov-90 to 27-Feb-92, (Adapted from Cherry, 1990, 1991, 1992).

4.1.1.2 Actual rainfall and average rainfall.

From Figure 4.2 it can be seen that from October 1990 to July 1991 rainfall exceeded the fifty year rainfall average. The rainfall for the 1991/1992 season was below average.

The months of July, August, September and October, 1991, all had rainfalls forty percent below the fifty year average. November and December had above average rainfalls of 74 and 84 mm respectively. The January and February rainfalls fell to fifty percent of the average rainfall with rainfalls of 28 and 34 mm respectively.

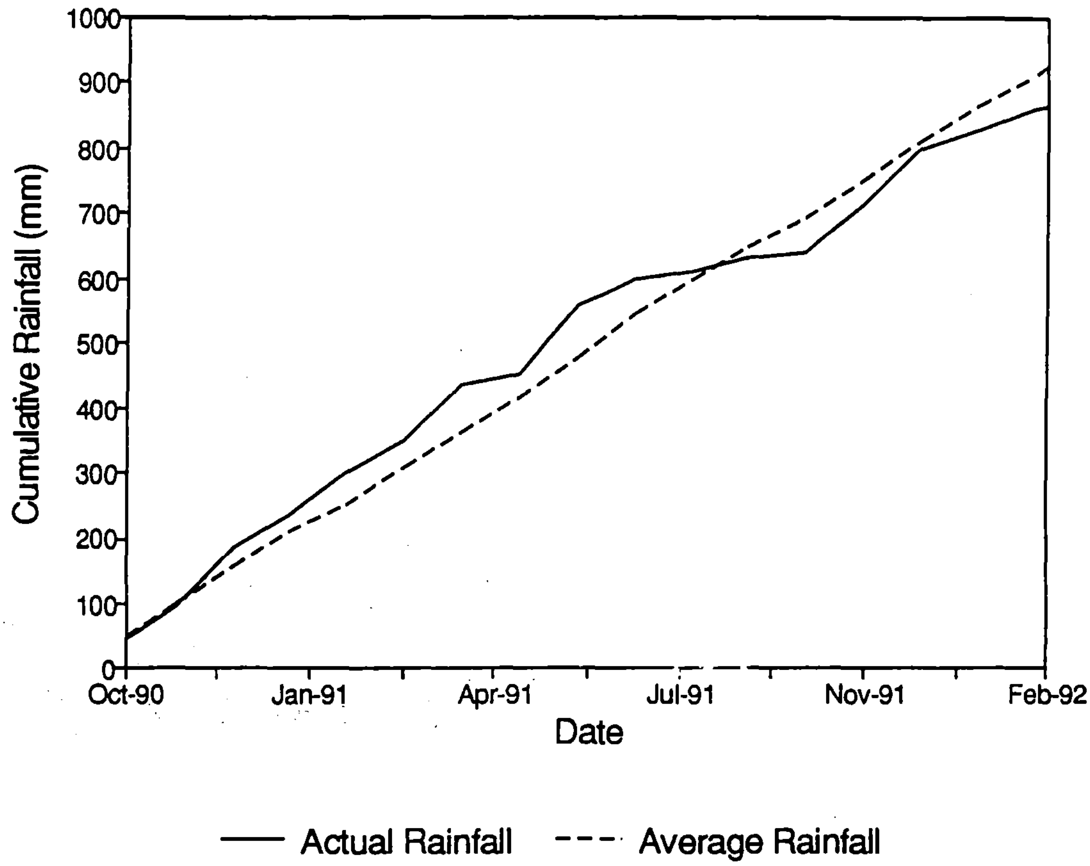

Figure 4.2: Cumulative rainfall compared to average rainfall from 1-Nov-90 to 27-Feb-92, (adapted from Cherry, 1990, 1991, 1992).

4.1.2 Evapotranspiration.

4.1.2.1 Evapotranspiration versus rainfall.

Evapotranspiration was calculated using the Penman Potential Deficit Method (Cherry, 1991). Evapotranspiration exceeded rainfall for the 1991/1992 season (Figure 4.3).

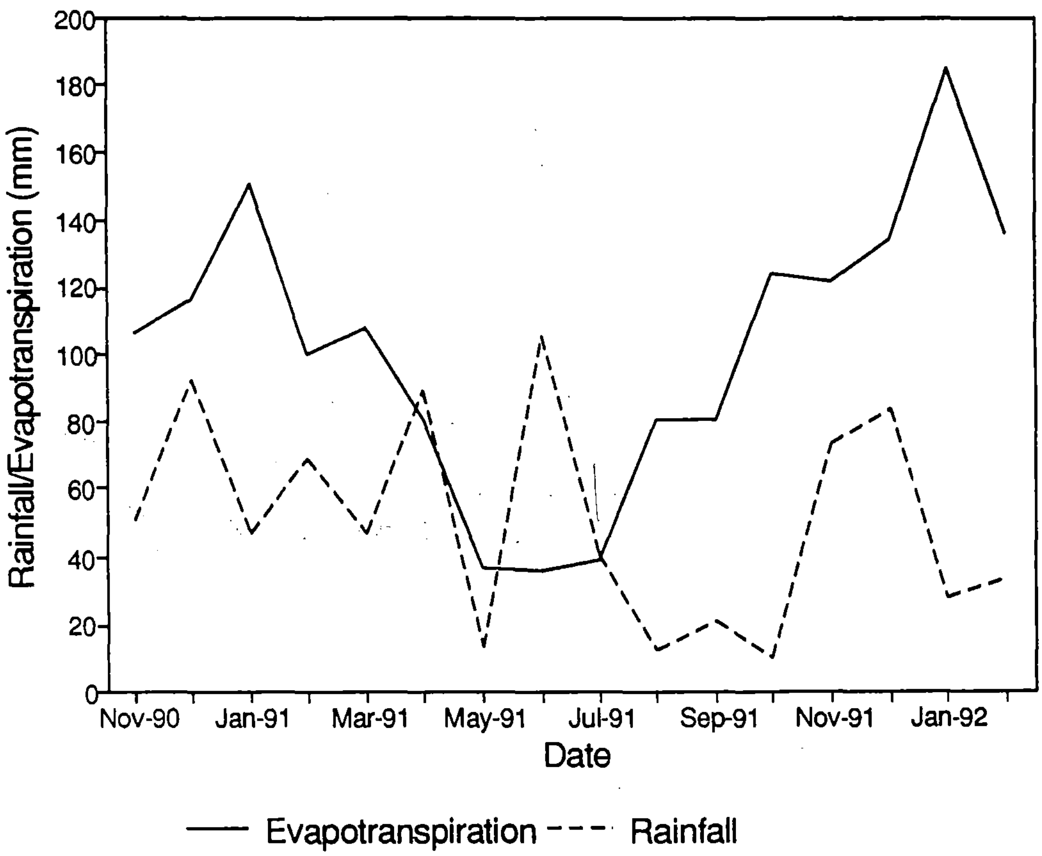

Figure 4.3: Evapotranspiration from 1-Nov-90 to 27-Feb-92, (adapted from Cherry, 1990, 1991, 1992).

4.1.2.2 Water deficient days.

Water deficient days were calculated using the 100 mm Soil Moisture Model (Cherry, 1991). Deficient days are defined as days when the evapotranspiration exceeds rainfall plus the soil water storage to a 100 mm depth (Table 4.1).

Month	Year	Deficient Days	Cumulative Deficient Days
October	1990	23	23
November	1990	14	37
December	1990	20	57
January	1991	15	72
February	1991	0	72
March	1991	19	91
April	1991	-	-
May	1991	-	-
June	1991	-	-
July	1991	-	-
August	1991	-	-
September	1991	18	18
October	1991	31	49
November	1991	13	62
December	1991	19	81
January	1992	22	103
February	1992	21	124

Table 4.1: Water deficient days from 1-Nov-90 to 27-Feb-92 (adapted from Cherry, 1990, 1991, 1992).

August 1991, was a very dry warm month causing an early start (September, 1991) to dry soil conditions. October was also a very dry month adding 31 deficient days. By December the deficient day total for the 1991/1992 season was 47 days above the average but fell back to 11 days above the average by the end of January 1992.

4.1.3 Soil and air temperatures at the start of Spring 1991.

Intensive measurements of pasture growth, root growth and water content began on 1-Aug-91. The soil temperatures at this time were low (Table 4.2).

Date	10 cm (^oC)	30 cm (^oC)	100 cm (^oC)
1-Aug-91	3.2	5.2	5.9
27-Aug-91	5.0	6.8	6.8

Table 4.2: Soil temperature at 1-Aug-91 and 27-Aug-91, (Cherry, 1991).

It was not until 27-Aug-91 that the soil temperature remained consistently above 5 ^oC. The soil profile (0-70 cm) moisture content on the 27-Aug-91 was approximately 30% (v/v) (Section 4.6.1). The average maximum daily temperature during August was 13.9 ^oC, 3.1 ^oC above the average.

4.2 Soil Physical Characteristics.

4.2.1 Effect of cultivation on bulk density.

The bulk density results presented here are from January 1991, measured using the Gamma Density Probe. The cultivated treatments of aeration (27 cm) and subsoiling (47 cm) were found to significantly reduce the soil bulk density (Table 4.3). This reduction in bulk density was especially noticeable at the depths of 20-25 cm and around 40 cm where the initial survey (Section 3.0) suggested that root growth was maybe restricted due to the high bulk density of the soil.

Depth (cm)	Cultivation Treatment			FProb	L.S.D (10%)
	Nil	Aerated	Subsoiled		
5	1.271	1.287	1.271	NS	-
10	1.348	1.309	1.314	0.021	0.0240
15	1.382	1.330	1.352	0.002	0.0217
20	1.339	1.244	1.273	0.008	0.0473
25	1.358	1.173	1.161	0.004	0.1002
30	1.421	1.219	1.079	<0.001	0.1033
35	1.531	1.403	1.237	<0.001	0.0795
40	1.631	1.558	1.418	<0.001	0.1657
45	1.687	1.672	1.616	<0.084	0.054[illegible]
50	1.685	1.728	1.715	NS	-
55	1.652	1.741	1.761	0.0[illegible]6	0.0824
60	1.648	1.745	1.754	NS	-
65	1.657	1.762	1.705	NS	-
70	1.662	1.732	1.664	NS	-

Table 4.3: Soil bulk density as affected by cultivation treatment, January 1991, for the 15/20 cm distance from the shear plane.

From Figure 4.4 it can be seen that to a depth of 30 cm the aerated and subsoiled cultivation treatments behaved in a similar fashion. From 30 cm to a depth of 50 cm the subsoiled cultivation treatment had lower bulk densities than the nil and aerated cultivation treatments. These results correspond to the depths of cultivation, that is the soil bulk density was reduced to the depth of cultivation.

Many previous researchers have found that aeration and subsoiling reduces soil bulk density: with the decreases in bulk density being particularly marked in layers that were previously of high bulk density.

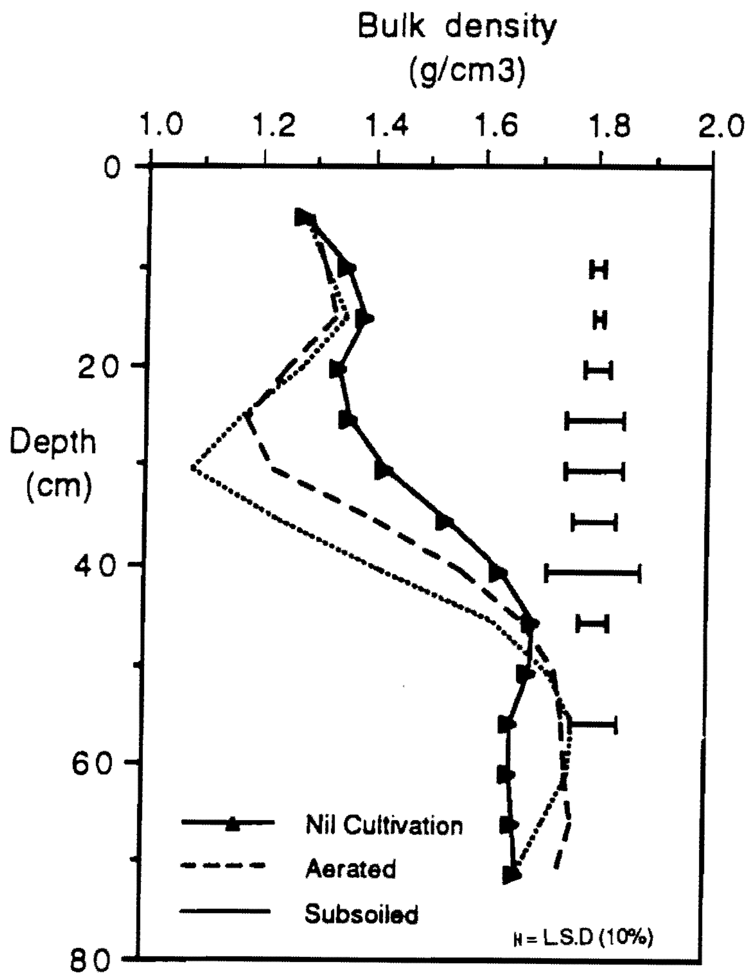

Figure 4.4: Soil bulk density as affected by cultivation treatment, January 1991.

4.2.2 Effect of cultivation on porosity.

The aerated and subsoiled cultivation treatments were found to have significantly higher porosity values than the nil cultivation treatment, from 10 cm to 45 cm (Figure 4.5) (Appendix 4.1). These increases in porosity are considered to be a result of the cracks and fissures created at the time of cultivation (Fraser, 1992).

Air-filled porosity was calculated using Equation A:

$$e_a = e - j_v \quad \textbf{Equation A}$$

Where:
e_a = Air-filled porosity (%)
e = Total porosity (%)
j_v = Volumetric water content (%, v/v).

The air-filled porosity is presented in Table 4.3(a).

	Air-filled porosity (%)		
Date	Nil	Aerated	Subsoiled
1-Aug-91	7.0	9.6	11.5
29-Nov-91	20.4	22.5	28.7
18-Jan-92	24.6	25.9	31.0

Table 4.3(a): Air-filled porosity for three dates.

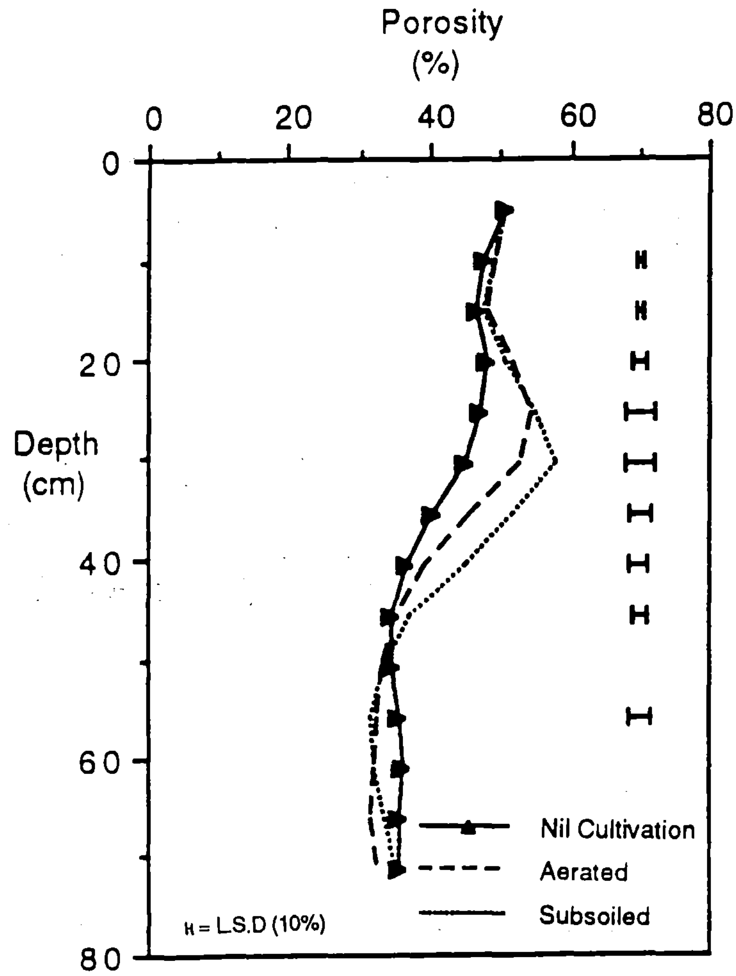

Figure 4.5: Porosity as affected by cultivation treatment, January 1991.

4.2.3 Effect of cultivation on hydraulic conductivity.

Hydraulic conductivity was measured at two times during the trial, May 1991 and January 1992. A similar trend of increased hydraulic conductivity with soil loosening for both dates emerged (Table 4.4). Note that for the aerated cultivation treatment the depth ranges 0-10 cm and 40-50 cm were not measured.

May 1991				
Depth (cm)	Nil	Aerated	Subsoiled	FProb
0-10	370.9	-	290.6	NS
10-20	86.5	163.3	83.6	NS
20-30	51.3	380.2	138.0	0.044
30-40	17.9	47.2	130.6	0.013
40-50	1.4	-	6.3	NS

January 1992				
Depth (cm)	Nil	Aerated	Subsoiled	FProb
0-10	34.6	-	285.7	NS
10-20	151.0	347.5	153.1	0.065
20-30	83.2	388.8	114.8	NS
30-40	26.3	43.7	58.9	NS
40-50	6.4	-	1.6	NS

Table 4.4: Geometric mean hydraulic conductivity (mm hr^{-1}) as affected by cultivation treatment.

Previous workers have considered hydraulic conductivity like other transport coefficients to be log normally distributed (Greenwood, 1989). Examination of the present data set also indicated a log normal distribution, therefore the data was log transformed to produce a normal distribution and thereby satisfy the assumptions of analysis of variance. To give scale, the log means were back transformed and are presented as geometric means of hydraulic conductivity.

The loosened treatments of aeration and subsoiling resulted in significantly greater hydraulic conductivities at the 20-30 cm depth during May 1991. The subsoil loosened treatment also had a significantly higher hydraulic conductivity at the 30-40 cm depth during May 1991, compared to the nil and aerated cultivation treatments (Figure 4.6).

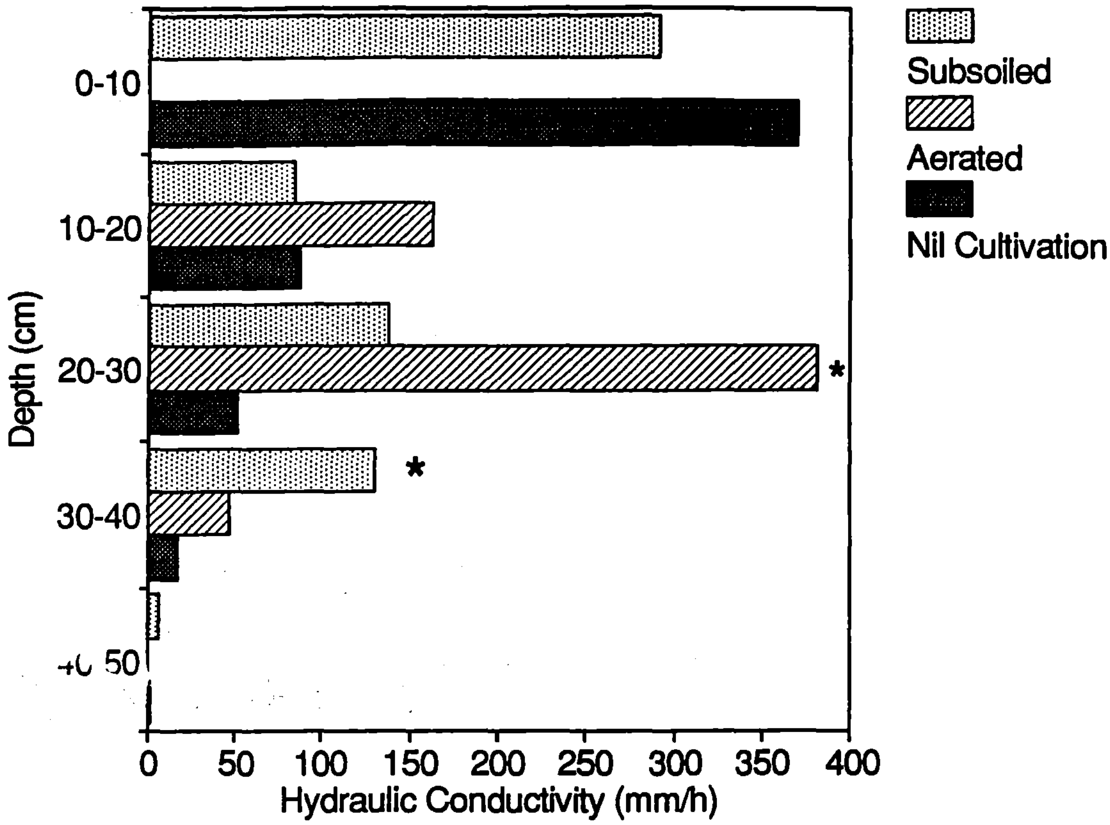

Figure 4.6: Hydraulic conductivity as affected by cultivation treatment, May 1991 (* indicates a significant difference of P <0.10).

In January 1992, the subsoil loosened treatment had a similar hydraulic conductivity to the nil cultivation treatment at the 10-20 cm and 20-30 cm depths. At the 10-20 cm depth the aerated treatment had a hydraulic conductivity significantly higher than the nil or subsoiled cultivation treatment. Though not significant the aerated cultivation treatment also had a larger hydraulic conductivity at the 20-30 cm depth than the nil or subsoiled cultivation treatments. However at the 30-40 cm depth, both loosened treatments had a larger hydraulic conductivity than the nil cultivation treatment, however the differences were not significant. The increased hydraulic conductivities at this depth are due to the creation of macropores as a result of soil loosening.

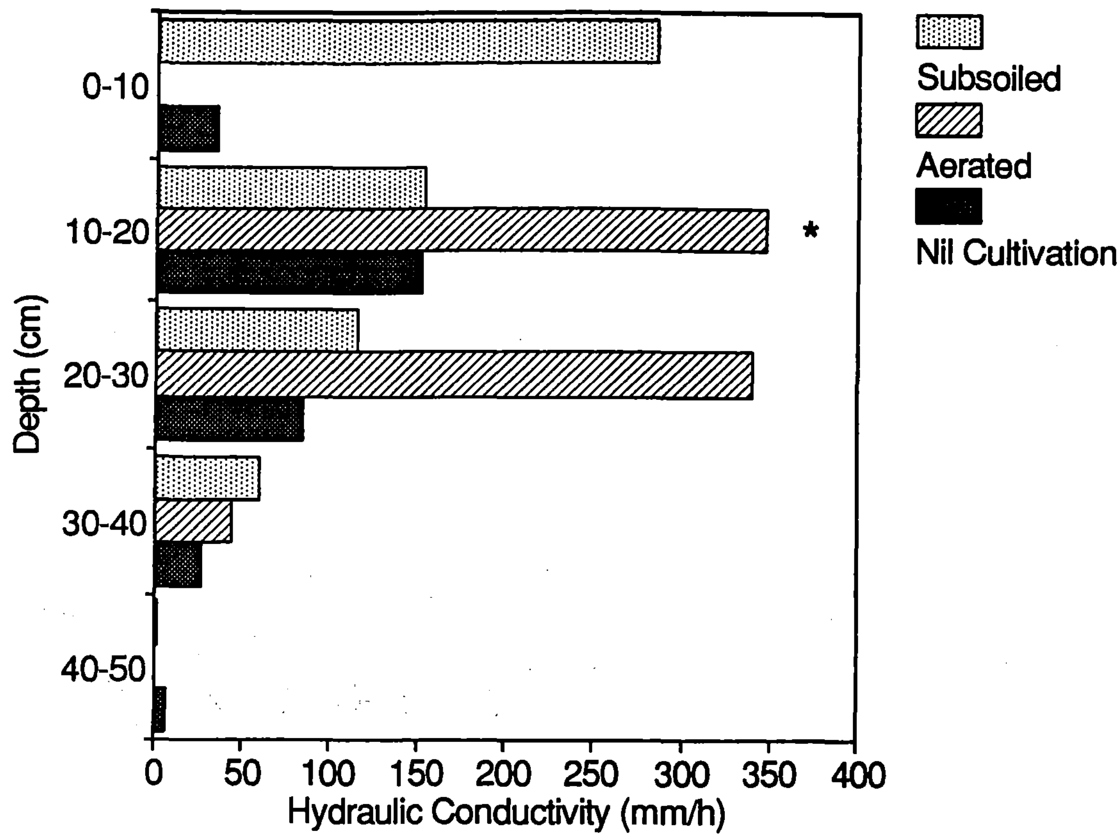

Figure 4.7: Hydraulic conductivity as affected by the cultivation treatment, January 1992 (* indicates a significant difference of P <0.10).

These hydraulic conductivities were measured on 20 cm diameter undisturbed cores (Section 3.4.2). Other workers have questioned the size of cores in relation to the measurement of hydraulic conductivity, because a small core may not accurately represent the full macropore system (Greenwood, 1989). Nevertheless the size of the cores used here and the standardised location of sample collection can still be considered to provide results which are useful for comparisons between treatments, rather than exact field values.

It can be concluded that the aerated (27 cm) and subsoiled (47 cm) treatments appear to have been effective at increasing the hydraulic conductivity at depth within the soil profile.

4.3 Pasture Production and Composition.

4.3.1 Pasture production.

4.3.1.1 Effect of cultivation on pasture production.

Pasture production was measured from November 1990 to February 1992 (Table 4.5).

Harvest Date	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
7-Nov-90	983	1122	1227	NS	-
5-Dec-90	1306	1450	1360	NS	-
15-Jan-91	1439	921	835	0.002	292.0
25-Feb-91	1439	1188	1245	NS	-
22-Apr-91	589	558	509	NS	-
1-Aug-91	994	1260	1285	0.073	223.4
5-Sep-91	766	1192	907	0.039	261.5
26-Sep-91	775	739	1004	NS	-
11-Oct-91	138	543	416	0.033	261.5
24-Oct-91	1087	1193	1195	NS	-
28-Nov-91	1558	1391	1689	NS	-
20-Dec-91	214	188	285	NS	-
16-Jan-92	48	333	129	0.023	177.8
12-Feb-92	536	685	625	NS	-

Table 4.5: Pasture production (kg DM ha^{-1}) from 7-Nov-90 to 12-Feb-92 as affected by cultivation treatment.

There were only a few months when a statistically significant difference occurred between the cultivation treatments. This lack of significant differences was due to large variations in pasture growth data. This variation was due, in part, to a grassgrub infestation from 1-Aug-91 to 28-Nov-91. The data from the thirteen affected plots, has been treated as missing data by the statistical package (Genstat 5) in an attempt to reduce its influence on the analysis.

Logarithmic transformations of the data were tried but did not improve the analysis of the data. Neither did the attempted modelling of the data using the Gompertz equation (Lane *et al.*, 1987).

A significance level of ten percent has been used throughout this thesis due to the large variation experienced with the field trial results. On all figures presented in this thesis significant differences will represented by L.S.D (10%) bars.

Cumulative pasture production.

The cumulative pasture production is presented in Figure 4.8 (Appendix 4.2).

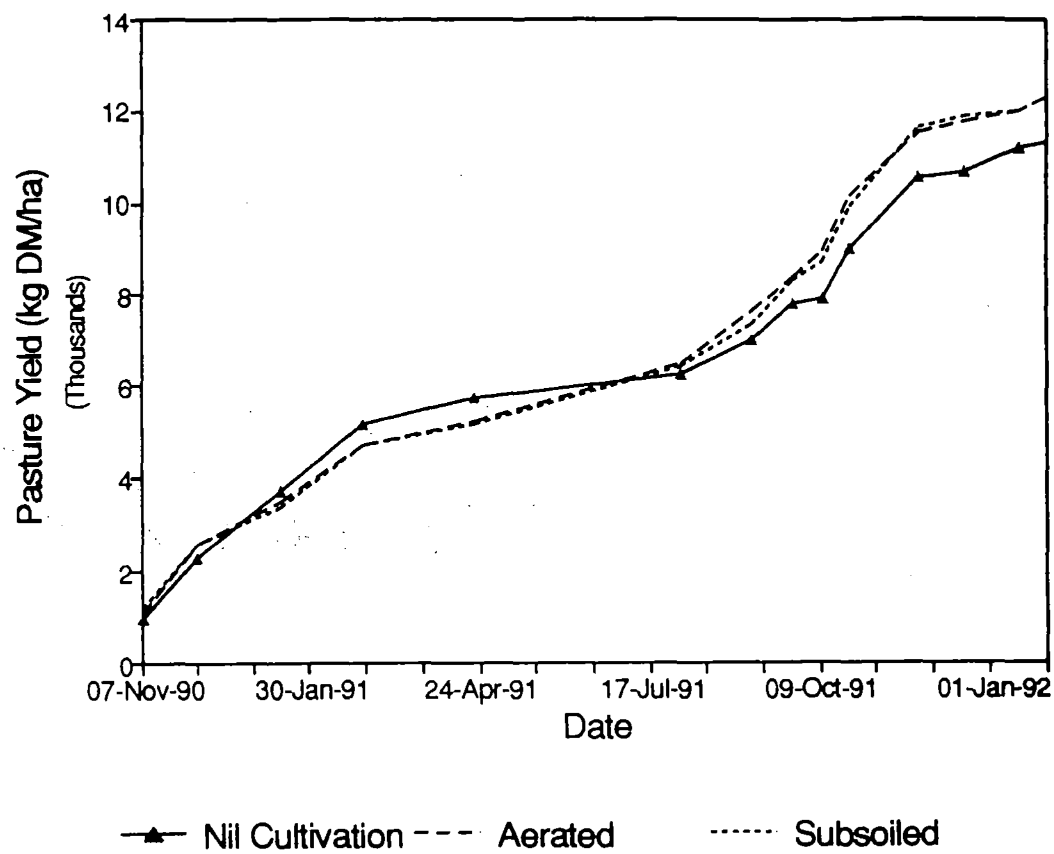

Figure 4.8: Cumulative pasture production as affected by cultivation treatment, 7-Nov-90 to 12-Feb-92.

From Figure 4.8 two distinct time periods can be identified. The 1990/1991 season (7-Nov-90 to the end of growth 22-Apr-91) and the 1991/1992 season (1-Aug-91 to 12-Feb-92). During the 1990/1991 season the loosened treatments of aeration and subsoiling had slightly lower pasture yields (Table 4.5 and Figure 4.8). This was considered to have been from root pruning caused by the cultivation implements. The occurrence of root pruning in pasture by deep cultivation methods has also been noted by MAFF (1982) and Chapman and Allbrook (1987).

The 1991/1992 season shows a different cumulative pasture production pattern (Figure 4.9).

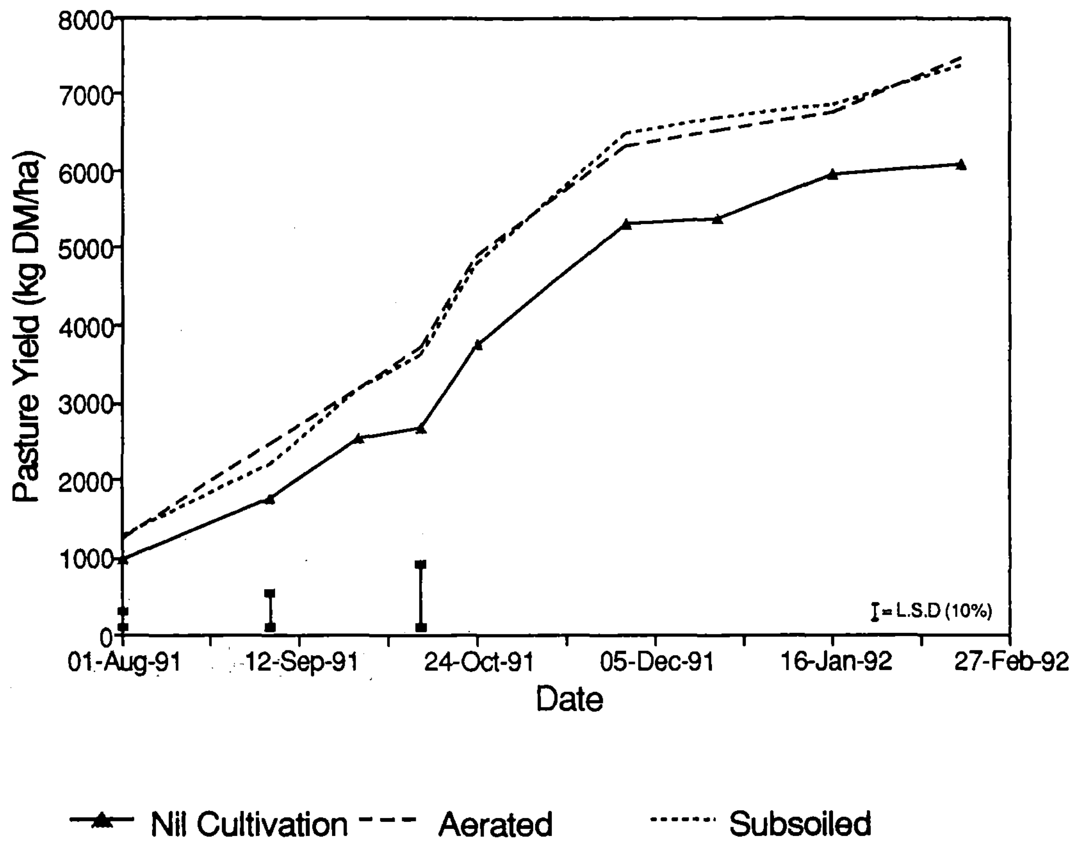

Figure 4.9: Cumulative pasture production of the cultivation treatments, 1991/1992 season (summed from 1-Aug-91).

The cumulative pasture production was significantly higher for the cultivated treatments (aerated and subsoiled) than the nil cultivation treatment on three dates, 1-Aug-91, 5-Sep-91 and 11-Oct-91 (Appendix 4.2). This is similar to Davies *et al.* (1989) who found that aeration (15 cm) increased pasture production over the English summer by 33%.

Pasture growth rate.

The pasture growth rates as affected by cultivation treatment are presented in Figure 4.10.

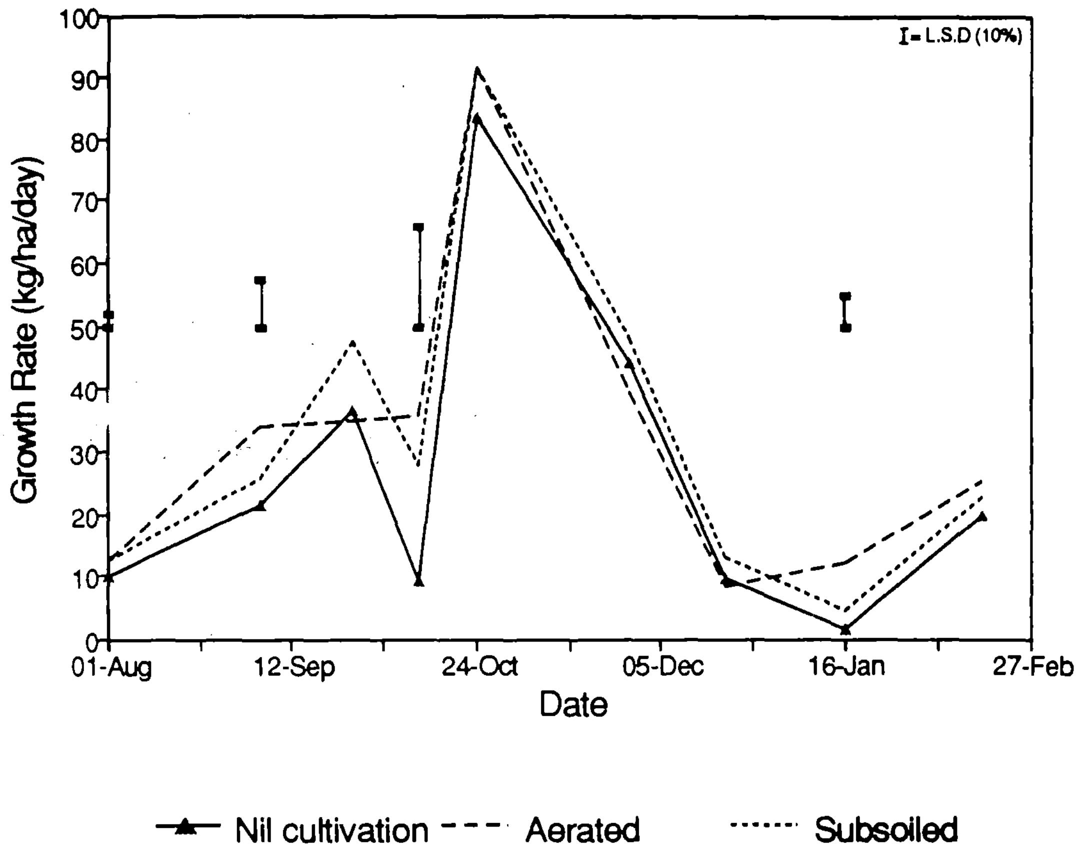

Figure 4.10: Pasture growth rates as affected by cultivation treatment, 1991/1992 season.

From 1-Aug-91 to 26-Sep-91 the soil temperature began to rise, as did the air temperature, thus signalling the beginning of spring growth. At this time (1-Aug-91 to 11-Oct-91) the subsoiled treatment consistently had a higher pasture growth rate than the nil cultivation treatment. The month of October was warmer than average (Cherry, 1991). There was no rainfall in October, however the soil profile had a sufficient water content to sustain a high pasture growth rate. Peak pasture growth rates (i.e. greater than 40 kg DM ha^{-1} d^{-1}) occurred between 11-Oct-91 and 28-Nov-91. However, from 24-Oct-91 the soil water content fell and the pasture growth dropped correspondingly (Appendix 4.3). On 16-Jan-92 when the soil profile was dry (10-12%, v/v) the aerated treatment had a significantly higher growth rate than the nil cultivation treatment.

4.3.1.2 Effect of fertiliser on pasture production.

The results of the fertiliser application on pasture production over the 18 month trial are presented in Table 4.6.

Harvest Date	Nil	P only	P & S	FProb	L.S.D (10%)
7-Nov-90	1063	1152	1117	NS	-
5-Dec-90	1407	1246	1436	NS	-
15-Jan-91	985	996	1213	NS	-
25-Feb-91	1146	1439	1288	NS	-
22-Apr-91	424	555	677	0.063	181.9
1-Aug-91	1115	1196	1227	NS	-
5-Sep-91	733	1051	1081	0.066	261.5
26-Sep-91	708	897	913	NS	-
11-Oct-91	305	411	381	NS	-
24-Oct-91	1200	1064	1210	NS	-
28-Nov-91	1415	1476	1647	NS	-
20-Dec-91	244	303	140	NS	-
16-Jan-92	135	201	173	NS	-
12-Feb-92	561	741	543	NS	-

Table 4.6: Pasture production (kg DM ha^{-1}) from 7-Nov-90 to 12-Feb-92 as affected by fertiliser treatment.

As expected the application of phosphate fertiliser (30 kg P ha^{-1}) alone or in combination with sulphate fertiliser (30 kg S ha^{-1}) generally increased pasture production.

The cumulative pasture production from the 18 month trial is presented Figure 4.11 (Appendix 4.2).

The effect of fertiliser was significant on four dates, 1-Aug-91, 5-Sep-91, 26-Sep-91 and 11-Oct-91. With the nil fertiliser treatment producing the least dry matter, and the combination of phosphate and sulphate fertiliser producing the highest dry matter production. The addition of sulphate fertiliser resulted in the largest dry matter production increase. Sulphur is deficient (Section 3.1.4) at this site, so a response to it's addition was to be expected.

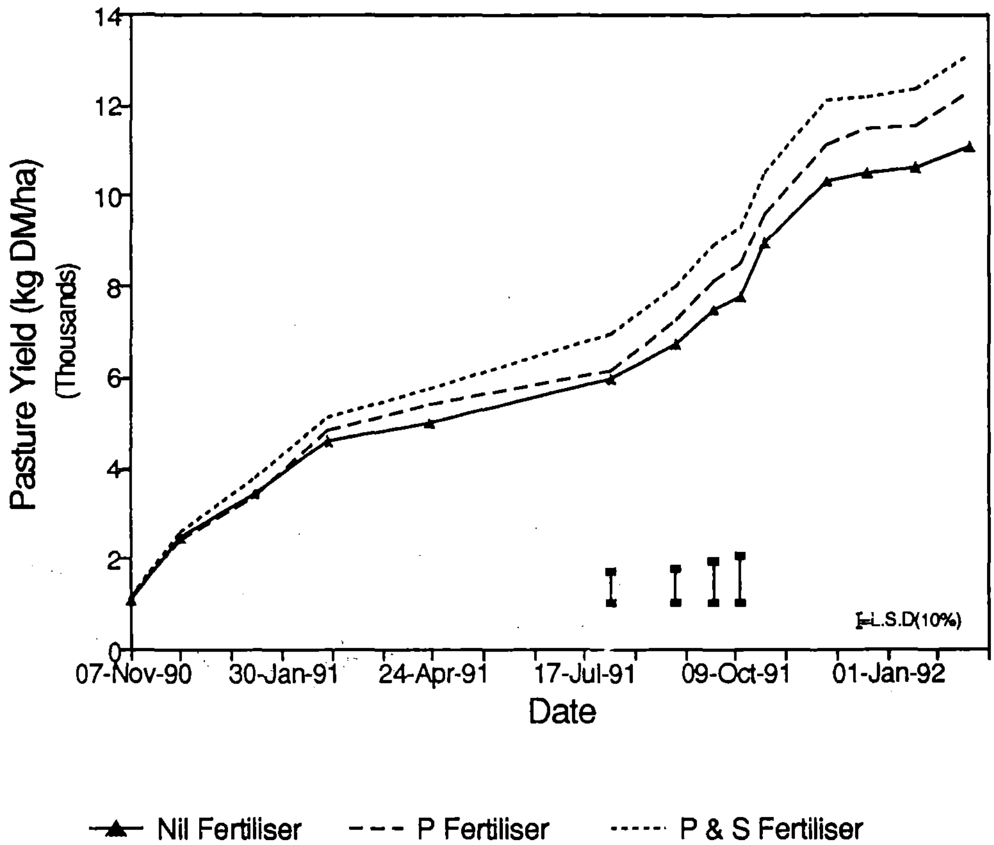

Figure 4.11: Cumulative pasture production as affected by fertiliser treatment, 7-Nov-90 to 12-Feb-92.

From Figure 4.11 it can be seen that fertiliser application significantly increased cumulative pasture yield during the 1991 spring, particularly the addition of sulphate fertiliser. During this time, even though it was a dry spring, water was not limiting, and high growth rates were recorded.

4.3.1.3 Cultivation and fertiliser interactions.

There were no significant pasture production interactions between the cultivation and fertiliser treatments over the 18 months of the trial (Table 4.7). Bowden (1986) observed positive responses in plant yield to nitrogen and soil loosening treatments but also found very little interaction between the two treatments. It was suggested that the rates of nitrogen used were not high enough to result in an interaction (Bowden, 1986).

Date	FProb
7-Nov-90	0.899
5-Dec-90	0.937
15-Jan-91	0.325
25-Feb-91	0.707
22-Apr-91	0.805
1-Aug-91	0.618
5-Sep-91	0.111
26-Sep-91	0.187
11-Oct-91	0.499
24-Oct-91	0.537
28-Nov-91	0.639
20-Dec-91	0.126
16-Jan-92	0.955
12-Feb-92	0.076

Table 4.7: Statistical significance tests (F-Probability values) for the cultivation and fertiliser interaction

4.3.1.4 Total dry matter production.

Cultivation treatment.

The effect, though not significant, of soil loosening (aeration and subsoiling) was to increase the pasture production by approximately 1,300 kg DM ha^{-1} over the dry 1991/1992 season (Table 4.8).

Cultivation Treatment		
Nil	Aerated	Subsoiled
6094	7487	7393

Table 4.8: Total pasture production (kg DM ha^{-1}) for the 1991/1992 season as affected by cultivation treatment.

Fertiliser treatment.

The effect of fertiliser application either as phosphorus alone or in combination with sulphur, though not significant, was to increase the pasture production during the 1991/1992 season by approximately 1,100 kg DM ha^{-1} (Table 4.9).

Fertiliser Treatment		
Nil	P only	P & S
6201	7372	7401

Table 4.9: Total pasture production (kg DM ha^{-1}) for the 1991/1992 season as affected by fertiliser treatment.

4.3.1.5 Relative pasture yield.

The relative pasture yield was calculated over the 1991/1992 season using Equation 4.1:

$$\text{Relative Yield} = \frac{Y_s - Y_n \times 100}{Y_n} \qquad \textbf{(Equation 4.1)}$$

Where: Y_s = Pasture yield of the subsoiled or aerated treatment (kg DM ha^{-1})

Y_n = Pasture yield nil cultivation treatment (kg DM ha^{-1}).

From Table 4.10 it can be seen that the subsoiled treatment consistently had a higher relative yield, while the aerated treatment was more variable in response. The cultivated treatments of aeration and subsoiling had higher dry matter yields during the 1991/1992 season than the nil cultivation treatment.

Date	Aerated (%)	Subsoiled (%)
1-Aug-91	29	29
5-Sep-91	56	18
26-Sep-91	-	30
11-Oct-91	294	201
24-Oct-91	10	10
28-Nov-91	-	8
20-Dec-91	-	33
16-Jan-92	594	169
12-Feb-92	28	16
Total	12	10

Table 4.10: Relative pasture yield of the aerated and subsoiled treatments for the 1991/92 season.

4.3.2 Pasture composition.

The results from the three pasture dissections are presented in Table 4.11.

	Nil (%)	Aerated (%)	Subsoiled (%)	FProb	L.S.D (10%)
Date: 7-Nov-90					
Grass	72.1	71.9	69.1	NS	-
Clover	19.1	19.0	16.7	NS	-
Weeds	3.3	3.9	8.4	0.080	4.01
Dead	5.5	5.3	5.8	NS	-
Date: 22-Apr-91					
Grass	48.5	50.5	44.5	NS	-
Clover	18.4	21.1	26.5	0.039	5.17
Weeds	9.0	7.0	7.6	NS	-
Dead	24.1	21.4	20.5	NS	-
Date: 12-Feb-92					
Grass	43.3	41.6	30.6	0.003	6.04
Clover	8.7	11.9	11.5	NS	-
Weeds	10.6	5.6	11.1	NS	-
Dead	35.1	38.0	42.0	0.008	3.39
Other Grass	4.8	2.9	4.5	NS	-

Table 4.11: Pasture composition as affected by cultivation treatment at the three sampling dates.

On 7-Nov-90 approximately one month after cultivation there was a significantly higher proportion of weeds in the subsoiled treatment. This was brought about by the soil disturbance, created in the subsoiling process, exposing weed seeds to the sunlight. On 22-Apr-91 the subsoiled cultivation treatment had a significantly higher proportion of clover than the nil cultivation treatment.

All treatments had a large proportion of dead material on 12-Feb-92. This was due to the high death rate of plant material over the dry January in 1992. This was created by the high pasture production in December 1991 that could not be sustained due to lack of water in January 1992 (Section 4.6.1).

4.4 Pasture Root Length.

4.4.1 Total profile root length.

There were no significant differences in total profile (0-100 cm) root length (cm cm^{-2}) between cultivation treatments from 5-Aug-91 to 18-Jan-92 (Appendix 4.5). Symons (1988) and Greenwood (1989) found that in some cases although subsoiling resulted in changes to vertical root distribution, it had no effect on total root length. Ide *et al.* (1984) also found although total root weights on the control and subsoiled plots were similar, there was a significant difference in the vertical root distribution. In the study by Ide *et al.* (1984) on the subsoiled plot, root weight in the first horizon (0-25 cm) was 20% smaller, but in the second (25-50 cm) and third (50-75 cm) horizons 125% and 325%, respectively, higher than the control.

Pasture root growth rate was calculated by subtracting the total root length (cm cm^{-2}) on the 1-Aug-91 from the total root length (cm cm^{-2}) on the 18-Jan-92.

4.4.2 The effect of cultivation on root distribution in the profile.

On 5-Aug-91 there was no significant differences in root length (cm cm^{-2}) between cultivation treatments (Figure 4.12) (Appendix 4.5).

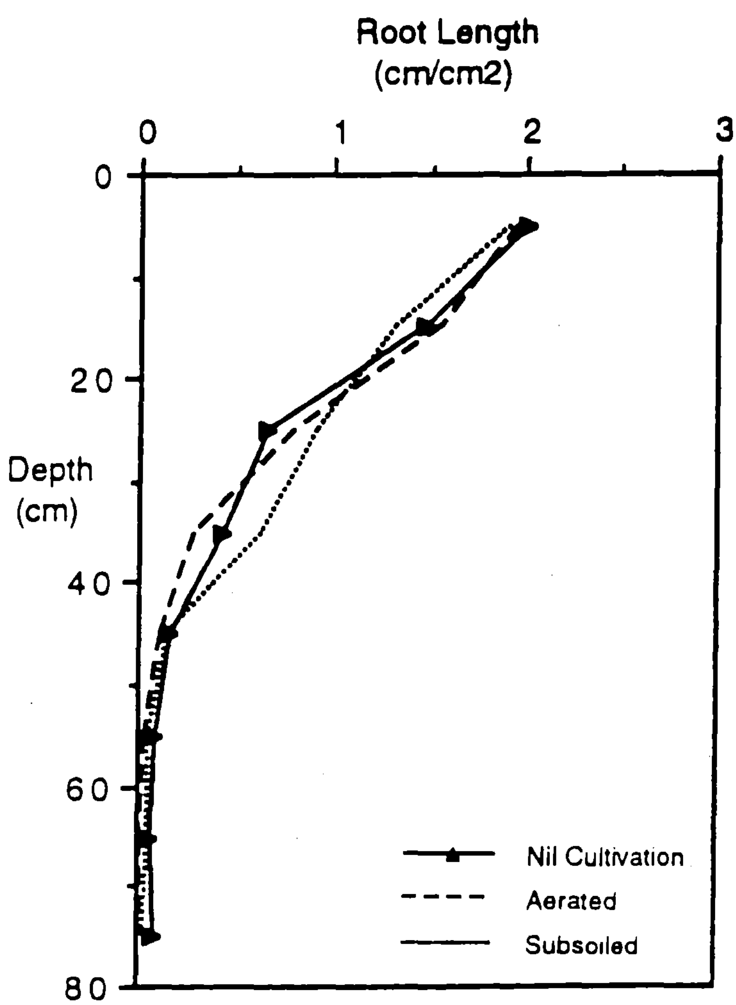

Figure 4.12: Root length as affected by cultivation treatment, 5-Aug-91.

By 29-Nov-91 significant differences had developed between cultivation treatments at the 20-80 cm depth (Figure 4.13).

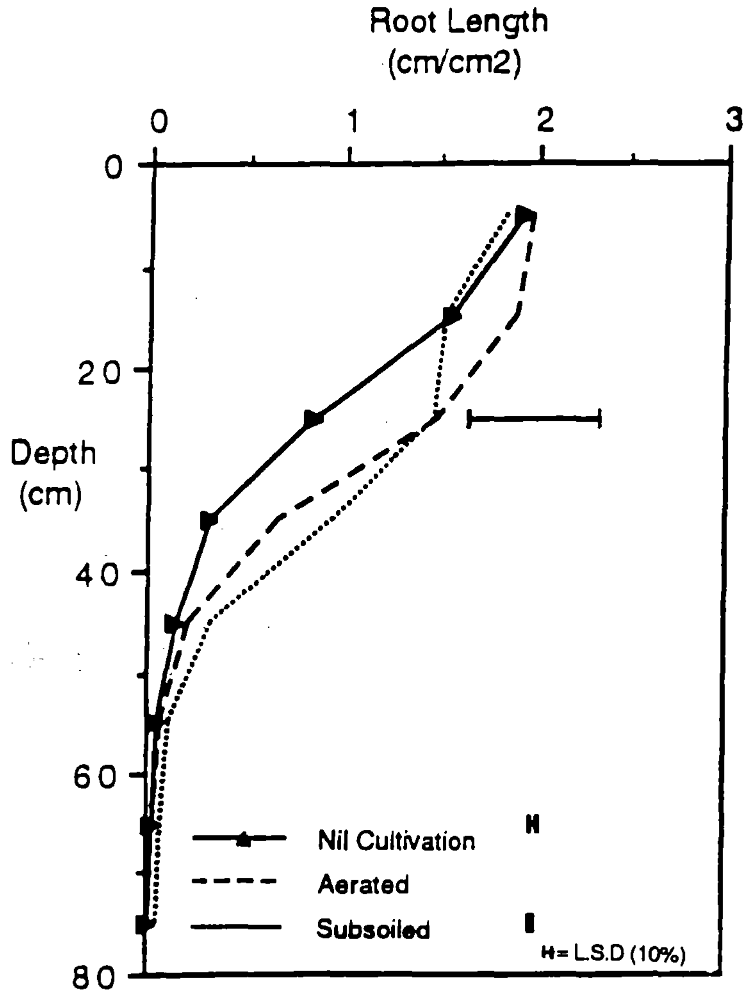

Figure 4.13: Root length as affected by cultivation treatment, 29-Nov-91.

At the 20 to 30 cm and 60 to 80 cm depths the subsoiled cultivation treatment had a significantly greater root length than the nil cultivation treatment. Although not significant the differences in root length from 30 cm to 60 cm are also apparent with the subsoiled cultivation treatment having the higher root lengths. The aerated (27 cm) cultivation treatment had greater root length at 10 to 20 cm compared with the other two treatments. At 20 to 40 cm the root length of the aeration treatment was similar to the subsoiled (47 cm) treatment and greater than the nil cultivation treatment. At 50 cm the aeration treatment was similar to the nil cultivation treatment. The greater root length of the subsoiled cultivation treatment compared to the nil cultivation treatment suggests that the subsoiled cultivation treatment had a greater root growth below 50 cm from 5-Aug-91. These differences remained apparent throughout the 1991/1992 season and became more pronounced by 18-Jan-92 (Figure 4.14).

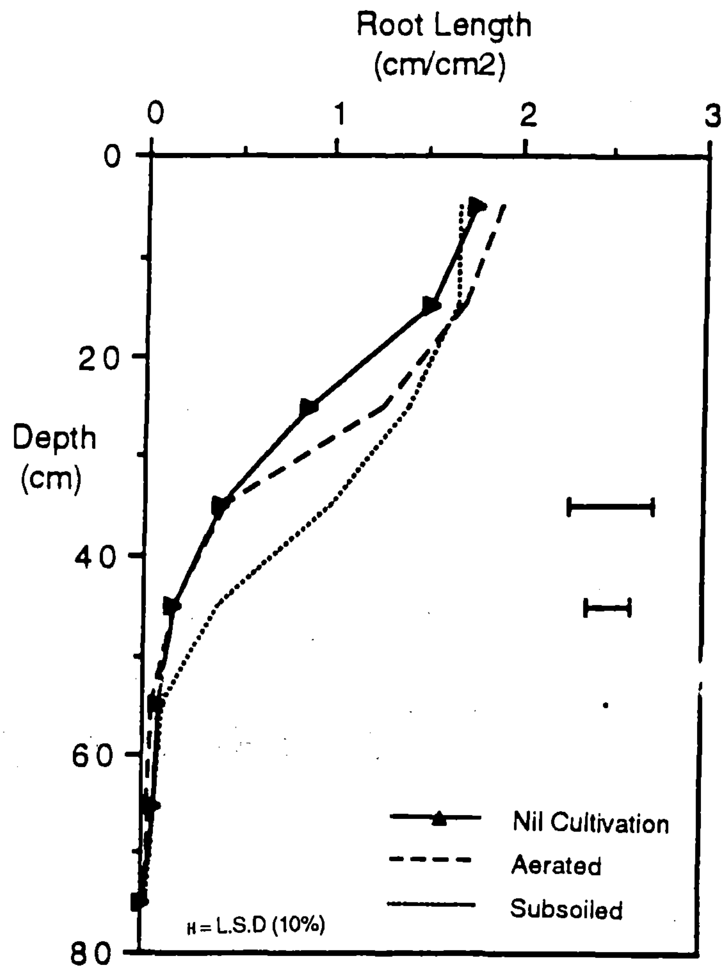

Figure 4.14: Root length as affected by cultivation treatment, 18-Jan-92.

On the 18-Jan-92 the subsoiled cultivation treatment had a very different pattern of root length distribution compared to the nil cultivation treatment. The subsoiled treatment had significantly less root length in the top 10 cm of the soil profile, but significantly more from 30 to 50 cm. The aerated cultivation treatment had a similar root length at 20-30 cm to the subsoiled treatment, but at 40 cm resumed a pattern similar to the nil cultivation treatment.

4.4.3 Relative vertical distribution of root length.

The relative vertical distribution is defined as the percentage of total profile root length present in each 10 cm depth increment (Appendix 4.6).

On 5-Aug-91 there was no significant difference in the relative vertical distribution of the pasture roots between cultivation treatments (Figure 4.15).

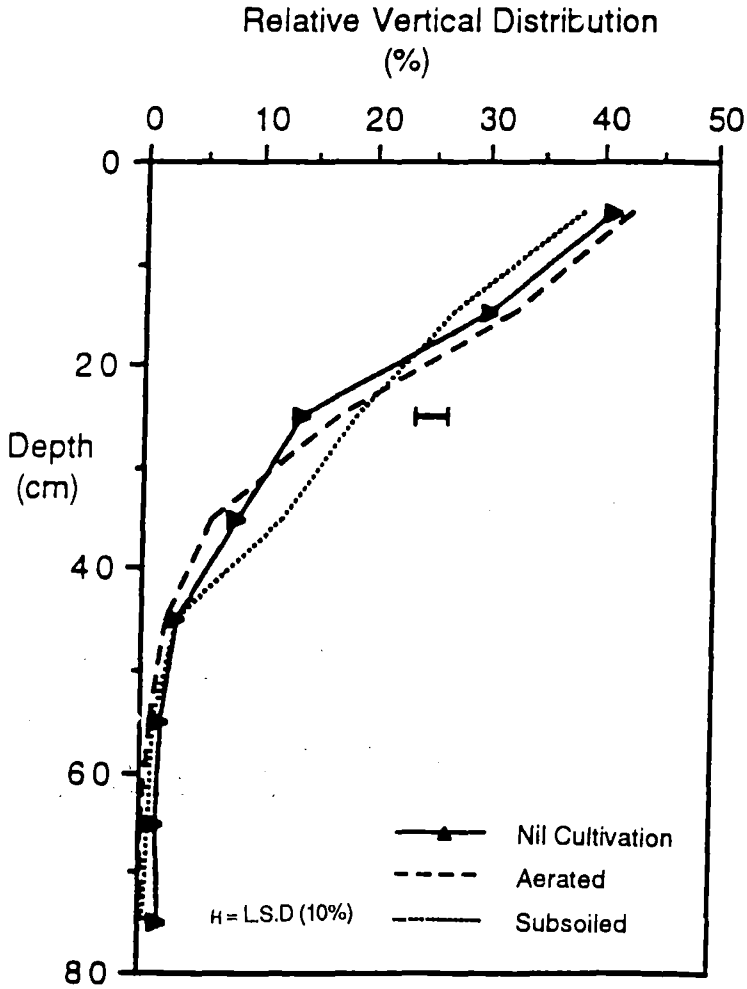

Figure 4.15: Relative vertical distribution of pasture roots as affected by cultivation treatment, 5-Aug-91.

On 5-Aug-91 all treatments had approximately 40% of their root length between 0-10 cm, by 18-Jan-92 this had fallen in all treatments, with the subsoiled cultivation treatment having significantly less than the nil cultivation treatment (Table 4.12).

Date	Cultivation Treatment			L.S.D
	Nil	Aerated	Subsoiled	(10%)
5-Aug-91	41	42	38	NS
18-Jan-92	36	31	27	6.6
Decrease	5	11	11	-

Table 4.12: Percentage (%) and change of root length present in the top 10 cm of the soil profile between 5-Aug-91 and 18-Jan-92 as affected by cultivation treatment.

The relative vertical distribution of roots on 29-Nov-91, suggests a higher root growth rate from the 5-Aug-91 in the subsoiled cultivation treatment compared to the nil cultivation treatment (Figure 4.16). These increased root growth rates occurred largely in depths that were previously inaccessible for root growth due to the high bulk density of the soil, for example 30-40 cm and 60-80 cm.

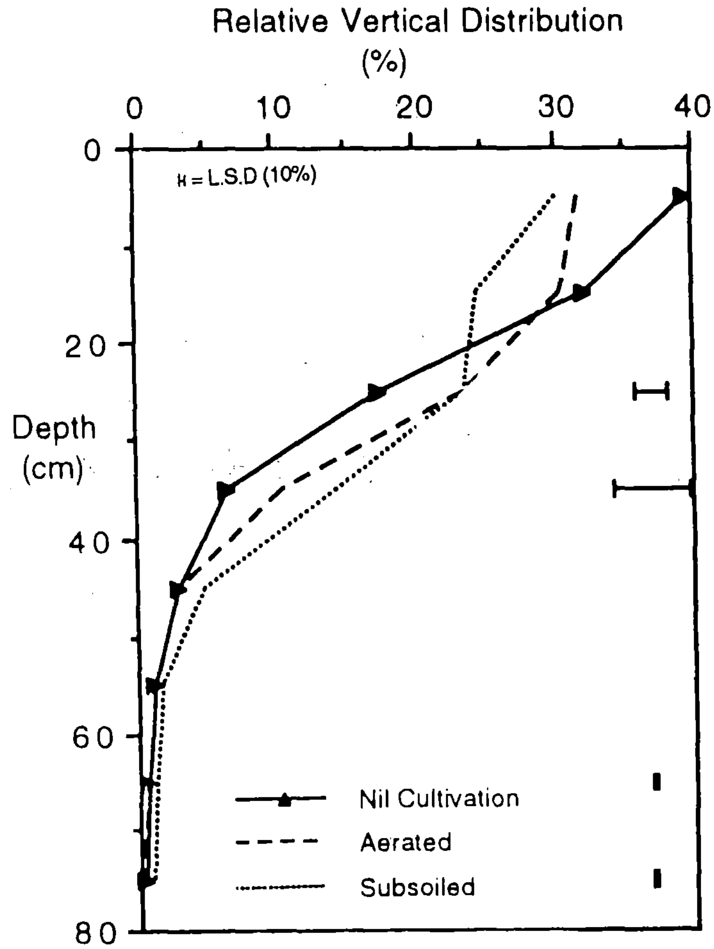

Figure 4.16: Relative vertical distribution of pasture roots as affected by cultivation treatment, 29-Nov-91.

The subsoiled treatment consistently had a higher percentage of roots between 30-40 cm depth in the 1991/1992 season than the aerated and nil treatments which had similar values (Table 4.13).

Date	Cultivation Treatment			L.S.D
	Nil	Aerated	Subsoiled	(10%)
5-Aug-91	8	6	12	3.0
5-Sep-91	7	6	11	NS
3-Oct-91	9	7	14	1.7
30-Oct-91	10	10	13	1.7
29-Nov-91	6	10	10	5.4
18-Dec-91	7	9	12	NS
18-Jan-92	8	8	16	3.2

Table 4.13: Percentage (%) of total root length present at the 30-40 cm depth in the soil profile as affected by the cultivation treatments.

On 18-Jan-92 the subsoiled treatment had a very different relative vertical distribution of roots compared to the nil and aerated cultivation treatments (Figure 4.17).

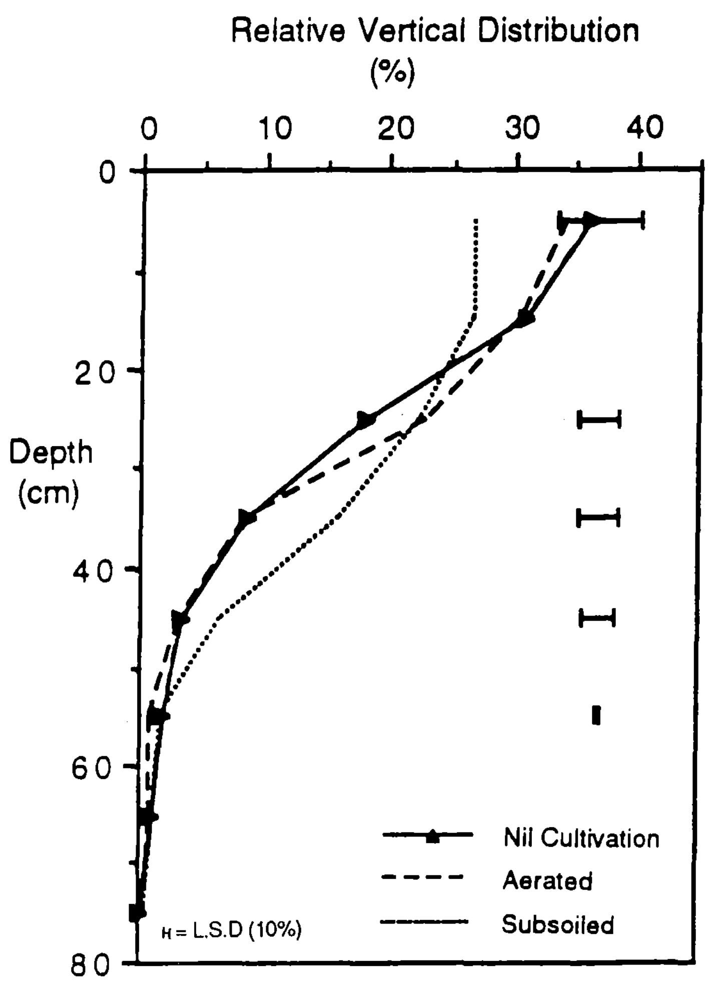

Figure 4.17: Relative vertical distribution of pasture roots as affected by cultivation treatment, 18-Jan-92.

In the subsoiled cultivation treatment 35% of root length was below 25 cm, that is within the B-horizon (Table 4.14). In the nil and aerated cultivation treatments only 25-28% of the root length was within the B-horizon.

Depth (cm)	Cultivation Treatment				L.S.D (10%)
	Nil	Aerated	Subsoiled	FProb	
0-10	36.3	34.2	26.6	0.072	6.61
10-20	31.1	32.5	26.7	NS	-
20-30	18.1	22.8	22.2	0.079	3.40
30-40	8.4	8.2	15.8	0.011	3.16
40-50	3.2	2.9	6.1	0.010	2.57
50-60	1.7	0.7	1.5	0.012	0.39
60-70	0.99	0.44	0.78	NS	-
70-80	0.13	0.22	0.35	NS	-

Table 4.14: Relative vertical distribution (%) of pasture roots as affected by cultivation treatment, 18-Jan-92.

4.4.4 Maximum rooting depth.

Maximum rooting depth is defined as the depth in the soil profile above which 99% of the root length (cm cm^{-2}) exists.

Maximum rooting depth was highly variable over the 1991/1992 season (Appendix 4.7). The change in maximum rooting depth over the 1991/1992 season is shown in Table 4.15. The maximum rooting depth of the nil cultivation treatment decreased by 15 cm over the dry 1991/1992 season.

Date	Cultivation Treatment		
	Nil	Aerated	Subsoiled
5-Aug-91	73	45	63
18-Jan-92	58	50	62
Change	$^{-}15$	$^{+}5$	$^{+}1$

Table 4.15: Maximum rooting depth (cm) and change in rooting depth between 5-Aug-91 and 18-Jan-92, as affected by cultivation treatment.

4.5 Pasture Root Density.

The pasture root length/density calibration data sets (Section 3.3.5) were examined in an attempt to provide a method of calculation of root density for all the sampling dates, (i.e. when only root length was measured).

4.5.1 Root density calibration curves.

The relationship between root length (cm cm^{-2}) and root density (cm cm^{-3}), was considered to be in the form described by a Gompertz equation (Equation 4.2) To graphically represent the Gompertz equation the X-parameter was considered as density and the Y-parameter as root length (Sedcole, 1992, *pers. comm.*)

$$y = (C*Exp(-Exp(-B*(X-M))$$

(Equation 4.2)

Where:
Y=length (cm cm^{-2})
X=density (cm cm^{-3})
C=variable parameter
B=variable parameter
M=variable parameter.

Each cultivation treatment was found to have different values for each of the Gompertz equation parameters (Table 4.16). This suggested different root distribution patterns were created by the cultivation treatments (Figure 4.18). These differences where brought about by the different effects of loosening on the lower soil profile.

Treatment	r^2	Gompertz Equation
Aerated	0.97	Length = (2.3261*Exp(-Exp(-3.377*(Density-0.4847)))
Subsoiled	0.92	Length = (1.9440*Exp(-Exp(-3.825*(Density-0.3989)))
Nil	0.91	Length = (1.5074*Exp(-Exp(-2.466*(Density-0.4847)))

Table 4.16: The Gompertz equations for the different cultivation treatments.

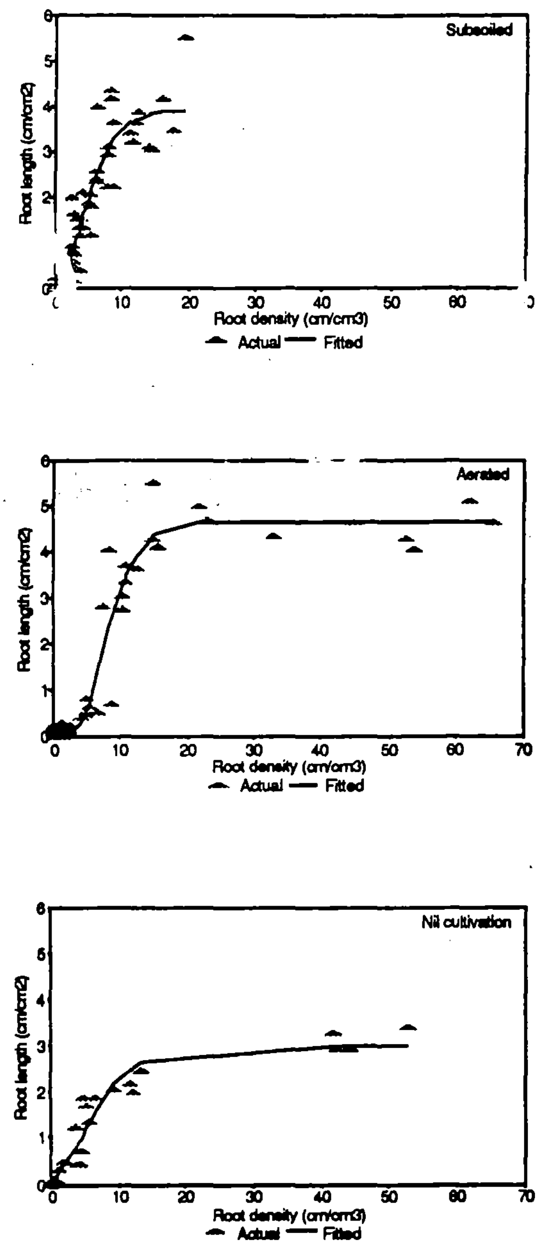

Figure 4.18: Relationships between root length (cm cm^{-2}) and root density (cm cm^{-3}) using the Gompertz equation for each cultivation treatment.

4.5.2 Calculation of root densities and associated problems.

The calculated root densities are presented in Appendix 8, here we will concentrate on two dates only 5-Aug-91 and 18-Jan-92. The Gompertz equation was rearranged as (Sedcole, 1992, *pers. comm.*):

```
Density = (M-(1/B)*Log(Log(C/Length)))
```

(Equation 4.3)

When the root densities were calculated two problems arose:

(i) The density could not be calculated if the root length was above the value of the C parameter;

(ii) below a certain root length the root density became negative, that is where the fitted Gompertz curve crossed the Y-axis above zero (Table 4.17) (Appendix 4.8).

Limiting Root Length	Cultivation treatment		
	Nil	Aerated	Subsoiled
Lower limit	0.05535	0.00003	0.01956
Upper limit	1.50740	2.32610	1.94400

Table 4.17: Upper and lower root length (cm cm^{-2}) limits of the Gompertz equations to calculating root densities for the cultivation treatments.

An attempt was made to calculate a linear equation from the lower end of the Gompertz curve, thus forcing the curve through zero, however this proved unsuccessful.

These two problems created difficulties with the statistical analysis at certain depths (Table 4.18).

Depth (cm)	Cultivation Treatment				L.S.D (10%)
	Nil	Aerated	Subsoiled	FProb	
0-10	1.000	1.000	1.000	NR	-
10-20	0.960	1.200	0.720	NR	-
20-30	0.733	0.874	0.716	NR	-
30-40	0.372	0.564	0.516	NR	-
40-50	0.146	0.421	0.272	0.042	0.129
50-60	0.201	0.296	0.106	0.005	1.124
60-70	0.140	0.280	0.010	NR	-
70-80	0.220	0.220	0.220	NR	-

NR = no result calculated by Genstat 5 due to an excess of missing values.

Table 4.18: Calculated root densities (cm cm^{-3}) as affected by cultivation treatment, 18-Jan-92.

The trend that emerged from the calculated root densities was for the aerated cultivation treatment to have higher root densities at all depths, often significantly higher than the subsoiled or nil cultivation treatments (Figure 4.19) (Appendix 4.8).

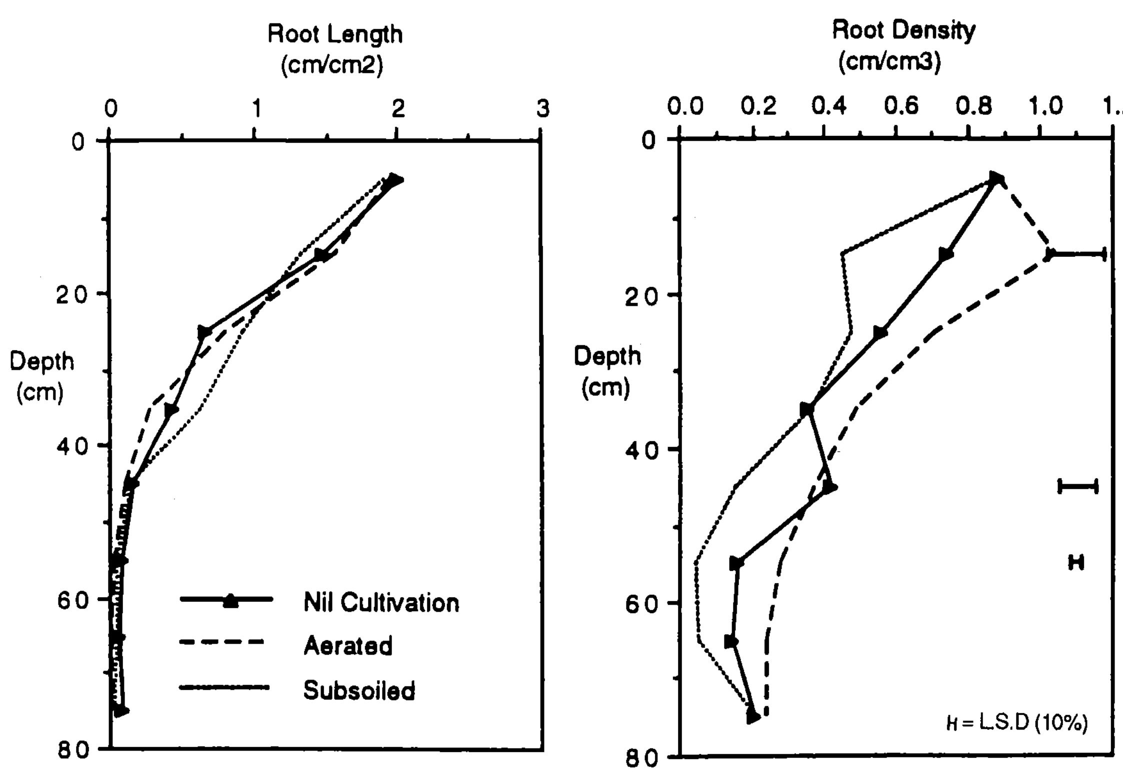

Figure 4.19: Root lengths and densities as affected by cultivation treatment, 5-Aug-91.

However, because of the limited sampling conducted it is impossible to conclude whether this was a true trend in root densities. The trend continued through all dates on which root densities were calculated (Figure 4.20). The root density pattern is very different from the one shown by the root length.

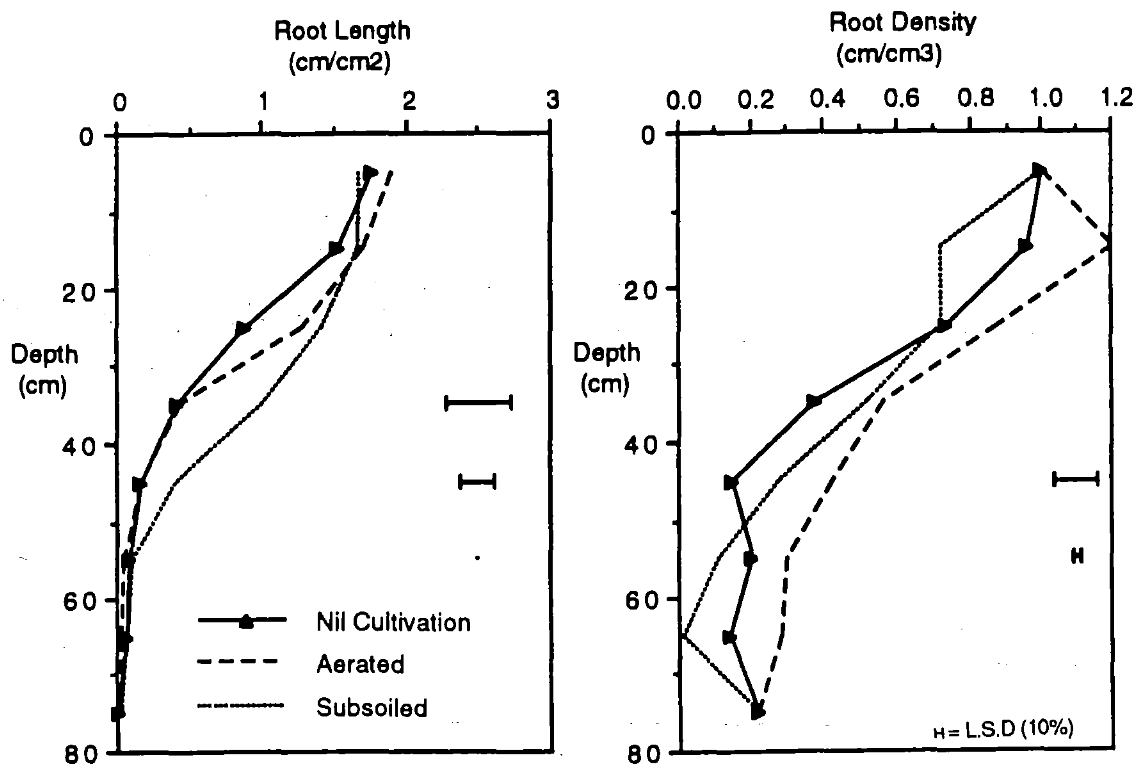

Figure 4.20: Root lengths and densities as affected by cultivation treatment, 18-Jan-92.

4.5.3 Criticism of method and suggestions for further work.

This method of calibrating and calculating root densities from root length measurements, has the potential to produce useful, accurate results, from limited destructive sampling, thus allowing seasonal trends in root growth to be followed.

In the experiment reported here , however not enough root density samples where taken to create an equation to convert the large range of root length measurements into densities. For this method to have been successful a wider range of root density samples was required. To achieve this, root density samples would need to have been collected in the spring and in the summer, particularly in depths where high values and very low values of root density occurred. In this study only one sampling occurred. At this sampling 80 samples per cultivation treatment were taken. The limiting factor is the time taken to count root density using the root intersect method of Tennant (1975).

4.6 Water.

4.6.1 Soil profile water content.

Soil profile (0-70 cm) volumetric water contents are presented in Table 4.19. The soil profile in the subsoiled (47 cm) cultivation treatment was significantly drier than the nil cultivation treatment during the 1991/1992 season (Figure 4.21).

	Cultivation Treatment				
Date	Nil (%, v/v)	Aerated (%, v/v)	Subsoiled (%, v/v)	FProb	L.S.D (10%)
31-Jul-91	33.62	32.15	31.76	NS	-
14-Aug-91	30.45	29.45	28.37	NS	-
23-Aug-91	31.61	30.03	28.80	0.083	1.644
29-Aug-91	30.05	28.79	27.93	0.080	1.228
05-Sep-91	29.97	28.53	27.82	NS	-
16-Sep-91	28.87	27.95	27.60	NS	-
23-Sep-91	28.25	27.38	25.95	0.013	0.975
30-Sep-91	27.70	26.58	24.99	0.003	0.826
14-Oct-91	25.33	23.38	21.42	0.002	1.082
18-Oct-91	23.73	21.78	19.40	0.002	1.108
25-Oct-91	21.85	20.08	16.93	0.002	1.310
01-Nov-91	19.93	18.28	15.33	0.005	1.562
08-Nov-91	23.6	22.30	18.02	0.014	2.029
21-Nov-91	20.23	19.25	14.65	0.018	2.356
04-Dec-91	20.01	18.98	14.33	0.018	2.400
10-Dec-91	19.27	18.55	14.13	0.034	2.674
19-Dec-91	18.35	17.80	13.51	0.040	2.672
23-Dec-91	17.59	17.00	12.73	0.046	2.787
13-Jan-92	18.25	18.05	14.43	0.044	2.460
17-Jan-92	16.06	15.82	12.33	0.035	2.237
22-Jan-92	15.47	15.50	12.75	NS	-
03-Feb-92	13.96	14.62	11.35	0.032	1.814
10-Feb-92	14.11	14.45	11.48	0.028	1.650
18-Feb-92	14.11	15.18	11.68	0.062	2.261

Table 4.19: Soil profile (0-70 cm) volumetric water content as affected by cultivation treatment.

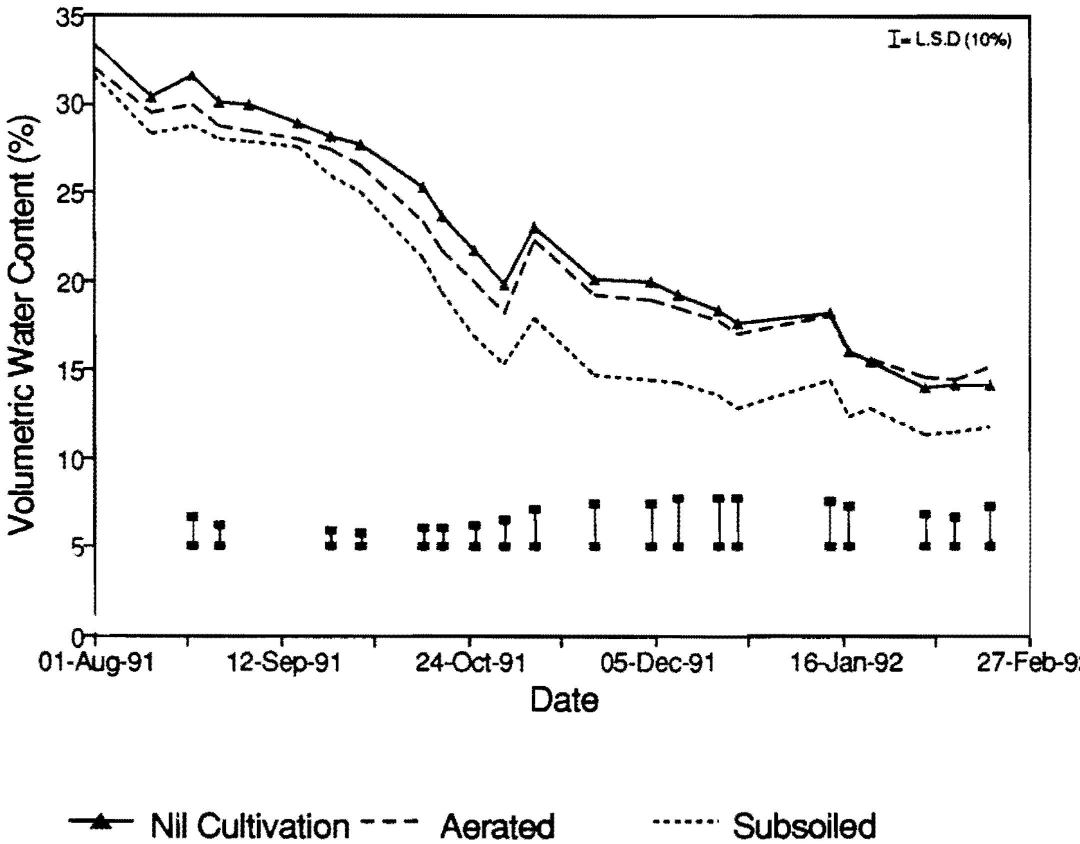

Figure 4.21: Soil profile (0-70 cm) volumetric water content as affected by the cultivation treatment, 1991/1992 season.

The soil profile was at field capacity (33%, v/v) (Thomas, 1993, *pers. comm.*) on the 1-Aug-91 and there was no significant difference between treatments on this date. Throughout the 1991/1992 season the subsoiled cultivation treatment was consistently drier, compared to the nil or aerated cultivation treatments. The subsoiled cultivation treatment in this trial continued to have a "drier" soil profile (0-70 cm) due to the higher porosity leading to higher drainage rates from the soil profile (Section 4.4.2 and Section 4.2.2). O'Sullivan (1992) also found that deep cultivation resulted in a drier soil profile (0-60 cm) compared to no cultivation. Delroy and Bowden (1986) reported that plants growing in soil which had been loosened (ripped) utilised more water from depth than plants grown in the control (non-ripped) plots.

4.6.2 Effect of cultivation on soil profile water content distribution.

The soil profile was divided into six depth increments: 0-20, 20-30, 30-35, 35-40, 40-50, 50-70 cm and the volumetric water content at each depth calculated using equation 4.4:

$$\theta = \frac{(D_2 \times \theta_2) - (D_1 \times \theta_1)}{(D_2 - D_1)}$$

(Equation 4.4)

where: D_2 = 2nd depth (cm)
D_1 = 1st depth (cm)
θ_2 = 2nd depth moisture content (%, v/v)
θ_1 = 1st depth moi ture content (%, v/v).

The vertical distribution (%) of water in each depth in the soil profile was then calculated as:

$$x = \frac{\theta}{\theta_t} \times \frac{100}{1}$$

(Equation 4.5)

where: θ_t = total profile water content (%, v/v)
θ = water content at the desired depth (%, v/v).

By the 19-Dec-91 the soil profile water content was rapidly decreasing. The loosened treatments (aeration and subsoiling) had the largest proportion of their water between 0-20 cm and between 50-70 cm (Figure 4.22).

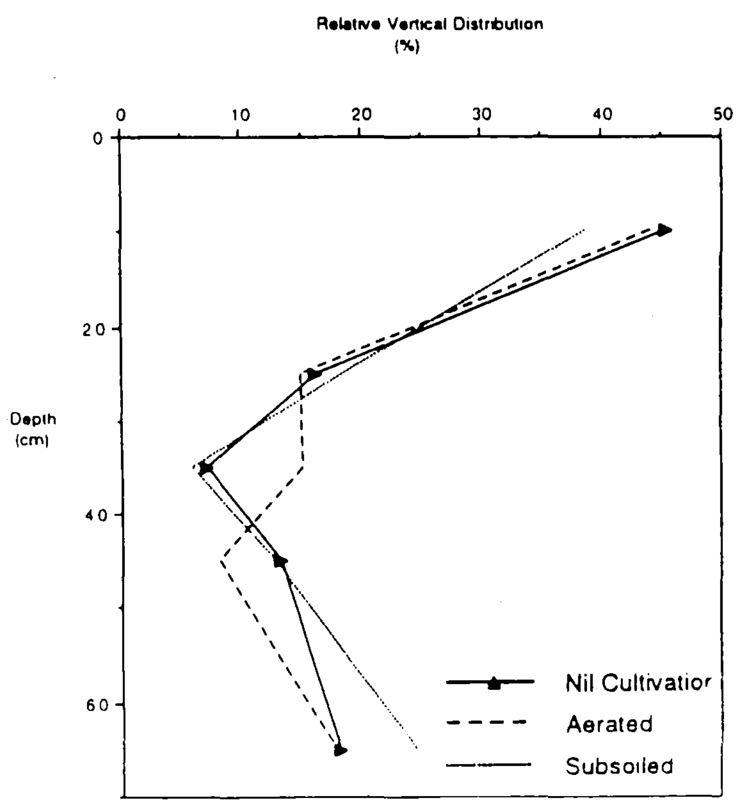

Figure 4.22: Vertical distribution of soil profile water as affected by cultivation treatment, 19-Dec-91.

However by 16-Jan-92 the top soil horizons had dried out considerably, the water that remained was below 40 cm in the soil profile (Figure 4.23). This pattern was the same for the three cultivation treatments.

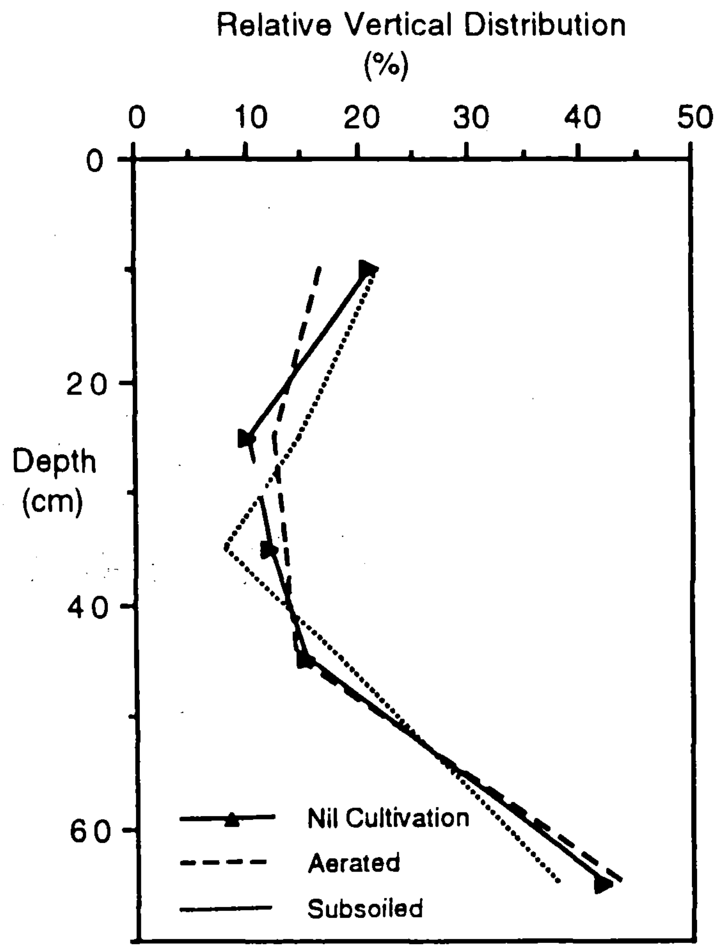

Figure 4.23: Vertical distribution of soil profile water as affected by cultivation treatment, 16-Jan-92.

4.6.3 Water use.

Water use was calculated using Equation 4.6 (Greenwood, 1989).

$$WU = P + I - \Delta W - R_o - D$$

(Equation 4.6)

where:

WU = water use (mm)
P = rainfall (mm) (Section 4.1.1)
I = irrigation (mm)
ΔW = change in soil water content (0-70 cm) (mm)
R_o = surface runoff (mm)
D = drainage (mm).

From the 1-Aug-91 to 18-Feb-92, irrigation, surface runoff and drainage were all assumed to be zero thus creating a simple water balance equation:

$$WU = P - \Delta W \qquad \textbf{(Equation 4.7)}$$

Weekly totals of rainfall and ΔW were used in Equation 4.7 and the results are presented in Table 4.20. No significant differences in water use occurred at any date during the 1991/1992 season.

	Cultivation treatment		
Date	Nil (mm)	Aerated (mm)	Subsoiled (mm)
31-Jul-91	0.0	0.0	0.0
14-Aug-91	34.3	26.3	28.0
23-Aug-91	7.1	7.4	9.0
29-Aug-91	14.8	5.3	9.2
05-Sep-91	8.2	9.2	8.2
16-Sep-91	7.9	10.0	3.7
23-Sep-91	15.4	7.7	23.1
30-Sep-91	7.9	11.0	10.0
14-Oct-91	20.6	21.0	29.9
18-Oct-91	16.2	12.3	19.8
25-Oct-91	14.3	12.7	18.6
01-Nov-91	50.3	48.5	48.1
08-Nov-91	0.0	0.0	0.0
21-Nov-91	35.8	25.3	36.7
04-Dec-91	46.3	55.7	42.8
10-Dec-91	7.5	4.4	4.4
19-Dec-91	9.4	8.8	6.2
23-Dec-91	42.5	42.3	43.8
13-Jan-92	8.0	5.8	6.3
17-Jan-92	24.9	24.5	23.3
22-Jan-92	9.0	7.1	7.5
03-Feb-92	32.7	28.0	25.2
10-Feb-92	6.5	8.2	7.0
18-Feb-92	2.2	4.1	0.1

Table 4.20: Water use over the 1991/1992 season as affected by cultivation treatment.

4.6.3.1 Cumulative water use.

The cumulative water use for each cultivation treatment is presented in Figure 4.24.

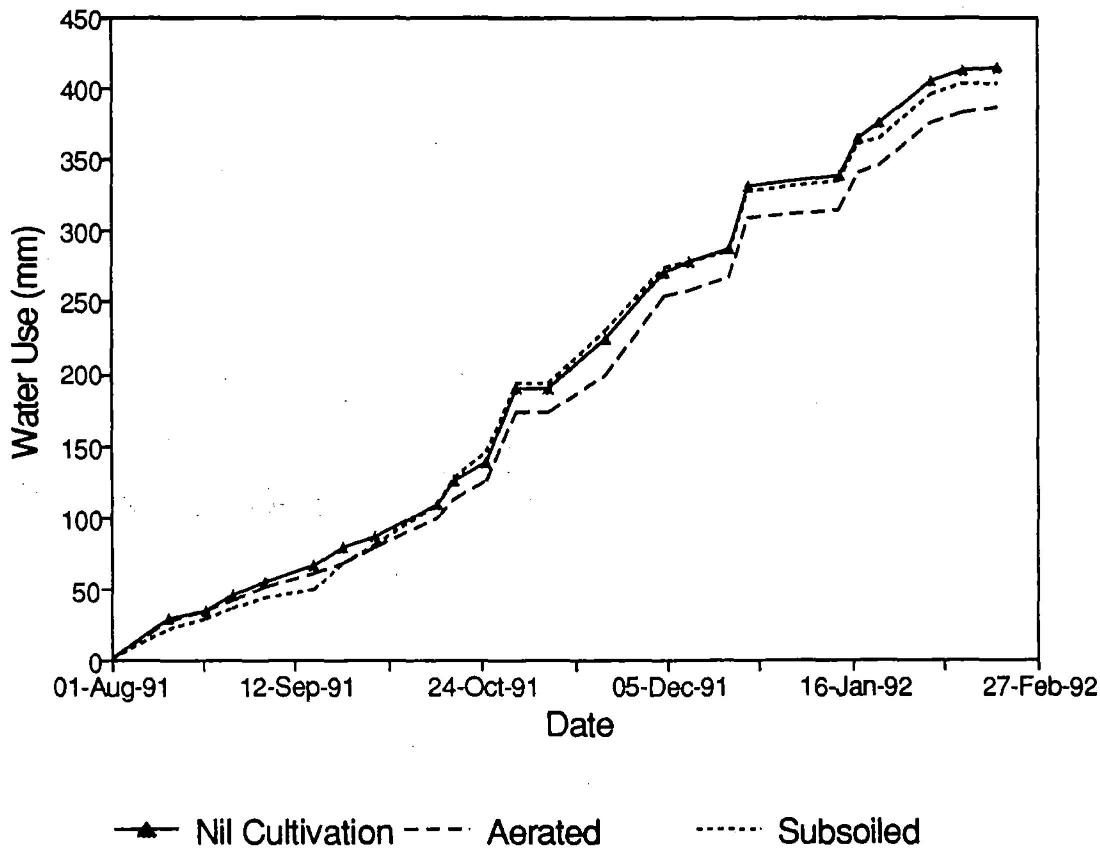

Figure 4.24: Cumulative water use over the 1991/1992 season as affected by cultivation treatment.

There were no significant differences in water use over the 1991/1992 season. Despite this, the subsoiled cultivation treatment produced a greater pasture mass (2,700 kg DM ha^{-1}) than the nil cultivation treatment (2,300 kg DM ha^{-1}) between November 1991 and late December 1991.

Martin (1990) has shown that for pasture grown on a Templeton silt loam, soil moisture extraction occurred mainly from the top 45 to 60 cm of soil at low water deficits. As the soil dried during summer, progressively more moisture was taken up from lower down the profile (to a depth of 1.05 m). During the experiment reported here, soil moisture content was only measured to a depth of 70 cm. All cultivation treatments are known to have had pasture roots present below 70 cm (Section 4.4.2). It is possible that the higher pasture production of the subsoiled cultivation compared to nil cultivation treatment was sustained from water extracted below 70 cm.

However from the results presented it seems unlikely that a difference in water use was the prime factor contributing to the greater pasture production of the subsoiled treatment.

4.6.3.2 Water use efficiency.

Water use efficiency (kg DM mm^{-1} Water Use) is presented in Table 4.21.

Cultivation Treatment		
Nil	Aerated	Subsoiled
16.6	20.1	17.1

Table 4.21: Water use efficiency (kg DM mm^{-1} Water Use) as affected by the cultivation treatment, 1-Aug-91 to 12-Feb-92.

There were no significant differences of water use efficiency between cultivation treatments over the 1991/1992 season.

4.7 Macronutrients.

4.7.1 Macronutrient concentration.

4.7.1.1 Effect of cultivation on macronutrient concentration.

Nitrogen.

There was no significant effect of cultivation on nitrogen concentration of the mixed pasture (grass, clover and weeds) at any sampling date throughout the 1991/1992 season (Figure 4.25) (Appendix 4.10). However, there was a trend for plants grown in the subsoiled and aerated cultivation treatments to have a higher concentration of nitrogen during the summer months (28-Nov-91 to 12-Feb-92). The nitrogen concentration of the pasture herbage increased in early spring then declined to lower levels during the late spring/early summer months (Figure 4.25). This seasonal trend is similar to results reported by others (Ledgard *et al.*, 1990).

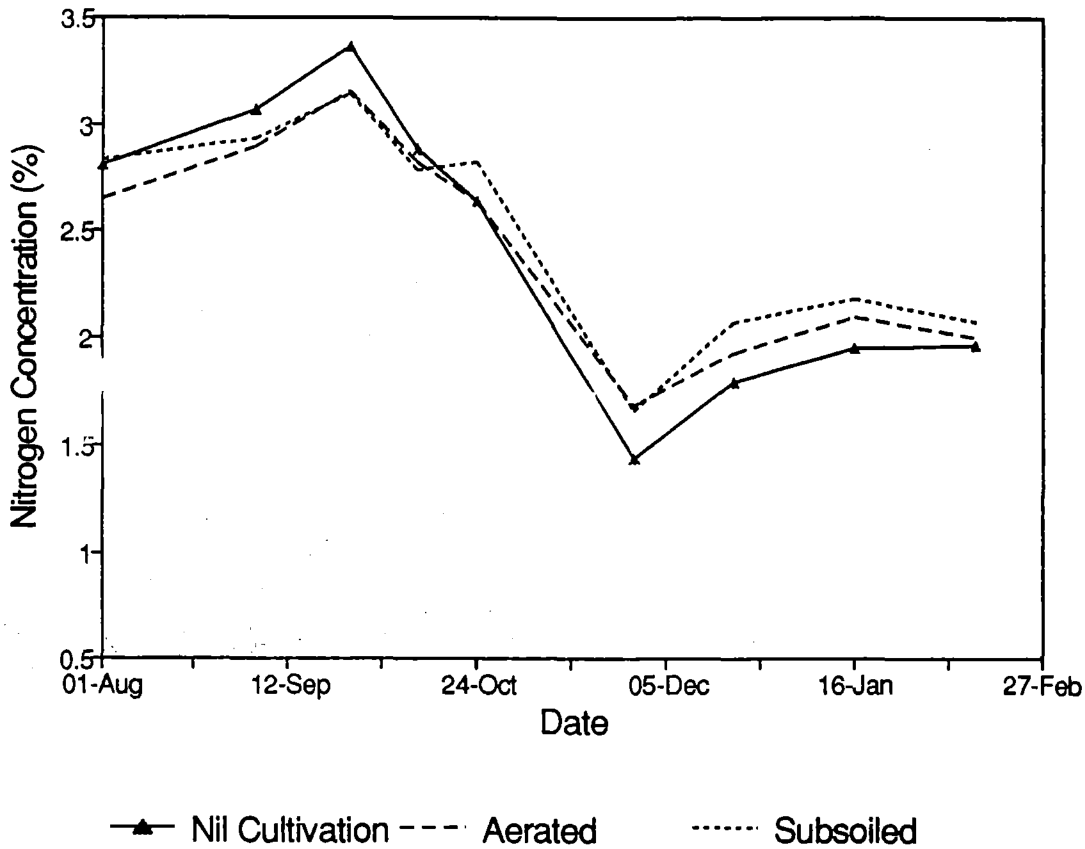

Figure 4.25: Pasture nitrogen concentration as affected by cultivation treatment, 1-Aug-91 to 12-Feb-92.

The nitrogen concentrations are below critical pasture levels of 4.4% N (Cornforth and Sinclair, 1984) for the 1991/1992 season . During periods of high dry matter production, the nitrogen concentration of herbage has been reported to decrease due to a dilution effect (McNaught and Dorofaeff, 1968; Ledgard *et al.*, 1990). During the trial reported here, this dilution effect occurred over the late spring/early summer period (11-Oct-91 to 28-Nov-91) when pasture growth rates were at their highest (Section 4.3.1.1). After 28-Nov-91 as the pasture growth rates declined, the nitrogen concentration increases because the nitrogen is less diluted in the dry matter of the pasture (Metson and Saunders, 1978b; Ledgard *et al.*, 1990). Chaney and Kamprath (1982) found that subsoiling (45 cm) significantly increased nitrogen concentration of corn as did Coventry *et al.* (1987b) in wheat.

Phosphorus.

There were no significant differences in phosphorus concentration between cultivation treatments, except on 16-Jan-92, when the subsoiled cultivation treatment had a significantly higher phosphorus concentration than the nil cultivation treatment (Figure 4.26).

The pasture phosphorus concentrations showed an increase in early spring (1-Aug-91 to 26-Sep-91) when the levels of available phosphorus increased (Saunders and Metson, 1971) (Figure 4.26). These increases in available phosphorus during the spring are due to the release of phosphorus from organic residues and soil organic matter (Saunders and Metson, 1971).

From 11-Oct-91 pasture growth rates were high (Section 4.3.1.1) and a dilution affect caused a rapid decline in the phosphorus concentration of the pasture. As pasture growth rates decreased from 28-Nov-91 onwards due to a reduction in soil profile water contents, the decline in phosphorus concentration of the pasture herbage became negligible. Between 28-Nov-91 and 12-Feb-92 the pasture phosphorus concentration reached the critical level of 0.3% P (Cornforth and Sinclair, 1984). The phosphorus concentration remained at or below this level for the remainder of the 1991/1992 summer. Phosphorus concentrations are known to reach their minimum in the summer months (Saunders and Metson, 1971).

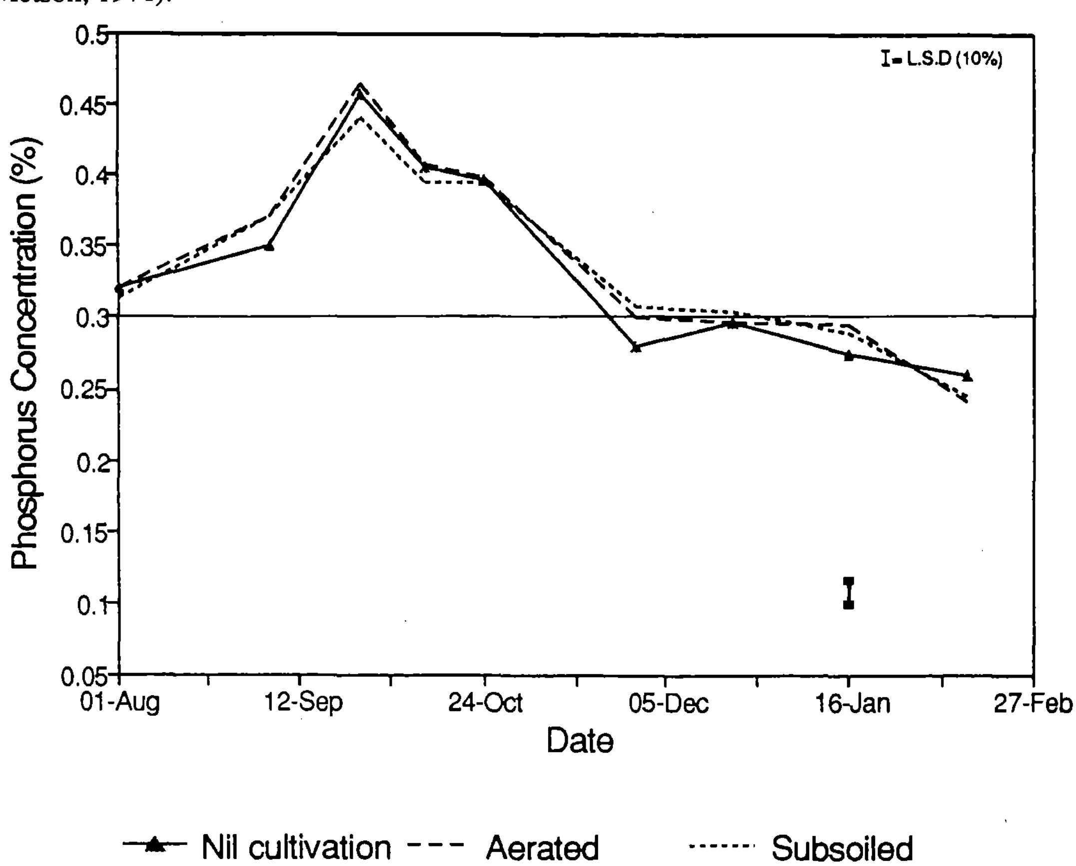

Figure 4.26: Pasture phosphorus concentration as affected by cultivation treatment, 1-Aug-91 to 12-Feb-92, '——' indicates critical level.

Sulphur.

There was a trend for higher concentrations of sulphur to occur in plants grown on the loosened treatments (aerated and subsoiled), however there was only one harvest date (16-Jan-92) when the difference was significant. Sulphur concentrations decreased from 11-Oct-91 when the pasture growth rates were high (Section 4.3.1.1), and a dilution effect caused the sulphur concentration to fall (Figure 4.27).

The critical concentration of sulphur in a mixed pasture is 0.22-0.25% S (Cornforth and Sinclair, 1984). The pasture of all the cultivation treatments was at or below this critical level for the 1991/1992 season. It is believed that the main effect of soil loosening on pasture production, for example 5-Sep-91 to 11-Oct-91 and 16-Jan-92, was in response to plant roots being able to access sulphur present at lower depths of the soil profile. This will be discussed further in Section 6.0.

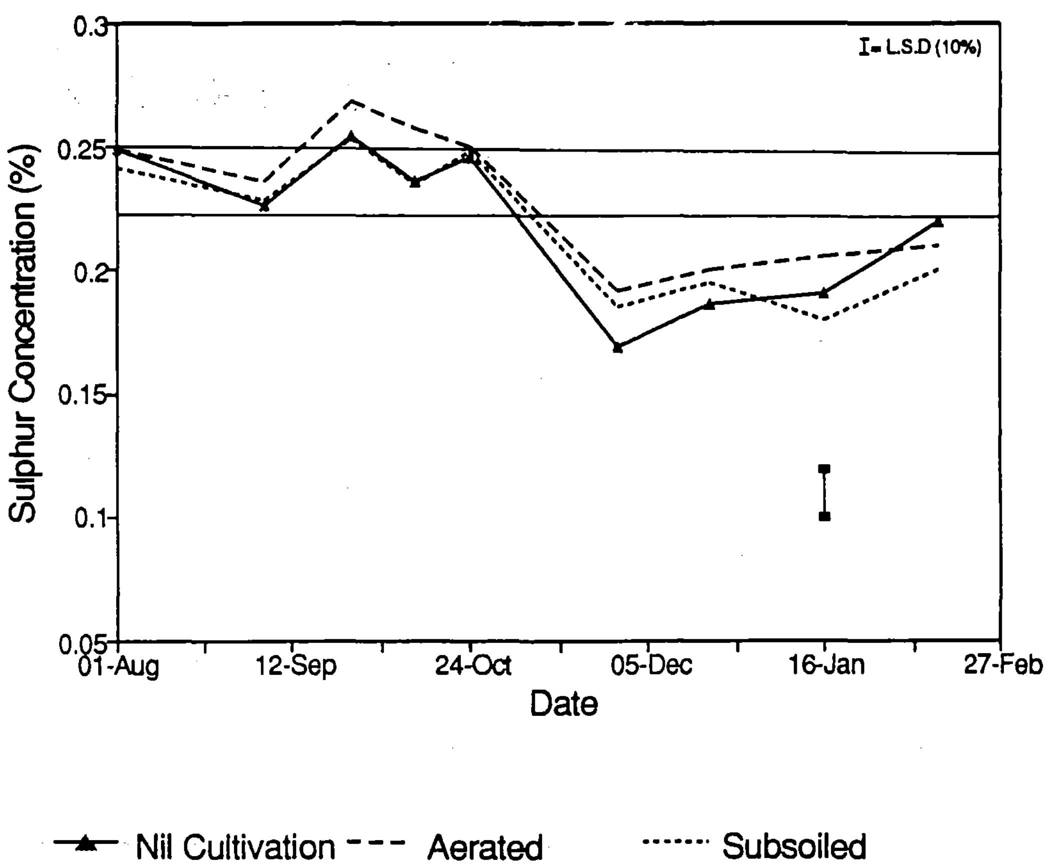

Figure 4.27: Pasture sulphur concentration as affected by cultivation treatment, 1-Aug-91 to 12-Feb-92, '——' indicates critical level.

Potassium.

The effect of cultivation treatment on pasture potassium concentration was significant at two dates throughout the 1991/1992 season (Figure 4.28). Potassium concentration in the pasture herbage increased during early spring in all treatments, with the aerated treatment reaching the highest potassium concentrations. As pasture growth rates increased from 11-Oct-91 the potassium concentration fell due to a dilution effect. Potassium concentrations reached the critical level (1.7% K) by 28-Nov-91 and remained below this level for the remainder of the 1991/1992 summer (Cornforth and Sinclair, 1984; De Nobili *et al.*, 1990). From 28-Nov-91 the nil cultivation treatment tended to have higher potassium concentrations. The results presented in Figure 4.28 do not support the findings of Ide *et al.* (1984) and Ide *et al.* (1987b) who reported that subsoiling (60 cm) increased the potassium uptake and concentration of plants (barley and sugar beet). This is because the potassium content of the soil profile in this trial decreases with depth (Figure 6.1). Thus any increase in root length below 25 cm would not lead to an increased pasture potassium concentration or uptake.

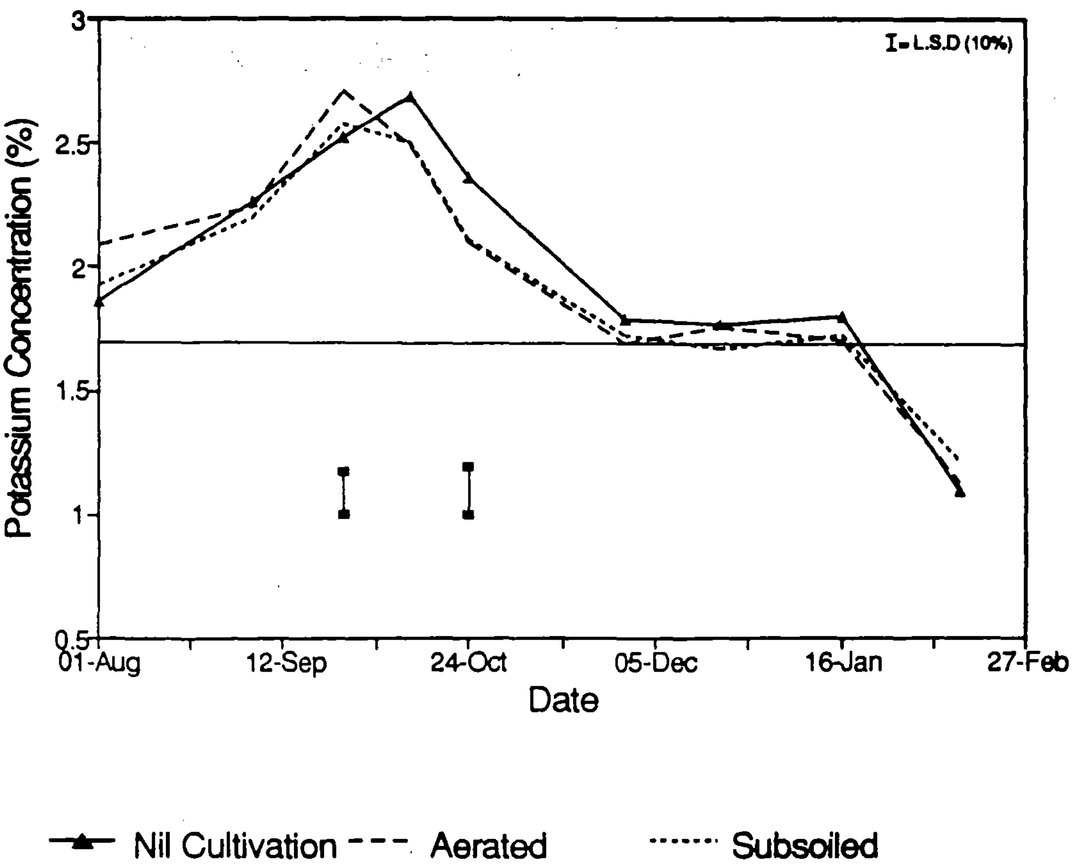

Figure 4.28: Pasture potassium concentration as affected by cultivation treatment, 1-Aug-91 to 12-Feb-92, '——' indicates critical level.

Calcium.

There was a trend for higher concentrations of calcium to be found in pasture grown on the aerated and subsoiled treatments compared with the nil cultivation treatment. Significant differences occurred at three harvest dates (P < 0.10) (Figure 4.29).

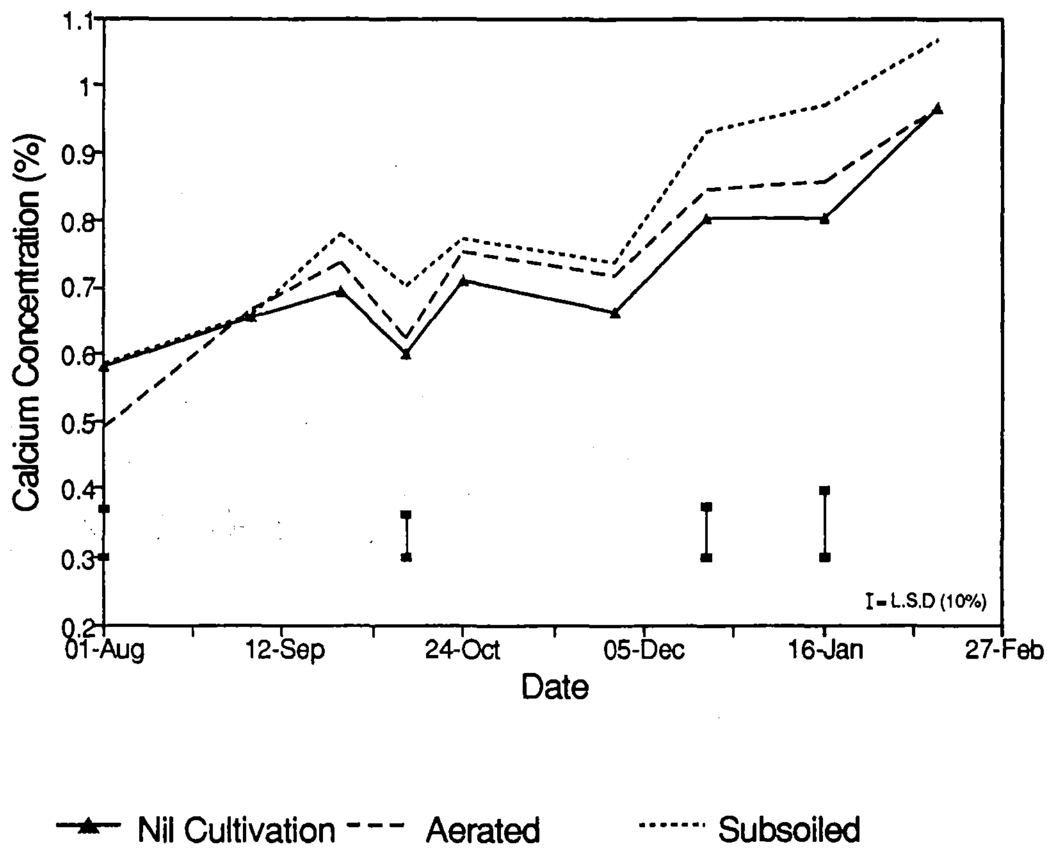

Figure 4.29: Pasture calcium concentration as affected by cultivation treatment, 1-Aug-91 to 12-Feb-92.

As the 1991/1992 season progressed the calcium concentration in the pasture herbage increased. Plant calcium concentrations have been reported to reach a maximum in summer and a minimum in winter (Metson and Saunders, 1978). Calcium tends to accumulate in the older plant leaves (Metson and Saunders, 1978; Mengel and Kirkby, 1982).

There is a trend for increased soil calcium concentrations to be present below the 50 cm depth within the profile of the Templeton silt loam (Figure 6.2). Active roots at this depth, such as those of the subsoiled cultivation treatment would have a greater access and therefore a larger uptake of calcium than in the nil cultivation treatment. This effect became more pronounced as the season progressed and the soil water content of the top soil horizons decreased, thus forcing the uptake of water from deeper in the soil profile. This increased uptake of water from depth was possibly accompanied by an increase in the uptake of calcium from depth.

The higher calcium concentration of the subsoiled cultivation treatment compared to the nil cultivation treatment during the drier months (28-Nov-91 to 12-Feb-92) was a result of the subsoiled cultivation having a larger active root length below 50 cm (Section 4.4.2). Barbosa *et al.* (1989) also found that deep tillage from 15 cm to 40 cm increased the calcium concentration in the roots of a Soya crop.

Magnesium.

There were no significant differences in magnesium concentration with cultivation treatment. However from 26-Sep-91 the pasture of the subsoiled cultivation treatment had a higher magnesium concentration than the nil cultivation treatment. The concentration of magnesium in the pasture herbage increased over the 1991/1992 season, and was never below the lower critical level of 0.15% Mg (Cornforth and Sinclair, 1984) (Figure 4.30). The magnesium concentration, was found to increase in the pasture herbage when the the soil profile water content declined and the roots deeper in the soil profile supplied a larger portion of nutrients and water to the pasture. Magnesium concentration also increases as the pasture matures (Fleming, 1973; Mengel and Kirkby, 1982). Coventry *et al.* (1987b) reported an increase in the magnesium concentration of wheat following soil loosening (40 cm).

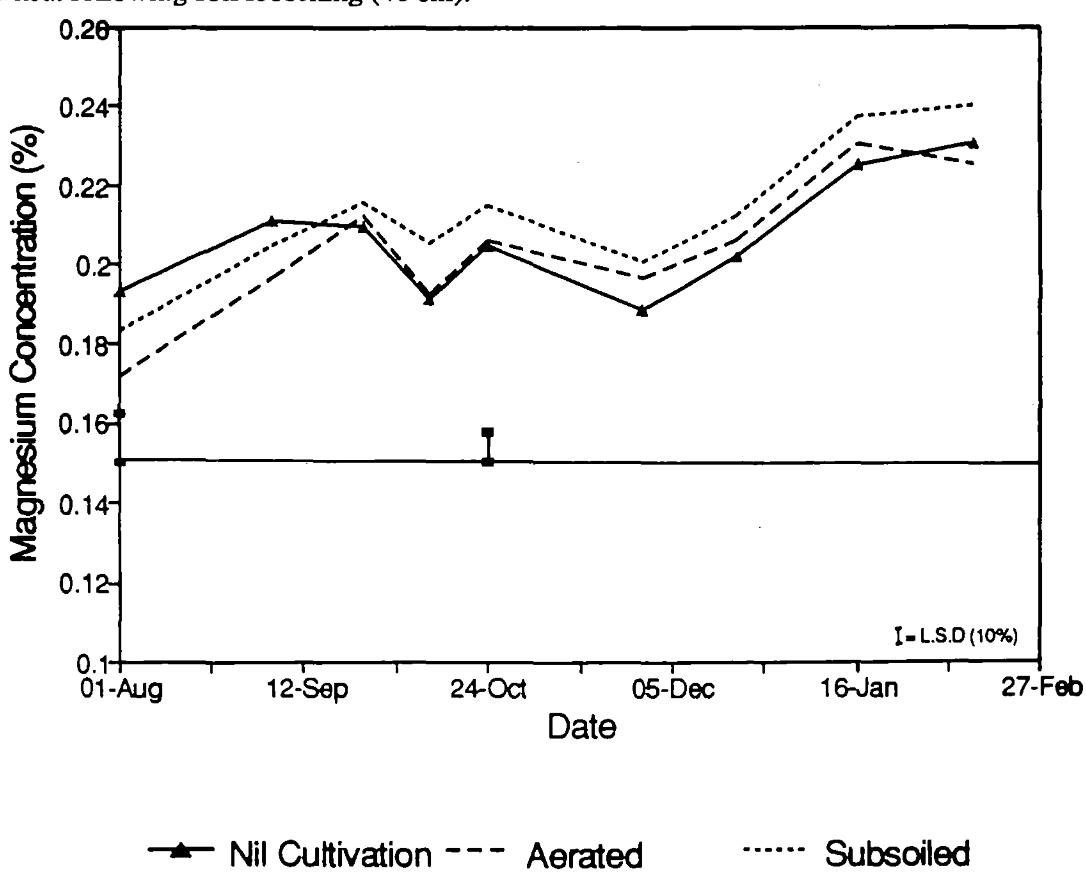

Figure 4.30: Pasture magnesium concentration as affected by cultivation treatment, 1-Aug-91 to 12-Feb-92, '——' indicates critical level.

Sodium.

The concentration of sodium in the pasture herbage increased from 1-Aug-91, but fell away after 11-Oct-91 when the growth rates of the pasture increased (Section 4.3.1.1) (Figure 4.31). From 28-Nov-91 when the pasture growth rates declined due to a reduction in soil water content the sodium concentration still decreased but at a much slower rate. The sodium concentration followed a similar pattern to phosphorus and potassium. Significant differences occurred at two dates (5-Sep-91 and 12-Feb-92). With the subsoiled cultivation treatment having a higher sodium concentration than the nil cultivation treatment. This is possibly due to the subsoiled cultivation having a larger root length below 50 cm where the sodium content of the profile is at it's highest (Figure 6.4).

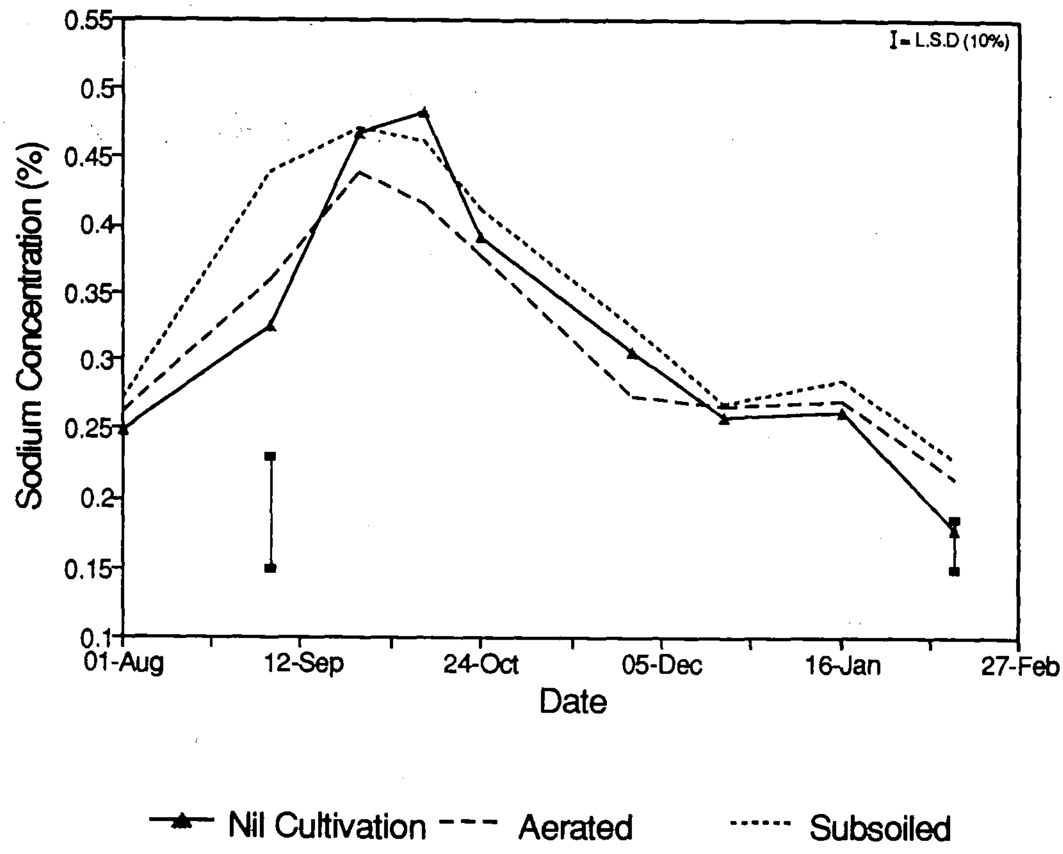

Figure 4.31: Pasture sodium concentration as affected by cultivation treatment, 1-Aug-91 to 12-Feb-92.

4.7.1.2 Effect of fertiliser on macronutrient concentration.

Fertiliser was applied on 22-Dec-90, i.e. six to fourteen months prior to the pasture harvest results reported (1-Aug-91 to 12-Feb-92).

Nitrogen.

The pattern of nitrogen concentration in the pasture herbage was unaffected by the application of phosphate and sulphate fertilisers. The changes in nitrogen concentration in pasture of the different fertiliser treatments over the 1991/1992 season followed the same trend as in Figure 4.25 (Appendix 4.10).

Phosphorus.

The application of phosphate alone and in combination with sulphate fertiliser increased the phosphorus concentration of the pasture herbage (Figure 4.32). The application of phosphate fertiliser kept the pasture herbage concentration above the critical level (0.3% P) until 28-Nov-91. The seasonal pattern of change in pasture phosphorus concentration has been described in Section 4.7.1.1.

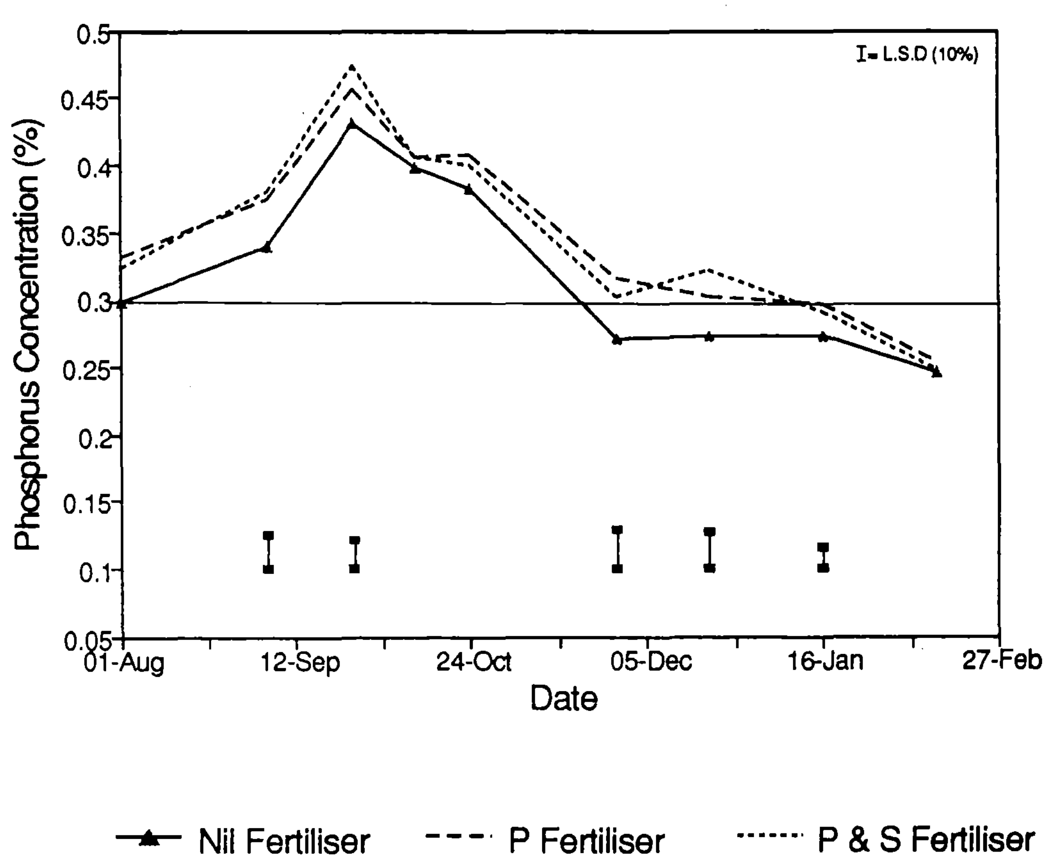

Figure 4.32: Pasture phosphorus concentration as affected by fertiliser treatment, 1-Aug-91 to 12-Feb-92, '——' indicates critical level.

Sulphur.

The application of sulphate fertiliser significantly increased the pasture herbage concentration of sulphur to above the lower critical level (0.22% S) (Cornforth and Sinclair, 1984) over the 1991/92 season (Figure 4.33). The seasonal changes in pasture herbage sulphur concentrations have been described in Section 4.7.1.1. The significant dry matter response to sulphate fertiliser suggests a sulphur deficiency existed at the trial site.

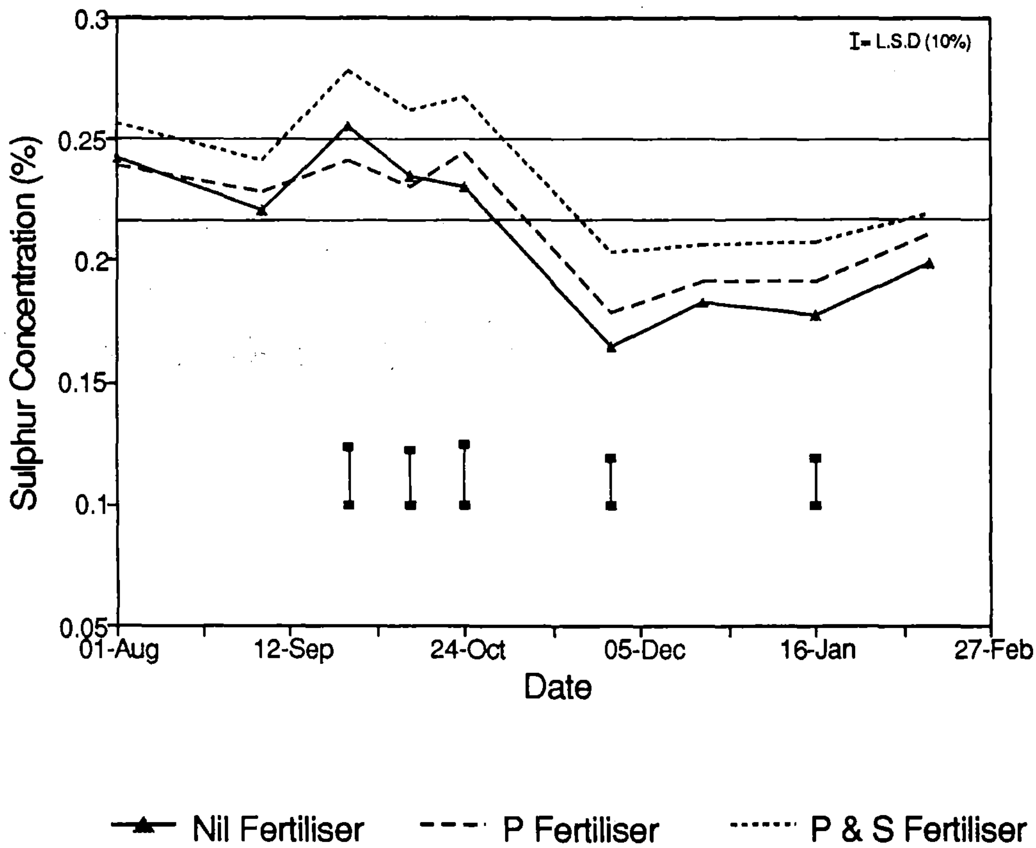

Figure 4.33: Pasture sulphur concentration as affected by fertiliser treatment, 1-Aug-91 to 12-Feb-92, '——' indicates critical level.

Potassium.

The addition of phosphate and sulphate fertilisers did not increase the pasture herbage concentration of potassium. The seasonal changes in pasture herbage potassium concentrations are described in Section 4.7.1.1.

Calcium.

The addition of phosphate and sulphate fertilisers did not increase the pasture herbage concentration of calcium. The seasonal changes in pasture herbage calcium concentration are described in Section 4.7.1.1.

Magnesium.

The addition of phosphate and sulphate fertilisers caused a significantly higher pasture herbage concentration of magnesium on two dates, 20-Dec-91 and 12-Feb-92. The seasonal changes in pasture herbage magnesium concentrations are described in Section 4.7.1.1.

Sodium.

The application of phosphate and sulphate fertilisers significantly increased the pasture herbage concentration of sodium at two harvest dates (Figure 4.34), and a trend for higher concentrations was apparent throughout the season. The application of fertiliser increased pasture growth (Section 4.3.1.2). This increased pasture growth probably resulted in more water being taken up from deeper in the soil profile. Sodium is present at it's highest levels within the B-horizon of the Templeton silt loam (Figure 6.4), thus roots present at this depth would access to the sodium present.

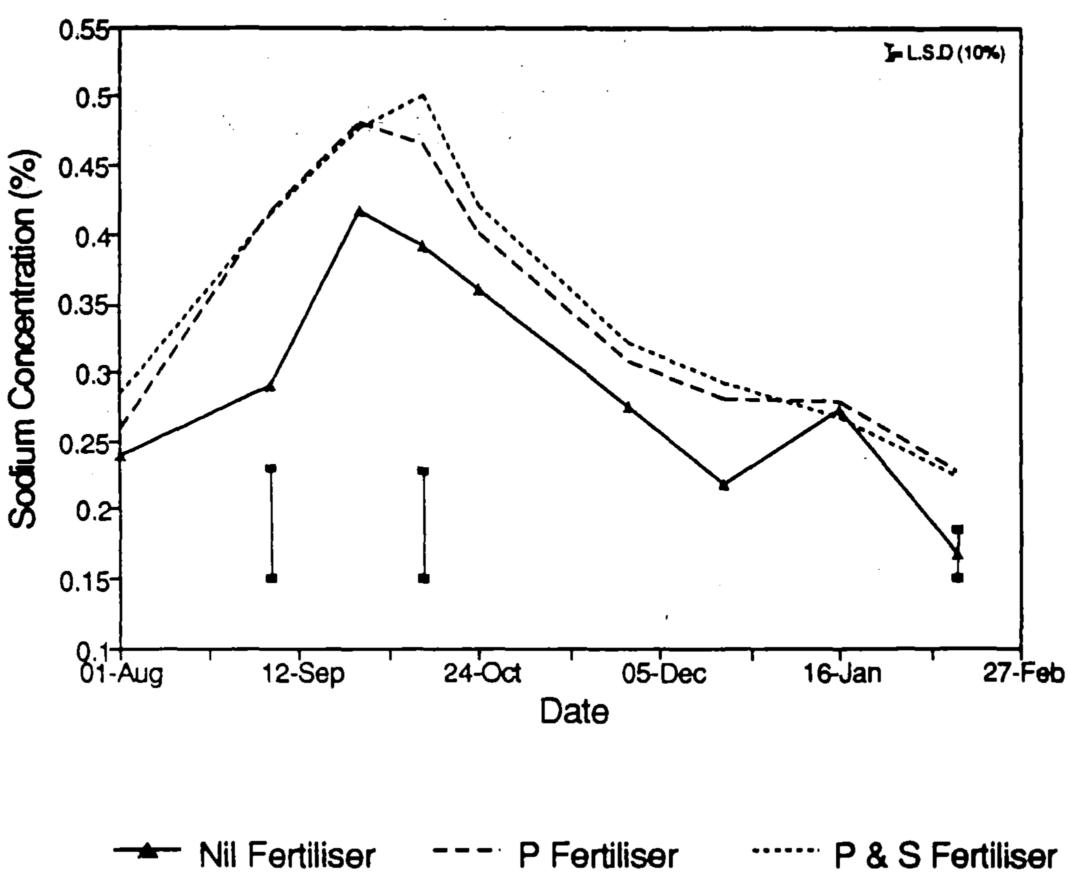

Figure 4.34: Pasture sodium concentration as affected by fertiliser treatment, 1-Aug-91 to 12-Feb-92.

4.7.2 Macronutrient uptake.

Macronutrient uptake was calculated at each pasture harvest date from the macronutrient concentration (Section 4.7.1) and pasture production (kg DM ha^{-1}) (Section 4.3.1.1) as in Equation 4.8 for each harvest date:

$$C_n * Y_n = \text{Uptake} \qquad \textbf{(Equation 4.8)}$$

Where: C_n= Macronutrient concentration (%)
Y_n= Yield (kg DM ha^{-1}).

4.7.2.1 Macronutrient uptake as affected by cultivation treatment.

The uptake of all macronutrients (N, P, K, S, Ca, Mg and Na) was significantly different between cultivation treatments on four dates. These four dates were the only dates (except 1-Aug-91) that pasture production (kg DM ha^{-1}) was significantly different (Section 4.? .1) (Table 4.22) (Appendix 4.11).

Nutrient	Date	Nil	Aer.	Sub.	FProb	LSD (10%)
Nitrogen	15-1-91	32.10	20.30	18.60	0.005	6.895
	5-9-91	23.27	34.37	25.97	0.078	8.172
	11-10-91	3.30	14.63	10.90	0.037	6.930
	16-1-92	0.82	7.24	3.24	0.030	3.894
Phosphorus	15-1-91	4.54	2.75	2.54	0.003	0.951
	5-9-91	2.85	4.63	3.37	0.033	1.067
	11-10-91	0.68	2.27	1.62	0.055	1.036
	16-1-92	0.12	1.03	0.39	0.020	0.524
Sulphur	15-1-91	3.10	2.03	1.74	0.011	0.739
	5-9-91	1.49	2.83	2.17	0.017	0.691
	11-10-91	0.29	1.42	1.04	0.032	0.666
	16-1-92	0.09	0.72	0.28	0.024	0.375
Potassium	15-1-91	19.68	11.09	9.88	0.000	3.700
	5-9-91	18.63	28.60	20.63	0.059	6.639
	11-10-91	3.53	13.43	9.97	0.042	5.869
	16-1-92	0.87	5.53	2.09	0.024	2.818
Calcium	15-1-91	15.63	10.57	9.89	0.014	3.360
	5-9-91	4.89	7.88	6.05	0.049	1.907
	11-10-91	0.74	3.27	2.67	0.028	1.500
	16-1-92	0.34	2.86	1.17	0.024	1.482
Magnesium	15-1-91	3.58	2.16	1.97	0.001	0.700
	5-9-91	1.54	2.32	1.75	0.040	0.490
	11-10-91	0.23	1.06	0.81	0.027	0.472
	16-1-92	0.70	0.76	0.29	0.019	0.380
Sodium	15-1-91	5.19	2.99	3.04	0.007	1.223
	5-9-91	2.46	4.20	4.46	0.055	1.417
	11-10-91	0.84	2.31	1.78	0.088	1.081
	16-1-92	0.15	0.83	0.33	0.023	0.406

Table 4.22: Macronutrient uptake (kg ha^{-1}) for each date when a significant affect of cultivation was detected.

The cultivation treatments of aeration and subsoiling showed larger macronutrient uptakes compared to the nil cultivation treatment at all dates in Table 4.22 except 15-Jan-91.

Cumulative macronutrient uptake as affected by cultivation treatment.

There were no significant differences between cultivation treatments for cumulative uptake of any macronutrients except sulphur (Appendix 4.12). The loosened treatments of aeration and subsoiling had consistently higher cumulative sulphur uptakes than the nil cultivation treatment. This was be attributed to the higher root lengths of the loosened treatments between 20-50 cm depth where the sulphur content was highest in the soil profile. The cumulative uptake of sulphur (kg S ha^{-1}) in the subsoiled and the aerated cultivation treatments from 1-Aug-91 to 12-Feb-92 was significantly different to the nil cultivation treatment at all harvest dates (Figure 4.35).

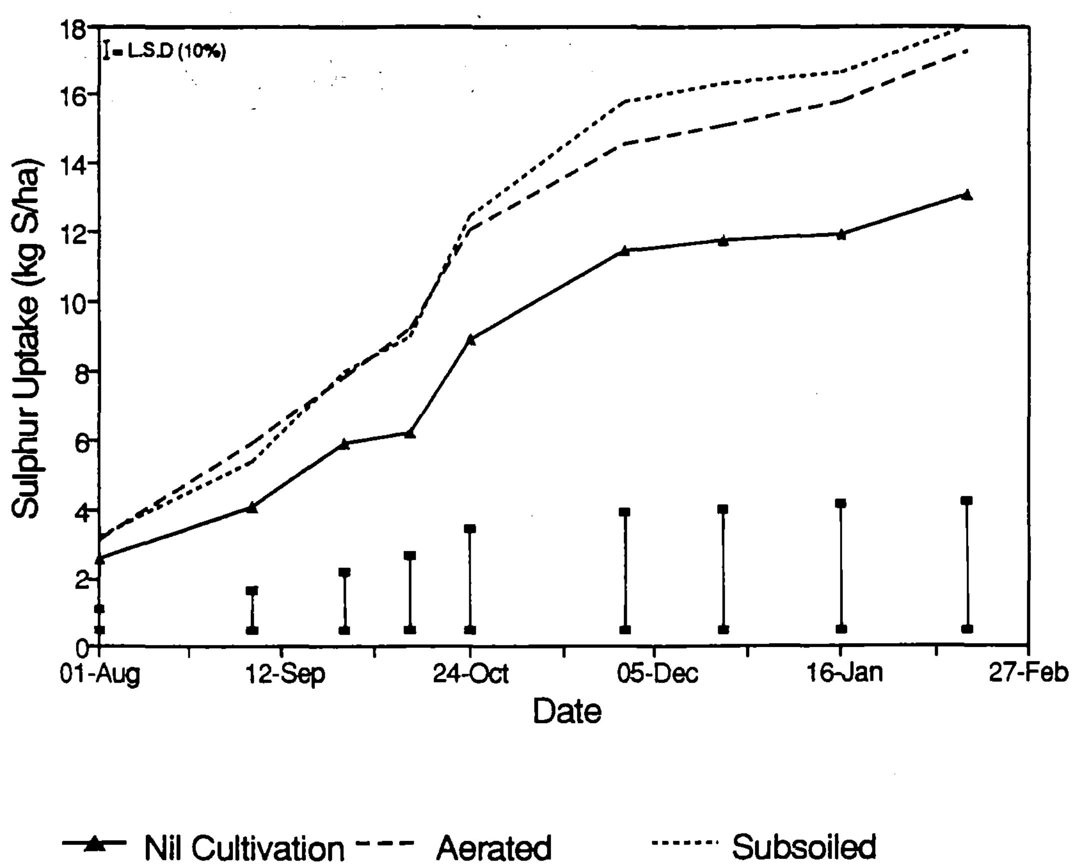

Figure 4.35: Cumulative pasture sulphur uptake as affected by cultivation treatment, 1-Aug-91 to 12-Feb-92.

The subsoiled treatment had the largest sulphur uptake with the aerated treatment being intermediate and the nil cultivation treatment having the lowest uptake. This result is a combination of higher sulphur concentrations and higher dry matter production.

Total macronutrient uptake at the end of the 1991/1992 season.

The total macronutrient uptake (kg ha^{-1}) only showed significant differences for sulphur (Table 4.23). However, all other macronutrients followed the same trend with the loosened treatments having a larger total uptake of each nutrient than the nil cultivation treatment (Appendix 4.12). Davies *et al.* (1989) found a similar trend, with loosening to a 15 cm depth resulting in an increase in the net uptake of phosphorus (83%, increase) and potassium (107%, increase) by pasture over two seasons.

Cultivation treatment			FProb	L.S.D
Nil	Aerated	Subsoiled		(10%)
12.93	17.30	17.95	0.074	3.712

Table 4.23: Total uptake of sulphur (kg ha^{-1}) as affected by cultivation treatment, 1-Aug-91 to 12-Feb-92.

Spring nitrogen uptake as affected by cultivation treatment.

In the early spring of 1991 (1-Aug-91 to 11-Oct-91) the total uptake of nitrogen by plants in the loosened treatments (aerated and subsoiled) was approximately 20 kg N ha^{-1} more than in the nil cultivation treatment. Although this difference was not statistically significant it could have represented an extra 0.33 kg N ha^{-1} d^{-1} (Table 4.24).

If this nitrogen had been applied as fertiliser nitrogen a response in pasture growth would have been expected.

	Cultivation treatment		
	Nil	Aerated	Subsoiled
kg N ha^{-1}	83.4	107.2	103.6
kg N ha^{-1} d^{-1}	1.16	1.49	1.44

Table 4.24: Spring nitrogen uptake as affected by cultivation treatment.

The increased uptake of nitrogen was considered to be one factor which was responsible for the higher spring pasture growth of the loosened treatments (aeration and subsoiling) compared to the nil cultivation treatment (Section 4.3.1.1). It is possible that because the loosened treatments had a lower water content during spring (Section 4.6.1.) soil conditions such as temperature and the aeration status were more favourable for mineralisation of nitrogen earlier in the spring (Haynes *et al.*, 1986).

Davies *et al.* (1989) that found increased aeration due to slitting (15 cm) increased the net mineralisation of nitrogen from soil organic matter. Over two seasons slitting increased the net uptake of nitrogen of pasture herbage by 95%. Delroy and Bowden (1986) found ripping increased the rate of root extension and this in turn led to larger uptake of nitrogen earlier in the season from the ripped areas.

4.7.2.2 Apparent recovery of applied fertiliser.

Apparent recovery of applied fertiliser was calculated using Equation 4.4.

$$\text{Recovery} = \frac{P^{+} - \text{Nil}}{30 \text{ kg P ha}^{-1}} * \frac{100}{1} \qquad \textbf{(Equation 4.9)}$$

Where: P^{+} = Uptake of P from P applied plots (kg P ha^{-1})
Nil = Uptake of P from control plots (kg P ha^{-1}).

Apparent recovery of applied phosphate fertiliser.

The apparent recovery of the applied phosphate fertiliser in spring was approximately 60% greater by the subsoiled cultivation treatment, than the nil cultivation treatment (Table 4.24).

Date	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
1-Aug-91	1.64	2.86	5.16	0.099	2.393
5-Sep-91	3.80	9.80	3.60	0.085	4.913
26-Sep-91	2.90	3.90	7.80	NS	-
11-Oct-91	0.75	4.74	0.88	NS	-
24-Oct-91	2.95	1.19	4.13	NS	-
28-Nov-91	5.90	2.10	6.70	NS	-
20-Dec-91	1.38	0.46	1.97	NS	-
16-Jan-92	0.08	2.04	1.26	NS	-
12-Feb-92	1.36	1.99	2.12	NS	-
Total	20.76	29.08	33.62	NS	-

Table 4.25: Apparent recovery of phosphate fertiliser (%) applied 22-Dec-90, as affected by cultivation treatment.

The differences in phosphate fertiliser recovery by the loosened treatments during the early spring period is due to the spring root growth of the loosened treatments intercepting more phosphate, before the roots of the nil cultivation treatment became active (Section 4.4.2). This earlier onset of root activity is due to the cultivation treatments of aeration and subsoiling having a lower water content and therefore higher soil temperatures.

Apparent recovery of applied sulphate fertiliser.

The apparent recovery of applied sulphate fertiliser over the 1991/1992 season from the subsoiled cultivation treatment was five times greater than the nil cultivation treatment. The aerated treatment had an apparent recovery of sulphate fertiliser two times greater than the nil cultivation treatment (Table 4.26).

Date	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
1-Aug-91	1.82	2.62	2.65	NR	-
5-Sep-91	0.50	2.93	3.99	NR	-
26-Sep-91	0.00	0.92	9.71	NR	-
11-Oct-91	0.00	2.59	0.88	NR	-
24-Oct-91	1.49	0.79	6.79	NR	-
28-Nov-91	3.14	0.14	8.06	NR	-
20-Dec-91	0.00	0.00	1.41	NS	-
16-Jan-92	0.00	1.78	1.00	NS	-
12-Feb-92	0.20	2.46	0.45	0.071	1.523
Total	7.15	14.23	34.94	NR	-

(N.B.: NR = no result due to excess missing values (Section 4.3.1.1)).

Table 4.26: Apparent recovery of sulphate fertiliser (%) applied 22-Dec-90, as affected by cultivation treatment.

The subsoiled cultivation treatment had a much greater recovery of sulphate fertiliser, due to its greater root length present below 50 cm from 29-Nov-91 (Section 4.4.2). The root length of the subsoiled cultivation treatment was significantly higher at 60-80 cm than the nil cultivation treatment on 29-Nov-91. It is possible that a large proportion of the sulphur was leached to these depths over the winter period. Freney (1986) states that in many cases fertiliser SO_4^{2-} not recovered by the pasture will be leached into deeper soil horizons and that this SO_4^{2-} may be retained in the subsoil horizons by absorption and can be recovered at least in part by deep plant roots. M^c^Laren *et al.* (1992) reported that the Templeton silt loam at the trial site was capable of retaining SO_4^{2-} at depth in the soil profile.

There are no reports in the literature on the influence of soil loosening on the recovery of sulphate fertilisers, however, Chaney and Kamprath (1982) found appreciable amounts of applied nitrogen was leached below the tillage pan in 1979 and that disruption of the tillage pan by subsoiling permitted the corn plants to utilise this leached nitrogen.

4.7.2.3 Effect of fertiliser on macronutrient uptake.

The effect of fertiliser on macronutrient uptake was most noticeable on the 5-Sep-91 (Table 4.27). At all other dates, even when fertiliser application had a significant effect on pasture production, macronutrient uptake was not affected by fertiliser application (Section 4.3.1.1) (Appendix 4.11).

	Fertiliser Treatment				L.S.D
	Nil	P	P & S	FProb	(10%)
P	2.56	4.07	4.22	0.033	1.067
S	1.61	2.39	2.48	0.088	0.691
Ca	4.96	7.19	6.69	NS	-
Mg	1.44	2.13	2.04	0.057	0.490
Na	2.12	4.16	4.83	0.014	1.417

Table 4.27: Macronutrient uptake (kg ha^{-1}) as affected by fertiliser treatment, 5-Sep-91.

Phosphorus.

The uptake of phosphorus was significant on two dates (Figure 4.36). On these dates the fertiliser treatments had a larger uptake of phosphorus than the nil fertiliser treatment.

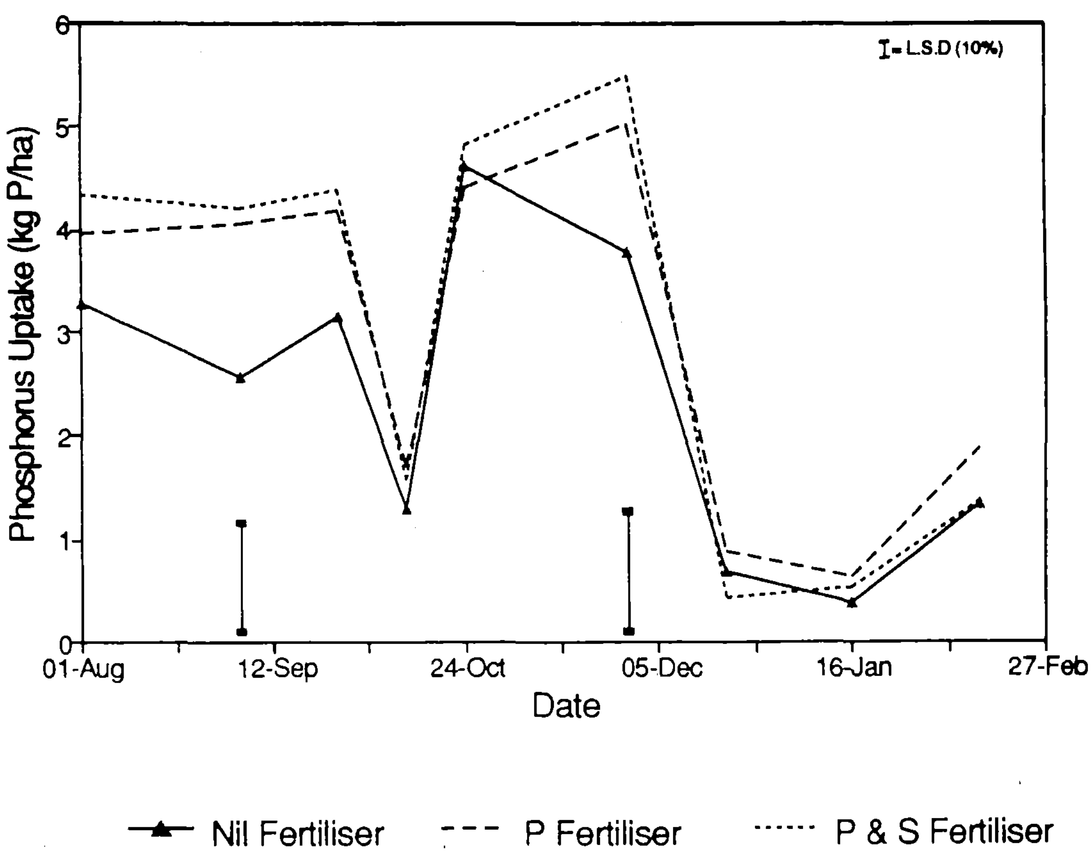

Figure 4.36: Pasture phosphorus uptake as affected by fertiliser treatment, 1-Aug-91 to 12-Feb-92.

Sulphur and Sodium.

The cumulative uptake of sulphur and sodium can be seen in Figures 4.37 and 4.38.

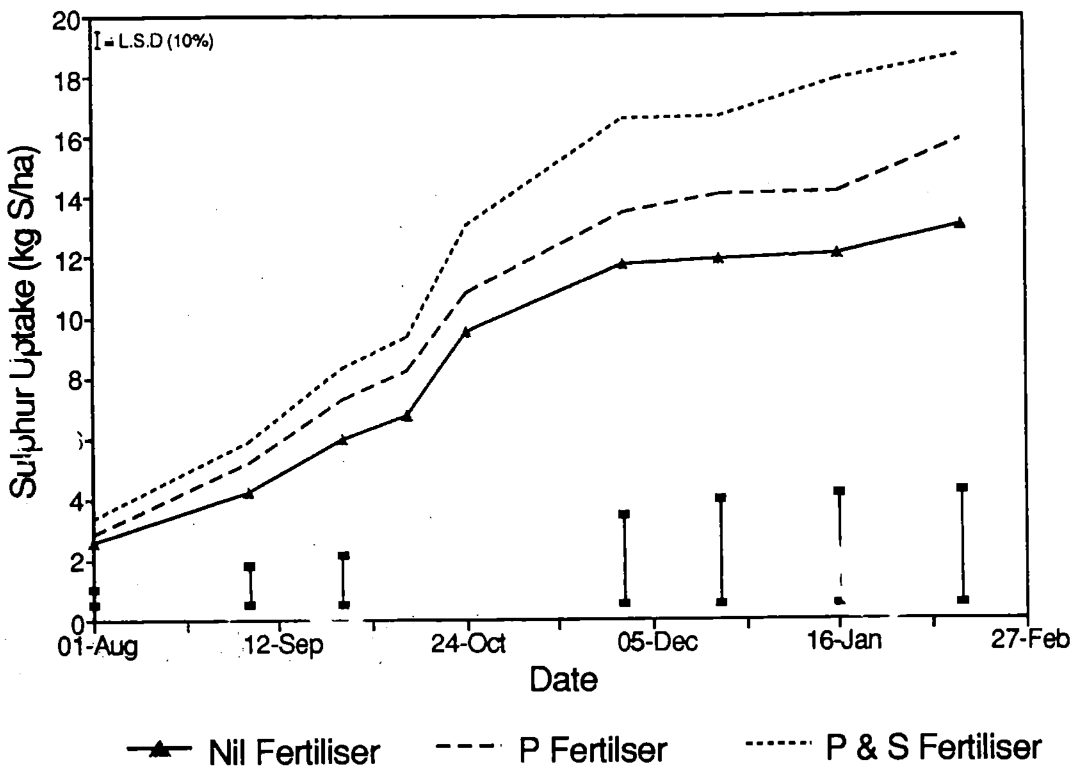

Figure 4.37: Cumulative sulphur uptake as affected by fertiliser treatment, 1-Aug-91 to 12-Feb-92.

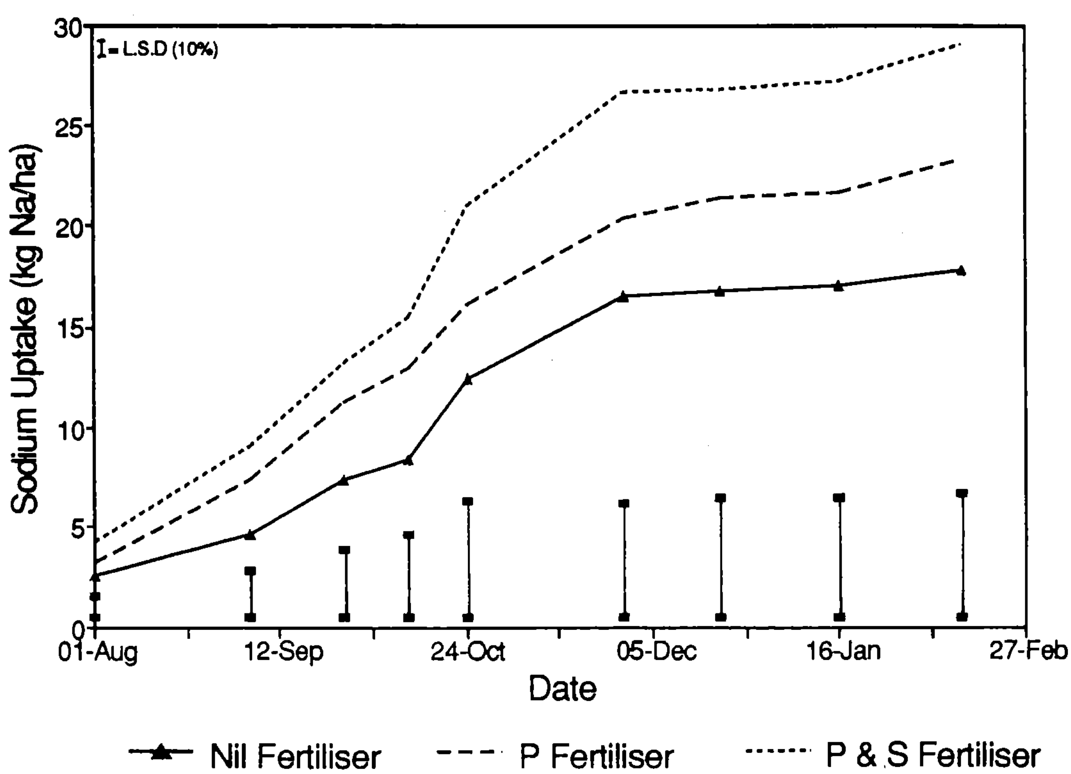

Figure 4.38: Cumulative sodium uptake as affected by fertiliser treatment, 1-Aug-91 to 12-Feb-92.

The application of phosphate and sulphate fertiliser at 30 kg ha^{-1} resulted in the largest uptake of sulphur and sodium, while the application of nil fertiliser had the least sulphur and sodium uptake. The large effect of fertiliser treatment on sulphur and sodium uptake is a combination of: (i) pasture growth increasing due to fertiliser application, and (ii) increased sulphur and sodium concentrations (Section 4.3.1.2) (Section 4.7.1.2) in the pasture herbage. The application of sulphate fertiliser resulted in the largest uptake of sulphur and sodium. The increased pasture growth seen in the sulphate fertiliser treatment encouraged root activity deeper in the soil profile in the search of water and nutrients. Sulphur and sodium are present deeper in the soil profile and therefore able to taken up by roots present at this depth (Figure 6.3 and Figure 6.4).

4.7.2.4 Cultivation and fertiliser treatment interactions.

There were no significant interactions between cultivation and fertiliser treatments on macronutrient concentration or macronutrient uptake during the field trial.

4.8 Micronutrients.

4.8.1 Micronutrient concentration.

Micronutrient concentration was measured at four dates during the 18 month field trial, 7-Nov-90, 5-Dec-90, 1-Aug-91, 12-Feb-92 (Appendix 4.12).

There were no noticeable differences between cultivation treatments on either 7-Nov-90 or 5-Dec-90, therefore these dates will not be reported.

The micronutrient manganese showed no response to cultivation or fertiliser treatment so will not be reported either. Manganese also showed no seasonal effect in concentration contrary to other studies (Fleming and Murphy, 1968; Metson *et al.*, 1979; M^c^Laren and Cameron, 1990).

4.8.1.1 Effect of cultivation treatment on micronutrient concentration.

The pasture plant concentrations of iron, zinc, copper and cobalt all showed significant responses to cultivation (Table 4.28).

	Cultivation treatment			FProb	L.S.D (10%)
	Nil	Aerated	Subsoiled		
Zinc					
1-Aug-91	37.42	34.75	34.67	0.002	2.525
12-Feb-92	40.17	34.58	36.25	0.041	4.187
Copper					
1-Aug-91	5.67	4.83	5.58	0.097	0.801
16-Feb-92	5.42	4.75	5.50	0.041	0.601
Iron					
1-Aug-91	1715	1009	1117	<0.001	249.6
12-Feb-92	500	399	484	0.032	66.0
Cobalt					
1-Aug-91	0.667	0.342	0.396	<0.001	0.096
12-Feb-92	0.238	0.171	0.238	0.002	0.032

Table 4.28: Effect of cultivation treatment on micronutrient concentration ($\mu g\ g^{-1}$).

Zinc.

Plants grown in all cultivation treatments at both dates (1-Aug-91 and 12-Feb-92) have zinc concentrations above the critical level (12 $\mu g\ g^{-1}$) (Cornforth and Sinclair, 1984) (Figure 4.39). At both dates plants grown in the nil cultivation treatment had a significantly higher zinc concentration than the loosened treatments of aeration and subsoiling. As expected zinc concentrations are lower during periods of high dry matter production, for example spring (Section 4.3.1.1) (Metson *et al.*, 1979).

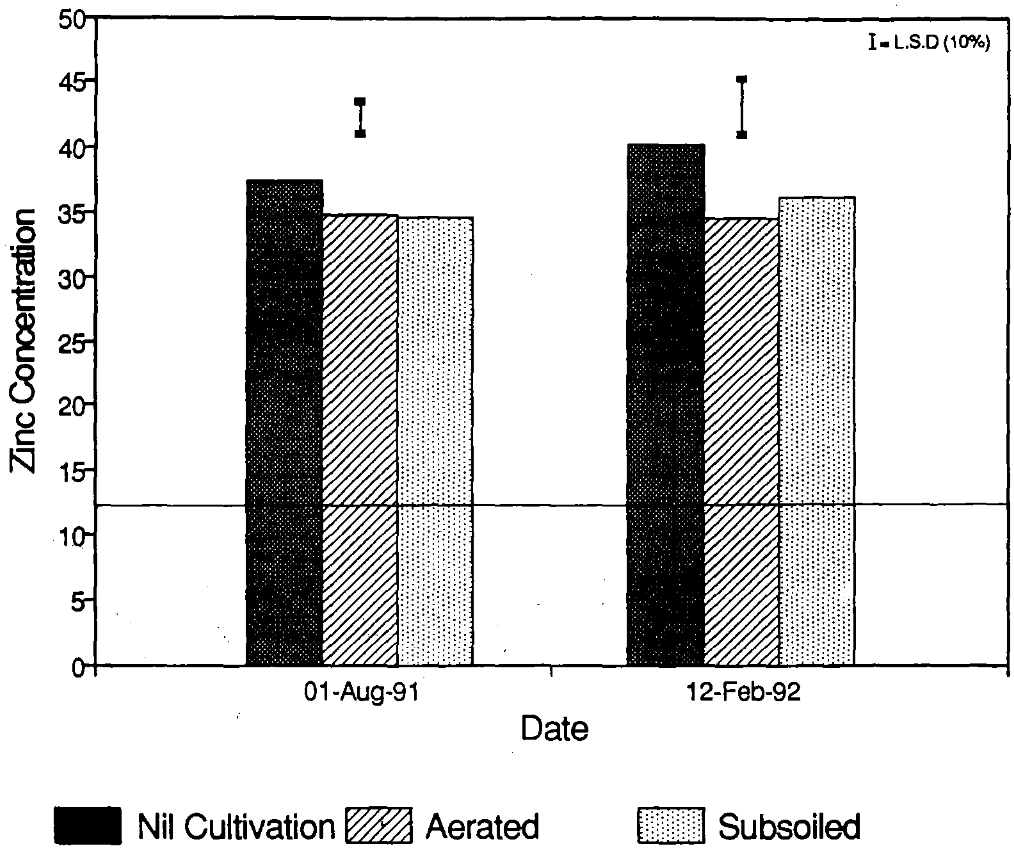

Figure 4.39: Pasture zinc concentration ($\mu g\ g^{-1}$) as affected by cultivation treatment, 1-Aug-91 to 12-Feb-92, '—' indicates critical level.

Copper.

The critical level of copper in pasture plants is reported to be 5 $\mu g\ g^{-1}$ at this level deficiency symptoms occur in sheep and cattle (Sherrell and M^cIntosh, 1987). Plants in the aerated cultivation treatment were slightly deficient in copper at both sampling dates (Figure 4.40). The subsoiled and nil cultivation treatments were not deficient at either sampling date.

Pasture in the aerated treatment had a significantly lower copper concentration than that in the subsoiled or nil cultivation treatment.

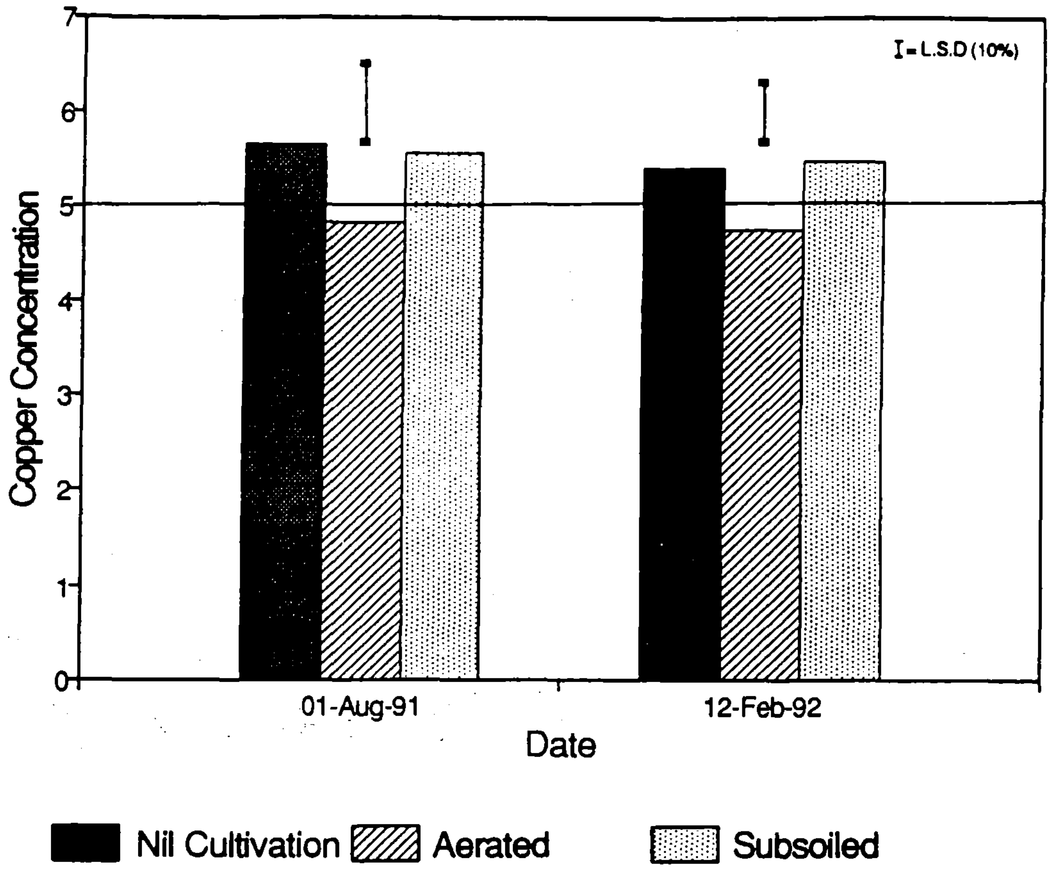

Figure 4.40: Pasture copper concentration ($\mu g\ g^{-1}$) as affected by cultivation treatment, 1-Aug-91 to 12-Feb-92, '—' indicates critical level.

Iron.

All cultivation treatments at both sampling dates had iron concentrations above the critical level (45 $\mu g\ g^{-1}$) (Cornforth and Sinclair, 1984) (Figure 4.41). On 1-Aug-91 the nil cultivation treatment had a significantly higher iron concentration. On 12-Feb-92 significant differences occurred between the cultivation treatments. With the nil treatment having the highest iron concentration, followed by the subsoiled cultivation and the aerated cultivation treatment having the lowest iron concentrations.

The concentration of iron in herbage has been shown to increase with increasing water content of the soil profile (Fleming, 1973; Mengel and Kirkby, 1982) (Section 4.6.1). The nil cultivation treatment had a wetter soil profile hence a lower redox potential resulting in higher pasture iron concentrations. Herbage iron concentration also decreases with pasture maturity (Fleming, 1973). This factor in combination with drier soils can be seen in a decrease in iron concentration from 1-Aug-91 to 12-Feb-92 of all cultivation treatments (Figure 4.41). Values of air-filled porosity are given in Table 4.3(a).

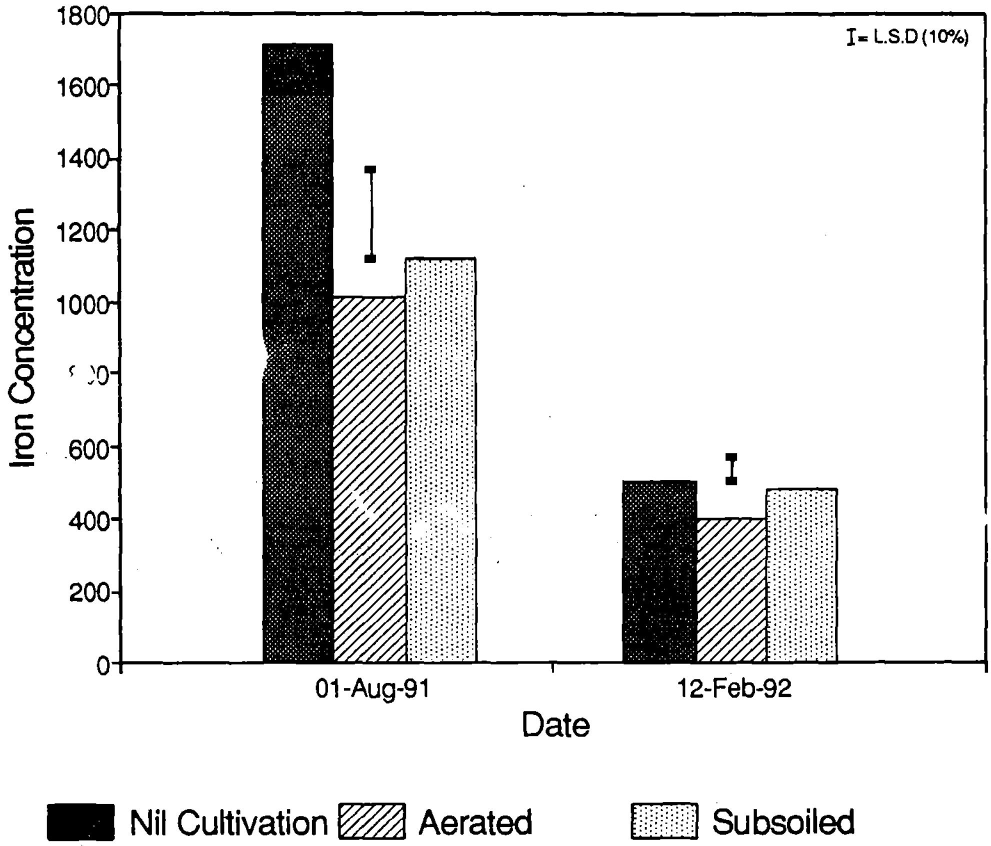

Figure 4.41: Pasture iron concentration ($\mu g\ g^{-1}$) as affected by cultivation treatment, 1-Aug-91 to 12-Feb-92.

Cobalt.

Pasture grown in the aerated cultivation treatment had a significantly lower cobalt concentration than the nil cultivation treatment at both dates. The subsoiled cultivation treatment had the lowest cobalt concentration on 1-Aug-91 (Figure 4.42). Cobalt is essential for the fixation of nitrogen by rhizobium bacteria. The amounts of cobalt required are so minute that cobalt deficiency severe enough to effect nitrogen fixation is unlikely. The importance of cobalt to New Zealand agriculture is due to its requirement by grazing animals (Critical level 0.08 mg Co kg^{-1}) (M^c^Laren and Cameron, 1990; Sherrell and M^c^Intosh, 1987).

Pasture plants growing in wet soils often have a higher concentration of cobalt (Fleming, 1973). This was found to occur in this trial. From the 1-Aug-91 the nil cultivation treatment had a wetter soil profile, resulting in higher cobalt concentrations than the drier subsoiled cultivation treatment (Fleming and Murphy, 1968; M^{c}Laren and Cameron, 1990) (Section 4.6.1).

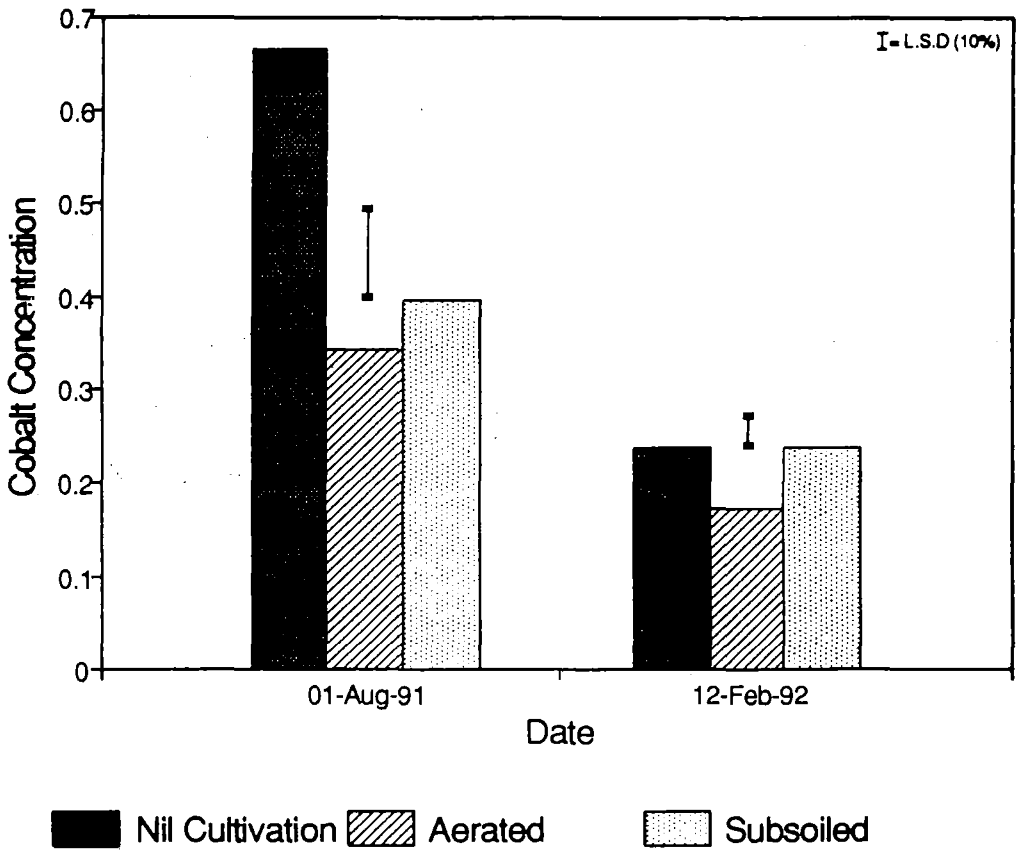

Figure 4.42: Pasture cobalt concentration ($\mu g\ g^{-1}$) as affected by cultivation treatment, 1-Aug-91 to 12-Feb-92.

4.8.1.2 Effect of fertiliser treatment on micronutrient concentration.

Cobalt was the only micronutrient that showed any trend or significant effect in relation to fertiliser treatment (Table 4.29).

Date	Fertiliser Treatment			FProb	L.S.D (10%)
	Nil	P	P & S		
1-Aug-91	0.467	0.445	0.492	NS	-
12-Feb-92	0.184	0.243	0.219	0.016	0.0323

Table 4.29: Pasture cobalt concentration ($\mu g\ g^{-1}$) as affected by fertiliser treatment, 1-Aug-91 to 12-Feb-92.

4.8.2 Micronutrient uptake.

4.8.2.1 Effect of cultivation treatment on micronutrient uptake.

The effect of cultivation treatment on micronutrient uptake is presented in Table 4.30.

	Cultivation treatment			FProb	L.S.D (10%)
	Nil	Aerated	Subsoiled		
Iron					
1-Aug-91	1.692	1.122	1.270	0.049	0.3752
12-Feb-92	0.420	0.325	0.248	0.067	0.1171
Zinc					
1-Aug-91	0.0398	0.0399	0.0442	NS	-
12-Feb-92	0.0312	0.0250	0.0187	0.052	0.0079
Cobalt					
1-Aug-91	0.000615	0.000403	0.000454	0.028	0.00012
12-Feb-92	0.000197	0.000133	0.000133	0.036	0.00004
Manganese					
1-Aug-91	0.1215	0.01210	0.1499	NS	-
12-Feb-92	0.1244	0.1130	0.0839	NS	-
Copper					
1-Aug-91	0.00703	0.00594	0.00698	NS	-
12-Feb-92	0.00444	0.00353	0.00290	NS	-

Table 4.30: Micronutrient uptake (kg ha^{-1}) as affected by cultivation treatment.

On the 1-Aug-91, the nil cultivation treatment had the largest uptake of iron and cobalt of the three cultivation treatments. This was discussed in Section 4.8.1, as being a result of the nil cultivation treatment having a wetter soil profile resulting in increased soil solution concentrations of iron and cobalt compared to the loosened treatments (Fleming, 1973; Mengel and Kirkby, 1982; M^{c}Laren and Cameron, 1990).

On the 12-Feb-92 plants grown in the nil cultivation treatment had a higher uptake of all micronutrients (Fe, Zn, Co, Mn and Cu). On this date the nil cultivation treatment had the lowest dry matter production (Section 4.3.1.1) and the highest micronutrient concentrations (Section 4.8.1.1).

This is contrary to the work by Coventry *et al.* (1987) who found that ripping (40 cm) increased manganese uptake by wheat, and that ripping had no effect on the uptake of other micronutrients.

4.8.2.2 The effect of fertiliser treatment on micronutrient uptake.

The addition of phosphate fertiliser alone or in combination with sulphate fertiliser significantly increased the uptake of iron, zinc, cobalt, manganese and copper on the 12-Feb-92 (Table 4.31). This was due to the increased pasture production resulting from these fertiliser treatments (Section 4.3.1.2).

	Fertiliser Treatment			FProb	L.S.D (10%)
	Nil	P	P & S		
Iron	0.222	0.389	0.389	0.044	0.1171
Zinc	0.0181	0.0288	0.0279	0.066	0.00799
Cobalt	0.00009	0.0002	0.00018	0.002	0.00004
Manganese	0.0742	0.1206	0.1264	0.058	0.0376
Copper	0.00252	0.00448	0.00387	0.053	0.00129

Table 4.31: Micronutrient uptake (kg ha^{-1}), as affected by fertiliser treatment, 12-Feb-92.

5.0 MICROPLOT TRIAL.

5.1 Introduction.

It has been stated that the production capacity of soils could be improved if nutrient reserves and water present in the subsoil were available to plants (Gediga, 1991). Root activity in the subsoil contributes considerably to crop uptake of sulphur, phosphorus and nitrogen (Haak, 1981). The value of certain cultivation techniques to increase nutrient and water uptake from the subsoil are under valued (Haak, 1981).

Chaney and Kamprath (1982) found subsoiling significantly increased corn leaf nitrogen concentration, to above that of conventional tillage, suggesting root extraction below the tillage pan. Ide *et al.* (1987b) state that these increases in nutrient uptake are due to subsoiling improving root growth. This effect of subsoil loosening has been found to be especially noticeable in drier years (Garwood and Williams, 1967).

Indications of better exploitation of the soil profile by roots is often deduced from changes in nutrient concentrations in the different soil depths as a function of time , for example Ide *et al.* (1987b) (Section 2.4.6). These methods however require destructive sampling which interferes with the determination of seasonal trends.

The problems involved in making non-destructive measurements of root length and recovery of nutrients from within the soil profile have resulted in the development of indirect methods involving the use of radioactive isotopes (Atkinson, 1990). For example Gediga (1991) used the calcium isotope, ^{45}Ca, in lysimeters to measure the effects of soil compaction on calcium uptake from different depths within the lysimeter. Various methods have been developed to inject radioactive tracers into field soils with some methods being more successful than others (Kafkafi *et al.*, 1965; Garwood and Williams, 1967; Bassett *et al.*, 1970; Hammes and Bartz, 1970; Newbould *et al.*, 1970).

The objectives of this microplot trial were to develop an improved method of radioactive isotope injection suitable for use in field soils and to assess the effect of soil loosening on nutrient uptake from different depths within the soil profile.

5.2 Methods and Materials.

5.2.1 Introduction.

For the injection of radioactive tracers to provide reliable information on the uptake of indigenous soil nutrients the following requirements must be met:

(i) The injection of the tracer must not alter the concentration of labile indigenous ions. The use of "carrier free" isotopes ensures this and therefore that the tracer does not act as a fertiliser.

(ii) The tracer must be allowed to equilibriate with the labile nutrients in the soil.

(iii) The sites of injection must be random relative to the distribution of the roots. The positioning of injection points in a constant geometric pattern at each depth ensures that this occurs.

(iv) The injection procedure should not alter the pattern of uptake by mechanical injury to the roots or by creating artificial pores through which roots could grow preferentially.

(v) The radioactive activity of the isotope must be of a sufficiently long half-life for enough observations to be made over an adequate time period.

5.2.2 Statistical design.

The microplot trial was conducted on three replicates of the main trial i.e. twenty-seven plots, in a randomised block design (Section 3.2.1). Only replicates one, two and four were used, because replicate three was found unsuitable due to variability in soil physical properties.

The three depths of injection (25, 40 and 55 cm) were randomly allocated within each replicate (Figure 5.1).

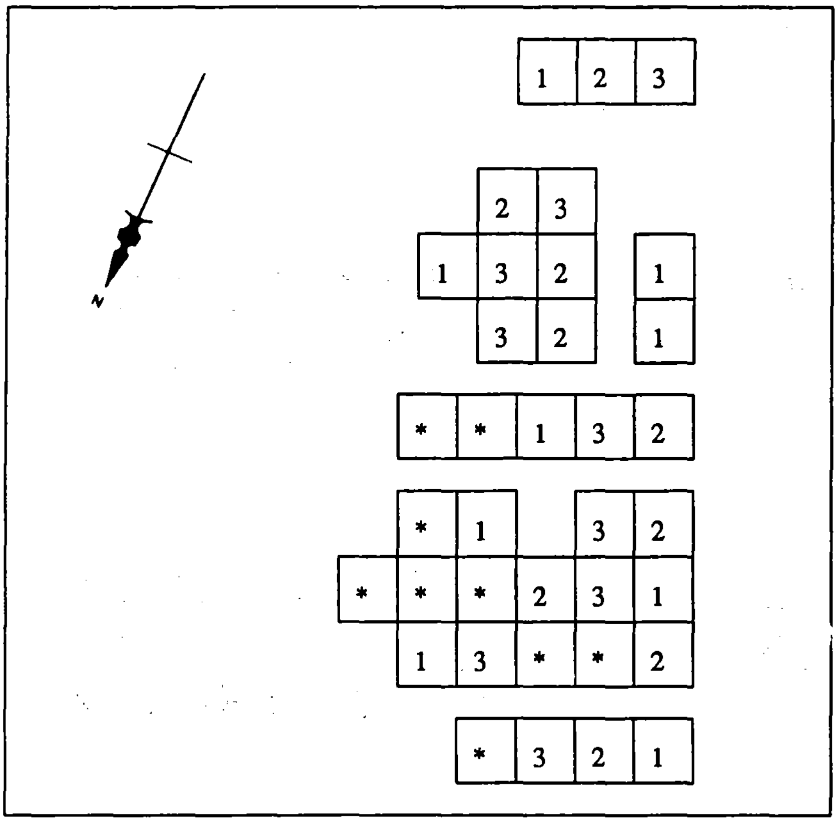

Figure 5.1: Allocation of radioactive tracer injection depths to plots.
Depths of injection:
1= 25 cm; 2= 40 cm; 3= 55 cm; *= not used.

5.2.3 Location of microplots.

The microplots were 800 mm in diameter located centrally on the shear plane in the non-fertilised portion of the mainplots (Section 3.2.3). Where possible, they were positioned near the Time-Domain- Reflectrometry wave guides (Section 3.3.1.1). On the east side of each microplot Gamma Probe access tubes were placed parallel to the same shear plane (Section 3.3.1.1).

5.2.4 Depths of injection.

Three depths of injection were used 25, 40, and 55 cm. The three depths of injection were chosen to allow the effects of the different depths of loosening to be determined (Figure 5.2).

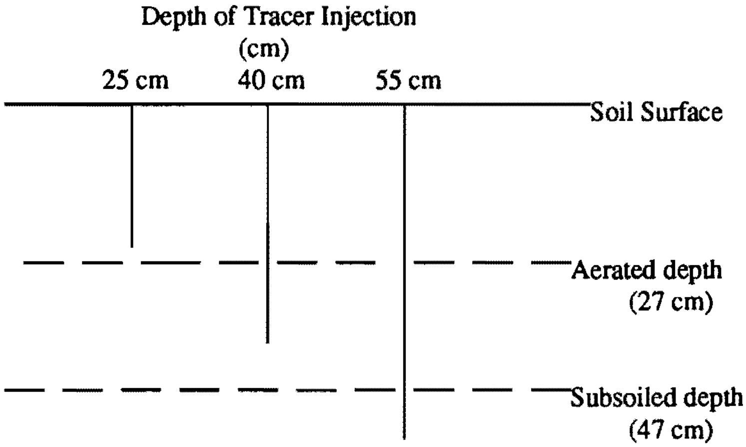

Figure 5.2: Depths of radioactive tracer injection used in the microplot trial.

5.3 Injection of Radioactive Isotope.

5.3.1 Installation of access tubes for the injection of radioactive isotope.

A template (100 cm x 100 cm) was constructed from 20 mm thick plywood. On the template a 800 mm diameter circle was drawn, and forty-five holes for injection drilled in a 100 mm x 100 mm grid pattern (Figure 5.3).

The template was placed on the surface of the microplot and access tubes were pushed through each hole to a depth 20 mm above the desired depth of tracer injection.

The access tubes were constructed of stainless steel tubing (6.2 mm external diameter). The leading edge of the tube was bevelled. A 4.1 mm diameter auger bit was inserted through the centre of each tube. The soil in the access tube plus 20 mm beyond the end of the access tube was augered out using a battery operated hand drill, thus removing any soil within the access tube. This created a small cavity beyond the end of the access tube and thus allowed the radioactive tracer to be injected at the desired depth (Figure 5.4).

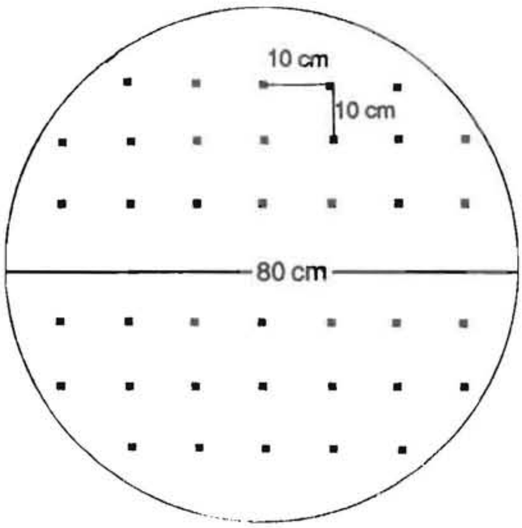

Figure 5.3: The injection template used for positioning of access tubes in the microplot trial.

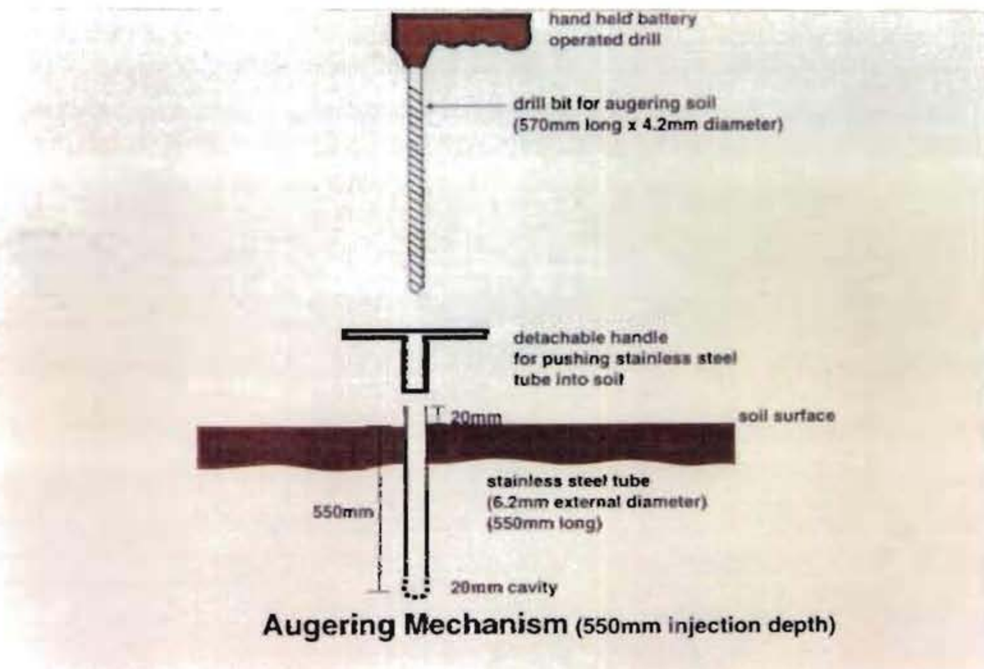

Figure 5.4: Installation of access tubes for the injection of radioactive tracer into the microplots.

5.3.2 Injection apparatus and technique.

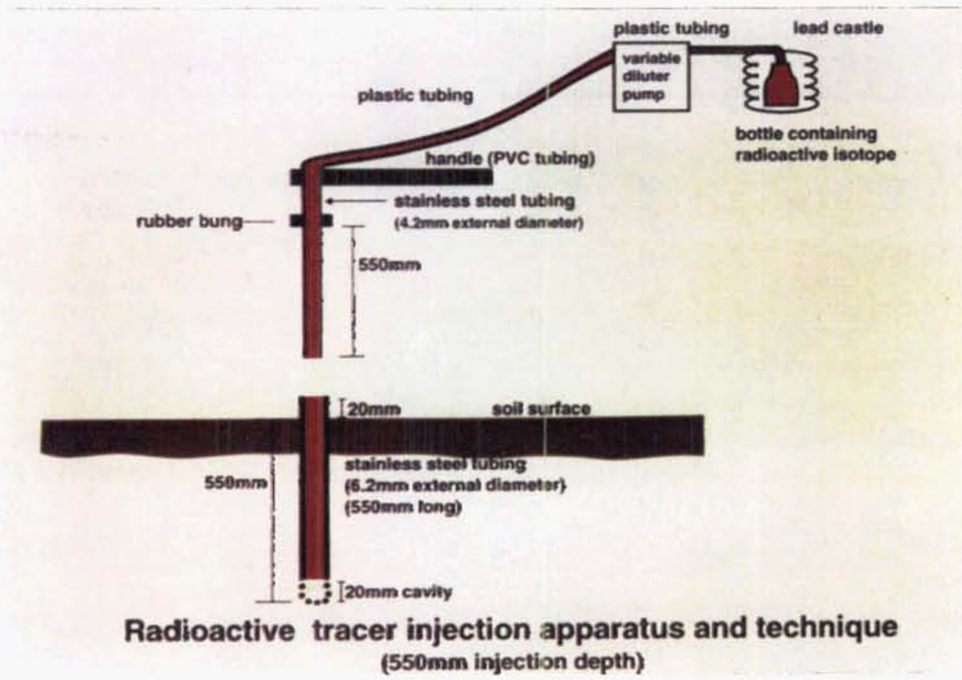

Figure 5.5: The injection apparatus used for the injection of radioactive tracer.

The radioactive tracer was stored in plastic bottles inside a lead castle (Figure 5.5). A plastic tube from the bottle led to an 'Autodilutor' (Automatic Variable Dilutor, Hook and Tucker, Made in England). The 'Autodilutor' was set to deliver exactly 1 ml of tracer solution. No drips occurred from the system due to the method of delivery from the 'Autodilutor'.

The radioactive tracer solution was delivered through a stainless steel tube (2.6 mm external diameter) inserted to the required depth through each access tube (Figure 5.5). A rubber bung on the stainless steel tubing was used to ensure that the tube did not enter the 20 mm cavity at any of the three injection depths. Once the injecter was in place, a 1 ml aliquot of tracer was supplied by the 'Autodilutor' (Table 5.1).

	$\mu C_i\ ml^{-1}$
^{32}P ^{35}S	4.5 4.5
	Plot total (μC_i)
^{32}P ^{35}S	202.5 202.5

Table 5.1: The concentration and amounts of ^{32}P and ^{35}S injected into the microplot trial.

Once the radioactive tracer had been injected into the cavity the microplot was left for at least two hours to allow the radioactive tracer to move into the soil.

After two hours, the stainless steel tubing was removed using a clamp device to prevent damage to the top of the tubing.

It was considered necessary to fill the hole left by the removal of the access tubes in order to prevent preferential root growth and water flow. This was done by injecting liquefied vaseline (45 °C) into the hole using a 50 ml syringe. Liquefied vaseline was used because it was able to flow within the hole left by the tube, whilst it was too viscous to enter the soil matrix (Plate 5.1).

Plate 5.1: Injection of molten vaseline into the cavity left by the access tube from the microplots.

The injection procedure took two days per replicate (nine microplots @ 45 injections) with the replicates being completed as close together as possible.

i.e. Replicate 1 15-16 August 1991,
Replicate 2 19-20 August 1991,
Replicate 3 21-23 August 1991.

At the time of radioactive tracer injection, the soil profile was near to field capacity moisture content (33%, v/v) (Table 5.2).

Depth (cm)	Nil (%, v/v)	Aerated (%, v/v)	Subsoiled (%, v/v)
25	29.3	30.2	31.0
40	30.7	42.7	20.6
55	34.4	32.8	32.2

Table 5.2: Soil volumetric water content at the time of radioactive tracer injection.

The soil temperature during the injection events (15-13 August 1991) ranged from 3.0 °C to 5.7 °C at the 10 cm depth and 5.6 °C to 7.7 °C at 30 cm depth.

There were three rain events from 15-Aug-91 to 23-Aug-91 (Table 5.3).

Date	Rainfall (mm)
17-Aug-91	3.5
22-Aug-91	6.4
23-Aug-91	0.2

Table 5.3: Rainfall events during the period of radioactive tracer injection.

5.3.3 Harvest of the microplots.

The microplots were harvested whenever there was sufficient plant material available for analysis (pasture height of approximately 60-80 mm). This usually occurred over a time interval of approximately three weeks. Microplot harvests were timed to coincide with mainplot harvests (Section 3.3.3) (Table 5.4).

Date of microplot harvests
9-Sep-91
28-Sep-91
23-Oct-91
29-Nov-91
18-Dec-91
16-Jan-92
12-Feb-92

Table 5.4: Microplot trial harvest dates.

The microplots were harvested using hand held shears. The microplots were cut to a height of approximately 20 mm above ground level. Plant samples from the central 400 mm diameter circle were kept for dissection and analyses. The outer circle was considered to be a buffer area and plants from there were safely discarded.

Once collected the samples went through the various steps outlined below (Figure 5.6):

(1) Fresh weight (g) of full sample determined.

(2) Plant dissection into grass, clover and other plants.

(3) Fresh weight (g) of each dissected sample determined.

(4) Dried (24 hrs at 60 °C).

(5) Dry weight (g) of dissected samples determined.

(6) Percentage of grass, clover and other plants determined.

(7) Total dry matter per microplot calculated.

(8) Each dissected dried sample was ground using a coffee grinder (Di Hong Jie, 1991).

5.3.4 Chemical analysis.

5.3.4.1 Activity of ^{32}P-Phosphorus.

Duplicate subsamples (about 100 mg) of ground plant sample were digested on a heating block using a nitric/perchloric (concentrated) acid digestion (Di Hong Jie, 1991).

A 15 ml plant digest solution was taken in a glass scintillation vial for Cerenkov counting (Di Hong Jie, 1991).

Calculation of the recovery of ^{32}P was only possible until 23-Oct-91 due to the short half-life of ^{32}P (14 days).

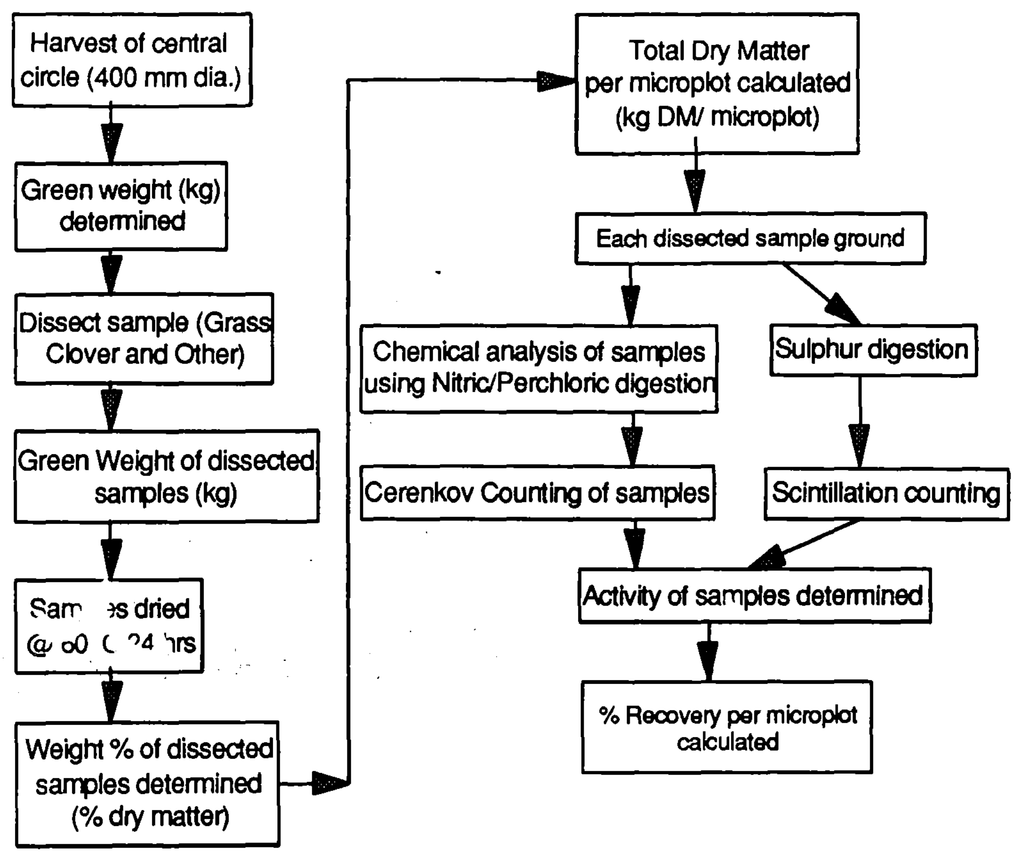

Figure 5.6: Flow diagram of sample treatment from the microplot trial.

At each counting event, two blanks and four standards were also counted. Each sample was counted for a period of ten minutes. The percentage error was generally less than 1%. Isotopic decay was taken into account by comparing the activity of samples with the standards counted at the same time. The background value provided by a blank was subtracted.

5.3.4.2 Activity of ^{35}S-Sulphur.

The determination of ^{35}S activity was delayed until a sufficient time period had elapsed to allow the decay of the ^{32}P.

Duplicate subsamples (30 mg) of ground plant sample were combusted in a muffle furnace @ 550 °C for six hours. The residue was extracted with KH_2PO_4 solution (500 mg P l^{-1}), shaken (end over end) for one hour, centrifuged @ 1000 rpm for ten minutes and filtered (N^o 5 Whatman). A 1 ml aliquot of extract and 10 ml of scintillation cocktail were mixed in a glass vial. The scintillation cocktail consisted of 1675 ml Toluene, 825 ml Triton X-100 (scintillation grade) and 15 g of 2,5-Diphenyloxazole (PPO). The activity of each sample was determined by the same procedure as for ^{32}P (Section 5.3.4.1).

5.3.5 Safety precautions.

Appı priate safety precautions for the use of radioactive materials were taken. The field trial . rea was fenced, and warning labels laced on radioactive areas. A 6.5 mm thick perspex glass sheet, which adequately absorbs energetic beta radiation such as that from ^{32}P, was used for shielding personnel in most operations. Lab ratory coats and disposable rubber gloves were worn during tracer injection procedures. Grinding of plant samples was carried out in a fume cupboard and a face mask was worn in addition to the protective clothing mentioned above. Radioactive wastes were disposed of at a designated dump for radioactive materials at Lincoln University. Contaminated glassware and equipment were stored in a safe place until the activity decayed to insignificant levels.

5.4 Results and Discussion.

5.4.1 Concentration of ^{35}S-Sulphur in pasture plants.

5.4.1.1 Concentration of ^{35}S-Sulphur in pasture plants as affected by cultivation treatment.

A full set of results is presented in Appendix 5.1.

On 28-Sep-91 and 16-Jan-92 the loosened treatments of aeration and subsoiling had higher ^{35}S concentrations than the nil cultivation treatment at the 25 cm injection depth (Figure 5.7 and Figure 5.8). No other significant differences or trends of ^{35}S concentration occurred between the three cultivation treatments, at other harvest dates during the microplot trial.

At the 25 cm injection depth the trends are exaggerated when the weed component is removed. On 16-Jan-92 the weed component was 23% of the microplot pasture compared to only 10% on 28-Sep-91 (Appendix 5.2). At both dates mentioned the subsoiled cultivation treatment had significantly more weeds and less grass than the aerated or nil cultivation treatments.

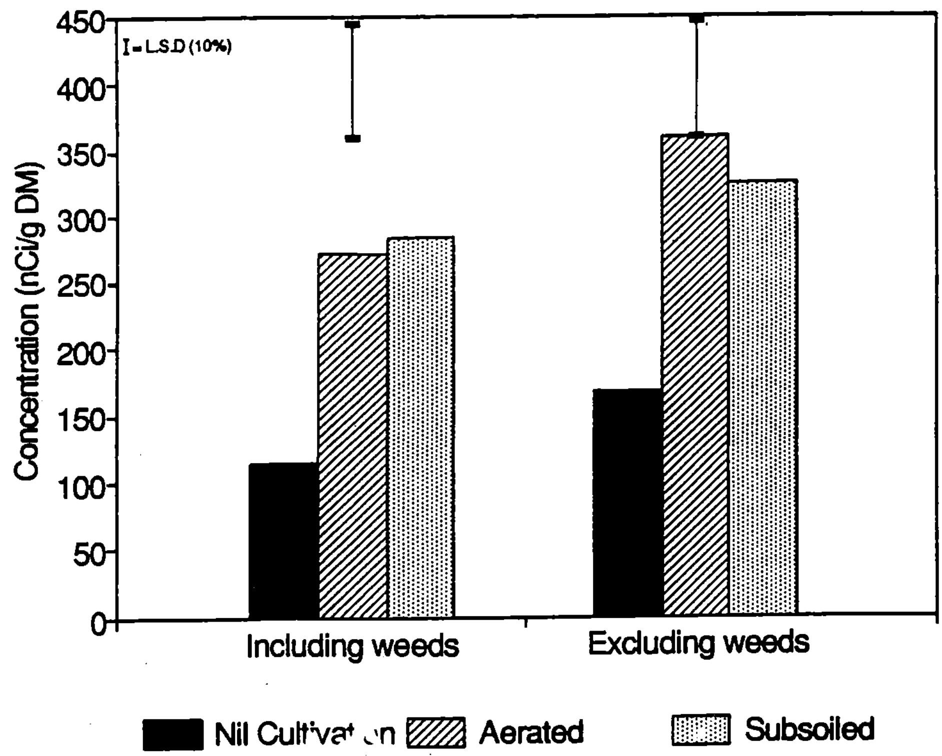

Figure 5.7: The effect of cultivation on pasture ^{35}S-Sulphur concentration, plus and minus the weed component, following injection at 25 cm depth, 28-Sep-91.

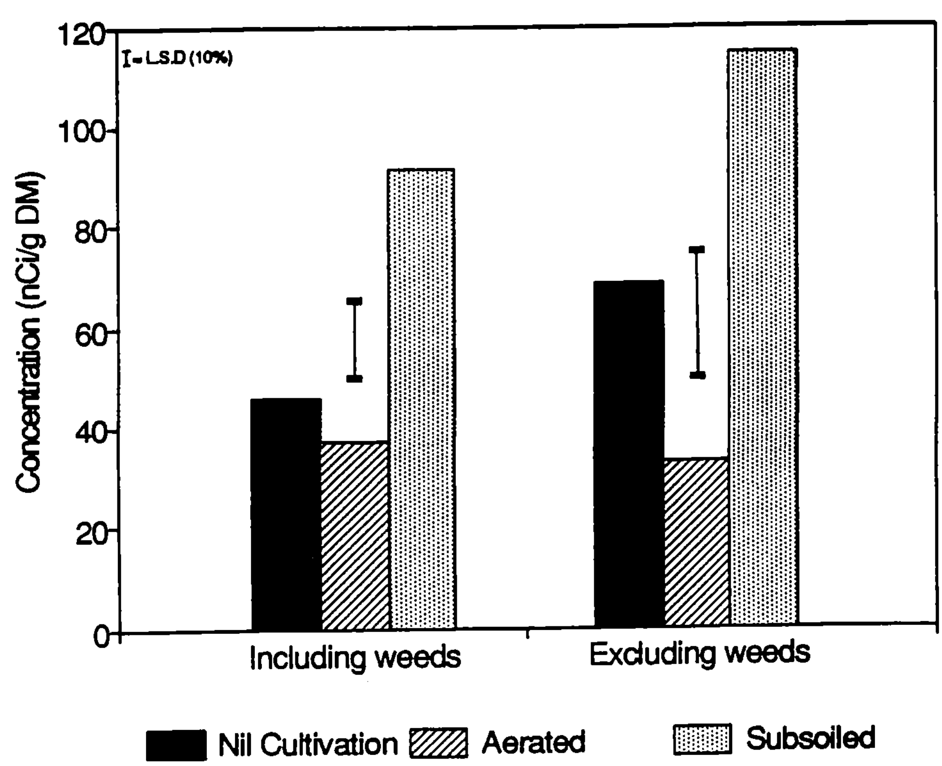

Figure 5.8: The effect of cultivation on pasture ^{35}S-Sulphur concentration, plus and minus the weed component, following injection at 25 cm depth, 16-Jan-92.

5.4.1.2 The ^{35}S-Sulphur concentration in the pasture components.

The ^{35}S concentration of the pasture components is presented in Table 5.5.

Date	Depth	Grass	Clover	Weeds	FProb	L.S.D(10%)
28-Sep-91	25	431	137	101	0.001	83.80
23-Oct-91	25	323	174	85	0.011	102.66
29-Nov-91	25	184	92	31	0.001	37.78
16-Jan-92	25	107	37	30	0.001	25.74
28-Sep-91	40	55.7	26.5	27.9	NS	-
23-Oct-91	40	61.9	25.5	1.2	0.003	24.08
29-Nov-91	40	36.3	61.1	91.9	0.031	31.67
16-Jan-92	40	29.0	62.0	24.0	NS	-
28-Sep-91	55	14.9	6.8	24.4	0.022	9.45
23-Oct-91	55	16.5	11.0	10.7	NS	-
29-Nov-91	55	23.7	20.3	10.1	NS	-
16-Jan-92	55	3.8	25.5	14.5	NS	-

Table 5.5: ^{35}S-Sulphur concentration (nCi g^{-1} DM) of pasture components.

Following injection at the 25 cm depth the ^{35}S concentration of the grass component was significantly higher than the other components (Figure 5.9), with the weed component having the lowest concentration.

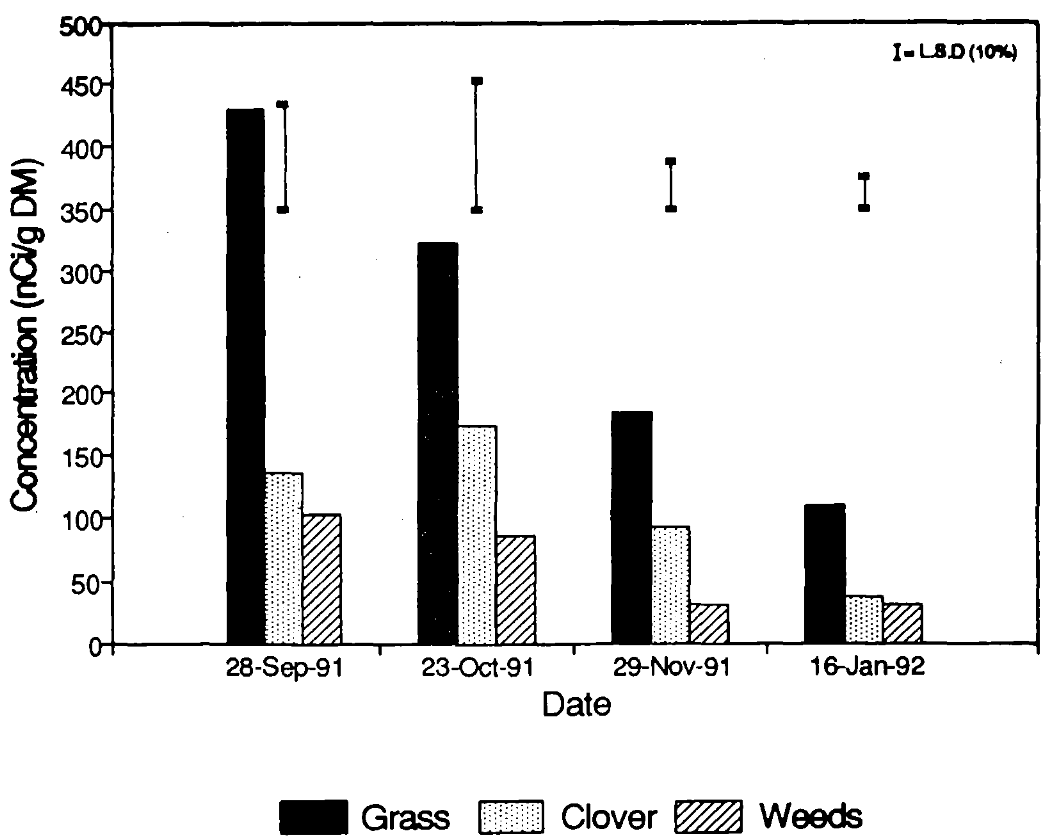

Figure 5.9: Concentration of ^{35}S-Sulphur in the pasture components at the 25 cm injection depth.

This reflects the dense rooting pattern of grass and it's rooting dominance at this depth (Harris, 1987). The grass component was at least 60% of the pasture harvested from the microplots (Appendix 5.2).

The ^{35}S concentration decreased between harvests. As the soil moisture content of the soil decreased from 23-Oct-91 to 16-Jan-92 the ^{35}S uptake decreased accordingly. Also with each harvest removed the ^{35}S present in the soil decreased due to plant uptake.

During mid spring 1991 (28-Sep-91 and 23-Oct-91) the concentration of ^{35}S was significantly greater in the grass component compared to the clover and weed component on plots with tracer injection at the 40 cm depth (Figure 5.10). However, this trend was reversed when the soil moisture content decreased (29-Nov-91 to 16-Jan-92).

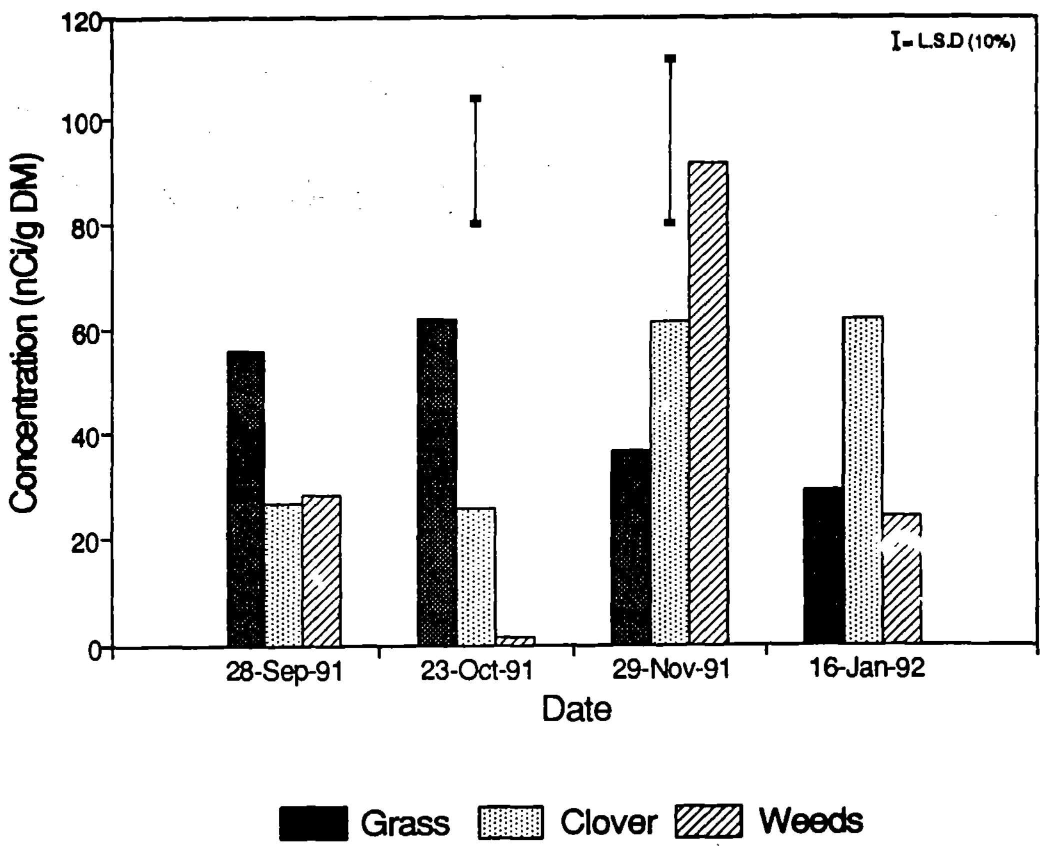

Figure 5.10: Concentration of ^{35}S-Sulphur in the pasture components at the 40 cm injection depth.

At the 55 cm depth of injection there is no notable trend in plant ^{35}S concentration. However it is worth noting the tendency for the clover to have a higher concentration during the summer months (Figure 5.11). This indicates continued activity by clover at depth in the soil profile over this period.

As the depth of injection increased the concentration of ^{35}S in the pasture components decreased.

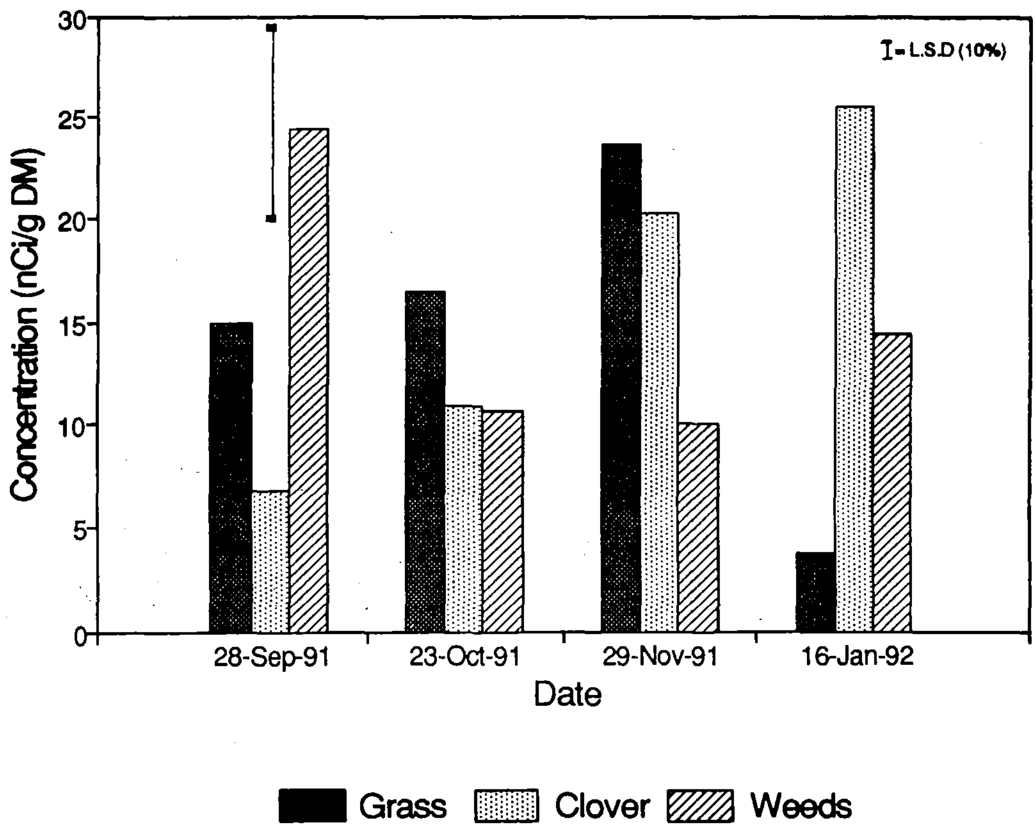

Figure 5.11: Concentration of ^{35}S-Sulphur in the pasture components at the 55 cm injection depth.

5.4.2 <u>Percentage recovery of ^{35}S-Sulphur.</u>

5.4.2.1 Total recovery of ^{35}S-Sulphur.

The total recovery of ^{35}S depth from all depths of injection (25, 40, 55 cm) at the end of the microplot trial (12-Feb-92) was not significantly different between cultivation treatments (Figure 5.12) (Appendix 5.3).

The total percentage recovery fell as the injection depth increased. At the 25 cm injection depth each cultivation treatment had a recovery of greater than 14%. However at the 40 cm injection depth the highest total recovery was only 5%, and at 55 cm it was only 1.5%. This in part is a reflection of the decrease in root length which occurred with increasing depth (Section 4.4.2). On 16-Jan-92, averaged over the three cultivation treatments, there was 30-50% of the total root length present between 20-30 cm depth, while between the 30-40 cm depth, this fell to 11-21%. With only 3-7% of the total root length present at the 50-60 cm depth.

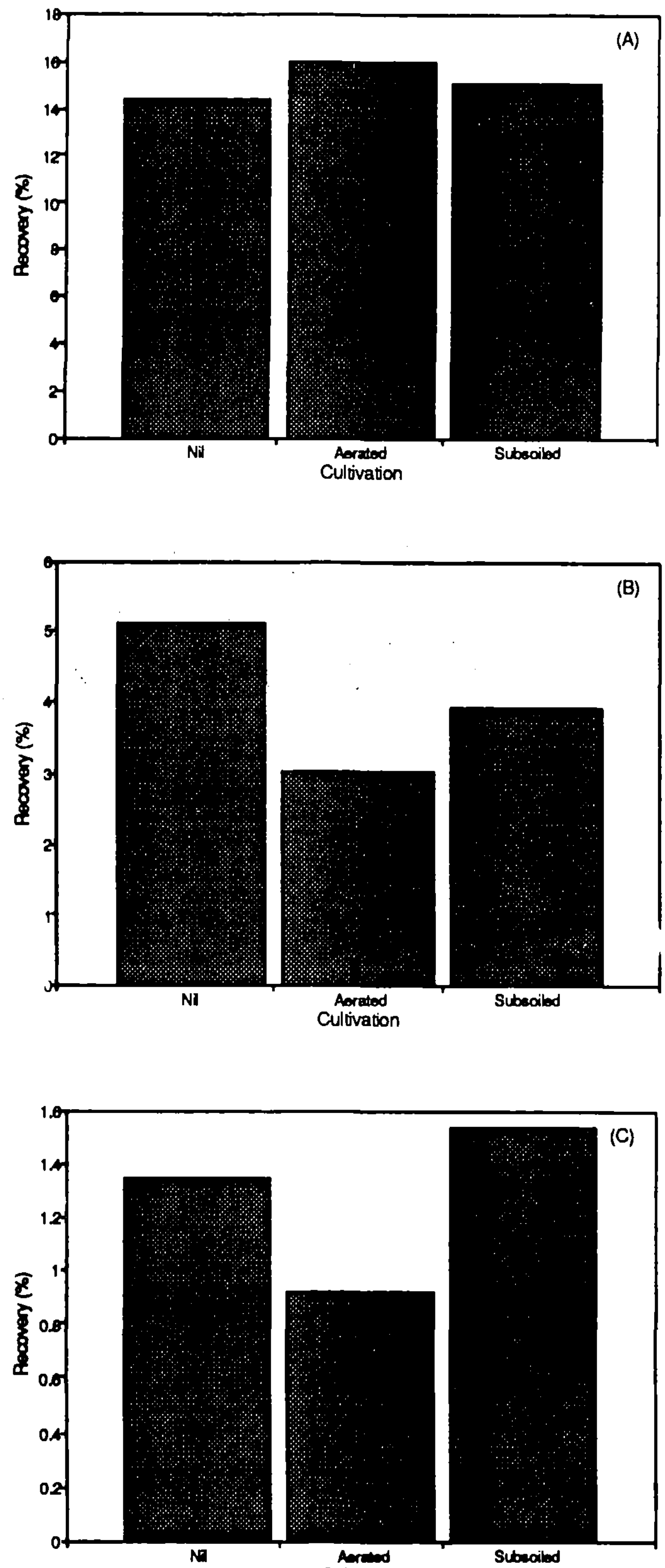

Figure 5.12: Total recovery of ^{35}S-Sulphur as affected by cultivation treatment. (A) 25 cm injection depth, (B) 40 cm injection depth and (C) 55 cm injection depth.

5.4.2.2 Recovery of ^{35}S-Sulphur as affected by cultivation treatment.

The seasonal pattern of ^{35}S recovery was similar between cultivation treatments. As the pasture began to grow at a faster rate reaching high production values, the roots would have exploited greater depths in the soil profile. This is indicated in Figure 5.13, on the 29-Nov-91, by the relatively high recovery of ^{35}S from the 55 cm injection depth (Appendix 5.3)

From 29-Nov-91 to 18-Dec-91 the soil, profile water content decreased rapidly, with 21 water deficient days being experienced (Section 4.1.2.2). The pasture growth (kg DM ha^{-1}) (Section 4.3.1.1) also fell, correspondingly the recovery of ^{35}S from all depths of injection fell (Figure 5.13, Figure 5.14 and Figure 5.15).

There was no significant differences between the recovery of ^{35}S in the three cultivation treatments, except on two dates at the depths shown in Table 5.6.

Date: 23-Oct-91 Depth: 55 cm				
Nil (%)	Aerated (%)	Subsoiled (%)	FProb	L.S.D (10%)
0.214	0.376	0.094	0.190	0.190
Date: 16-Jan-92 Depth: 25 cm				
Nil (%)	Aerated (%)	Subsoiled (%)	FProb	L.S.D (10%)
1.050	0.340	2.450	0.005	0.6396

Table 5.6: Significant differences in percentage recovery of ^{35}S-Sulphur from the three depths of injection as affected by cultivation treatment.

On the 23-Oct-91 the subsoiled treatment had the lowest recovery of ^{35}S, it also had the lowest concentration of the three cultivation treatments. This treatment also had significantly less pasture production, which is the opposite to the results from the main trial. On 16-Jan-92 the subsoiled cultivation treatment had a significantly higher ^{35}S concentration and pasture production, which resulted in a significantly higher ^{35}S recovery. The soil was dry on the 16-Jan-92 (10-12%, v/v) (Section 4.6.1). The subsoiled cultivation treatment had higher growth rates when the soil was dry, this was in part due to the more extensive rooting pattern present at depth in the soil profile.

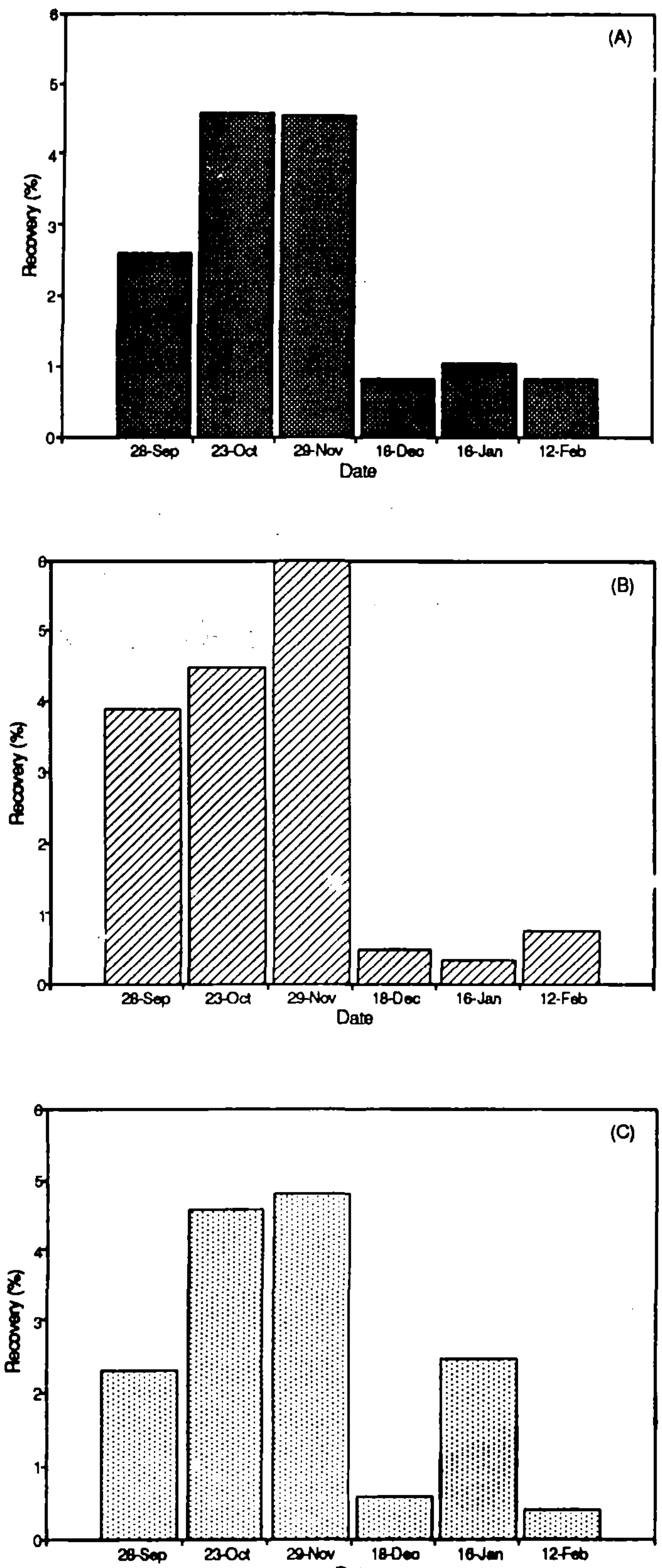

Figure 5.13: Recovery of ^{35}S-Sulphur from the 25 cm injection depth as affected by cultivation treatment. (A) Nil cultivation; (B) Aerated; (C) Subsoiled .

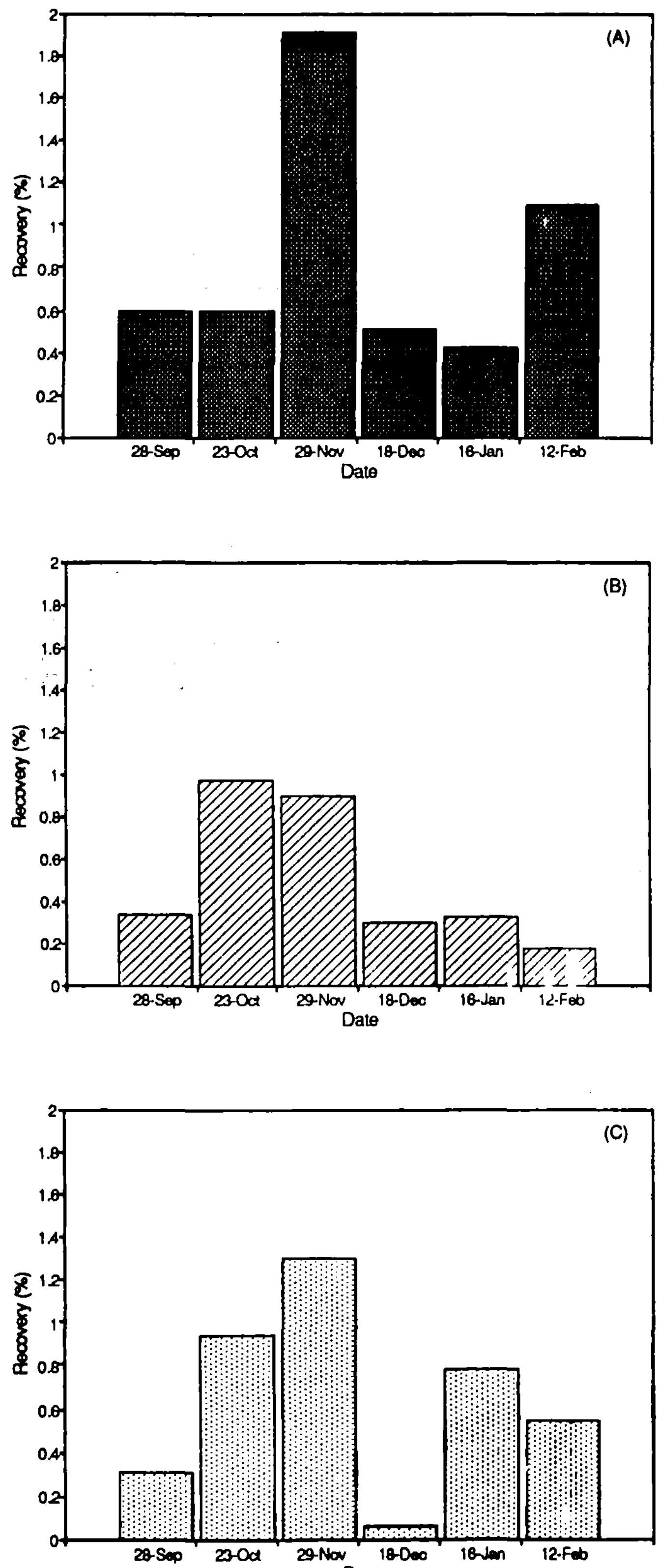

Figure 5.14: Recovery of ^{35}S-Sulphur from the 40 cm injection depth as affected by cultivation treatment. (A) Nil cultivation; (B) Aerated; (C) Subsoiled .

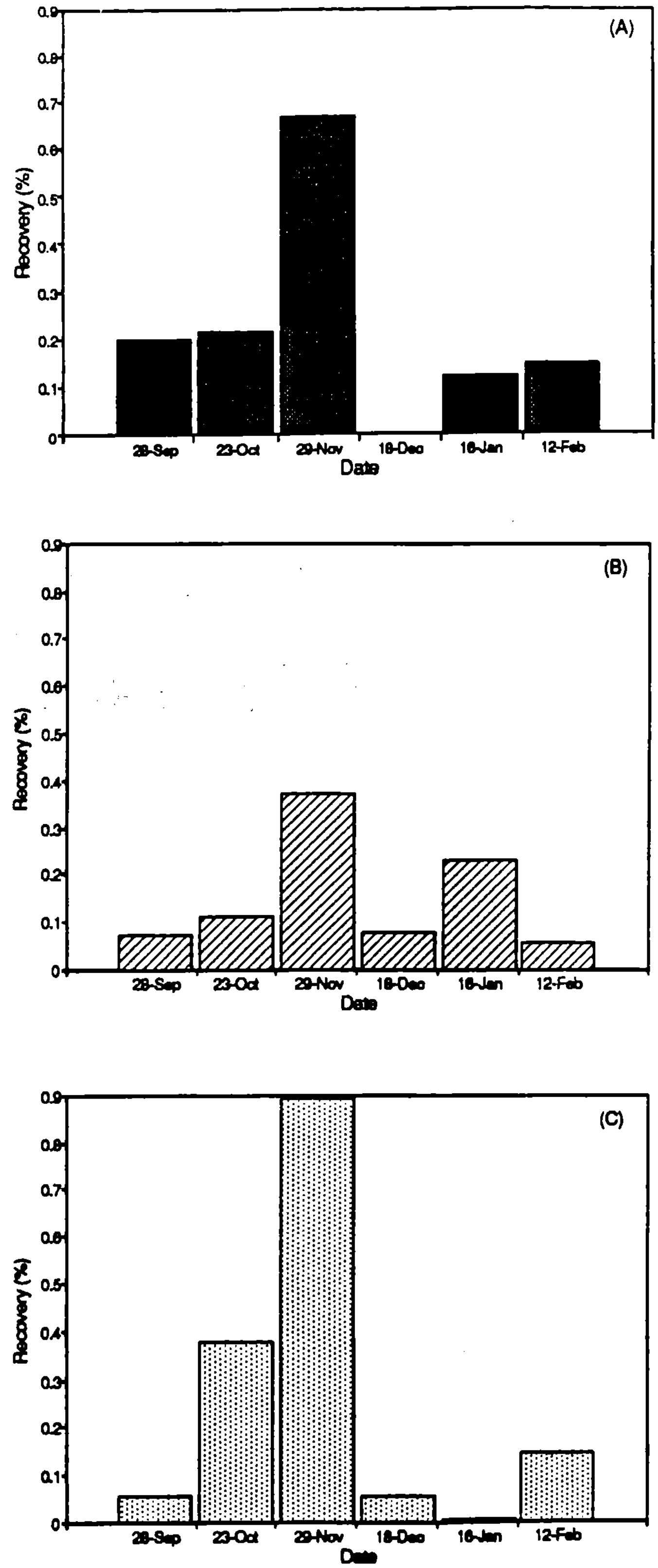

Figure 5.15: Recovery of ^{35}S-Sulphur from the 55 cm injection depth as affected by cultivation treatment. (A) Nil cultivation; (B) Aerated; (C) Subsoiled .

5.4.3 Cumulative recovery of ^{35}S-Sulphur as affected by cultivation treatment.

Over the late spring of 1991 (28-Sep-91 to 29-Nov-91) the subsoil loosened treatment had the greater cumulative recovery of ^{35}S from the 55 cm injection depth (Figure 5.16). This could indicate the earlier onset of root activity and faster spring root growth at depth within the soil profile of the loosened treatments. The roots of the subsoil loosened treatment increased in length during spring, growing to deeper depths in the soil profile, and were thus more active at depth than in the nil cultivation treatment (Section 4.4.2).

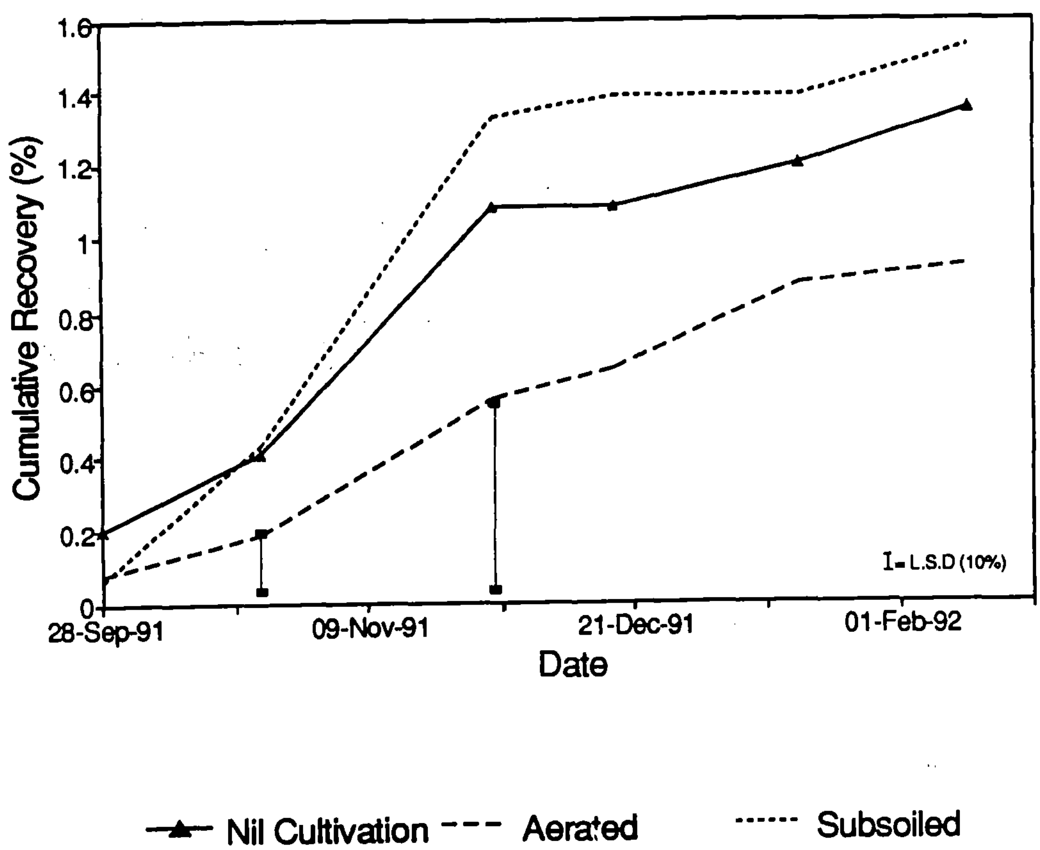

Figure 5.16: Cumulative recovery of ^{35}S-Sulphur from the 55 cm injection depth as affected by cultivation treatment.

Over this period (28-Sep-91 to 29-Nov-91) the subsoiled cultivation had significantly less pasture production on the microplots (Table 5.7), which is the opposite to the results from the main trial (Section 4.3.1.1).

	28-Sep-91 (kg ha^{-1})	23-Oct-91 (kg ha^{-1})	29-Nov-91 (kg ha^{-1})
Nil	35.9	76.3	149.7
Aerated	33.5	70.5	147.3
Subsoiled	26.1	55.6	119.2
+/- S.E	2.05	4.45	7.93

Table 5.7: Microplot pasture production as affected by cultivation treatment, 28-Sep-91 to 29-Nov-91.

This could be explained by the subsoiled treatment having significantly more clover and weeds over this time. These plants tend to be tap rooted in dryland populations (Harris, 1987; Woodfield and Caradus, 1987).

5.4.4 Total recovery of ^{35}S-Sulphur by the pasture components.

Different pasture components, grass, clover and weeds exhibit different rooting habits within the soil profile (Harris, 1987). We therefore calculated the total recovery of ^{35}S of the different pasture components to see if the loosened treatments had favoured the root development of any particular pasture component (Table 5.8).

Date	Depth (cm)	Grass (%)	Clover (%)	Weeds (%)	FProb	L.S.D (10%)
28-Sep	25	1.18	2.20	0.57	0.057	1.026
	40	0.245	0.158	0.072	NS	-
	55	0.065	0.035	0.041	NS	-
23-Oct	25	2.450	3.940	1.010	0.063	1.8678
	40	0.677	0.097	0.214	0.038	0.3784
	55	0.067	0.101	0.177	NS	-
28-Nov	25	2.270	3.750	2.160	NS	-
	40	0.990	0.340	0.340	0.043	0.5172
	55	0.322	0.258	0.258	NS	-
16-Jan	25	0.720	0.500	0.590	NS	-
	40	0.300	0.148	0.133	NS	-
	55	0.133	0.001	0.017	NS	-

Table 5.8: Total recovery of ^{35}S-Sulphur of each pasture component during the microplot trial.

At the 25 cm injection depth the clover component had a higher percentage recovery of ^{35}S than the grass or weed component, even though it comprised no more than 20% of the microplots pasture over the 1991/1992 season. While the grass had a significantly higher ^{35}S concentration.

At the 40 cm injection depth the grass component tended to have a higher percentage recovery of ^{35}S. The concentration of ^{35}S in the grass component was not always higher at the 40 cm depth of injection, suggesting that there was a dilution effect due to the higher dry matter production. At the 55 cm injection depth, the results of percent recovery are varied and no significant differences occurred.

When the weed component was removed from the statistical analysis the differences in percent recovery of ^{35}S from the aerated and subsoiled cultivation treatments on the 29-Nov-91 became significantly different to the nil cultivation treatment (Table 5.9) (Section 5.4.2.2). The percent recovery of the weed component was not significantly different itself, but when included in the statistical analysis created large variation in the statistical analysis.

Date: 29-Nov-91					
Depth (cm)	Nil (%)	Aerated (%)	Subsoiled (%)	Fprob	L.S.D (10%)
25	0.9651	4.4681	4.5110	0.003	0.1484

Table 5.9: Recovery of ^{35}S-Sulphur in grass plus clover components of the microplot trial as affected by cultivation treatment, 29-Nov-91.

Even though the weed component only comprised 6-7% of the microplot pasture its relative recovery was still enough to confound the results. On 29-Nov-91 the weed component of the subsoiled cultivation treatment had a significantly higher ^{35}S concentration (229.3 nCi g^{-1} DM) than the other pasture components, and the subsoiled treatment had a significantly larger proportion of weeds compared to the other treatments.

5.4.5 Summary.

Tracer techniques based on the use of stable sulphur isotopes are seldom reported in the literature. The literature review showed that there were no reported studies of the uptake of labelled sulphur from depths in the soil profile. Hence, it is difficult to compare the results from this study to other studies.

The tracer injection technique which was developed was successful for ^{35}S labelling of indigenous soil sulphur and provided a useful estimate of the activity of plant roots at different depths in the profile.

Over the period of rapid pasture root growth (28-Sep-91 to 29-Nov-91) (Section 4.4.2) pasture on the loosened treatments developed a root system which was significantly different to that of the nil cultivation treatment. The subsoil loosening cultivation permitted a greater root length to develop between 30-60 cm depth (Section 4.4.2) and this resulted in the significantly higher cumulative recovery of ^{35}S from the subsoil loosened treatment at the 55 cm injection depth over the time of rapid root growth (Section 5.4.3).

5.4.6 Percentage recovery of ^{32}P-Phosphorus.

There was no significant differences in total recovery of ^{32}P between the cultivation treatments at any of the injection depths (Table 5.10).

Depth (cm)	Nil (%)	Aerated (%)	Subsoiled (%)	FProb
25	0.5226	0.5658	0.4229	NS
40	0.1499	0.3291	0.0835	NS
55	0.0343	0.0835	0.0139	NS

Table 5.10: Total recovery of ^{32}P-Phosphorus at the three injection depths as affected by cultivation treatment.

Uptake of phosphorus by plant roots occurs mostly by the diffusion process, which occurs in response to concentration gradients. It is therefore influenced by the water content of the soil profile. Phosphorus is absorbed by soil components and has been found to diffuse at best a distance of only a few millimeters during a growing season (Power, 1990).

When phosphorus is at a low concentration in the soil, the root surface area is most likely to be the limiting factor in phosphorus adsorption (Vose, 1990).

The coefficient of variation of the total percentage recovery of ^{32}P was 102% in this experiment, which is similar to values reported by Broeshart and Nethsinghe (1972). Broeshart and Nethsinghe (1972) found that percent recovery of ^{15}N gave a lower error variance due to the greater movement of nitrogen in the soil. The recovery of ^{35}S reported in Section 5.4.2 gave a coefficient of variance (50%) which was less than that for ^{32}P. This suggests that the recovery of ^{32}P was a chance event since the ^{32}P was present only in small confined locations in the soil profile. Plant roots would have to grow to within a few millimeters, or less, of the point of tracer injection. McLaughin *et al.* (1988) found that in their pot trial the uptake of fertiliser ^{32}P was variable. This was expected because the ^{32}P had been applied to a small volume, and the uptake of ^{32}P by the wheat plants was therefore influenced to a large extent by root distribution. The variation decreased as the plants matured and the root mass within the pots increased.

There were no significant differences present in root length (cm cm^{-2}), over the period when ^{32}P activity was measured (9-Sep-91 to 23-Oct-91) (Section 4.4.2).

The use of carrier free ^{32}P as a tracer for the uptake of indigenous phosphorus in this field trial was not successful for two main reasons:

(i) The injected ^{32}P did not label a sufficient volume of the soil profile at the injection depth.

(ii) The half-life of ^{32}P (14 days) was not sufficient to allow the study of root growth and the subsequent effect on ^{32}P recovery over a growing season.

6.0 DISCUSSION.

6.1 Introduction.

In the trial reported here, soil loosening resulted in an increased pasture production over the 1991/1992 season of approximately 1,300 kg DM ha^{-1}. The result was not however statisically significant due to the high variability associated with the field trial, but there was a clear trend towards higher dry matter production on the loosened soil treatments. The reasons for this trend are complex but are mostly attributed to improved plant nutrition resulting from nutrient uptake from greater depths in the loosened soil. Many researchers have stated that an increase in dry matter production following soil loosening is due to increased water availability brought about by increased root growth. However, in the present trial no differences in water use occurred between cultivation treatments. Therefore this discussion will expand on the beneficial effect of soil loosening on root growth and the subsequent increase in nutrient availability to the pasture.

6.2 The Effect of Soil Loosening on Pasture Root Growth.

The soil/root environment exerts an overriding effect on pasture production, through moisture and nutrient uptake. It is therefore surprising that so little data is available on the root systems of New Zealand pastures. Agronomic experiments seldom include root data and grazing experiments rarelv include a measurement of roots (Davidson, 1978). Excessive soil compaction is commonly considered to limit pasture growth due to restricted root growth and development (Marks and Soane, 1987). Previous workers in Canterbury, New Zealand, have indicated that poor root penetration of pea crops in the yellow-grey earths is associated with compact subsoils (Reid *et al.*, 1987; Greenwood, 1989). Although compact layers were indentified in this soil (Section 3.1.1) there was no obvious quantifiable impediment to root growth observed in the initial survey. However, the high bulk density was considered to have influenced root growth in these layers.

Subsoiling consists of loosening and disturbing soil, without turning the subsoil or bringing it to the surface (Ide *et al.*, 1987; M^c^Laren and Cameron, 1990). This cultivation practice has been shown to improve soil conditions for pasture root growth (Braim *et al.*, 1984; Chapman and Allbrook, 1987; Ide *et al.*, 1987b; Steed *et al.*, 1987).

Soil physical conditions.

In the trial reported in this thesis, loosening of compacted layers by aeration (to 27 cm) and subsoiling (to 47 cm) were found to significantly reduce bulk density by 11% and significantly increase porosity by 8%, compared to the nil cultivation treatment.

At the natural depth (30-50 cm) of soil compaction, root measurements made on 18-Jan-92 showed that the subsoil loosened treatment had a 41% greater root length and a 54% higher proportion of the total profile root length than the nil cultivation treatment at this depth. This was a direct result of the lower bulk densities and higher porosities found at the 30-50 cm depth, following subsoil loosening. Oussible and Crookston (1987) found in the zone through which the subsoiler had passed that the soil bulk density was reduced by 11% and soil porosity increased by 17%. At this depth (20-35 cm) roots were 54% longer in the subsoiled plots compared to the control plots.

Researchers have also suggested that the removal of a layer of high bulk density reduces root distortion, thus increasing root length and root activity (Coventry *et al.*, 1987). Oussible and Crookston (1987) noted there was an important change in root morphology within the 20-35 cm depth following subsoiling, where roots from the subsoiled plots tended to be finer and more profuse. Fine roots are reported to be more efficient in water absorption and nutrient uptake.

Greenwood (1989) found a weak correlation between root length and penetration resistance (r^2=0.58) at the 20 to 30 cm depth but a stronger correlation between root length and bulk density (r^2=0.77) at the same depth.

Linear correlations of bulk density and root length from the present study are presented in Table 6.1. Good relationships between bulk density and root length exist at the 10-30 cm depth. At these depths bulk density gives a measure of the resistance the soil offers to root growth since the porosity of the soil is included in the measure of bulk density. However, below 30 cm (B-horizon) the growth of roots is dependent on the existence of a few stable macropores. The volume of these macropores is not enough to lower the overall bulk density of the soil but their presence is enough to allow root growth to occur. Therefore a bulk measure of soil such as bulk density may not necessarily reflect the ease of root penetration at lower depths (i.e. >30 cm) in the soil profile.

Depth (cm)	r^2
0-10	0.06
10-20	0.92
20-30	0.87
30-40	0.28
40-50	0.34
50-60	0.04
60-70	0.03

Table 6.1: Linear relationship between root length and soil bulk density of the three cultivation treatments.

In this study, bulk density was therefore only used as a measure of rootability for the 10-30 cm depth. The reasonable bulk density/root growth relationships for these upper soil horizons suggest a significant positive influence of macroporosity on root growth. Physical stresses such as anaerobosis and mechanical impedance are directly influenced by the pore characteristics of the soil.

The stability of adequate pores which permit aeration, drainage and root penetration is known to be a major requirement for good root growth (Russell, 1981). Greenwood (1989) observed a good correlation between root length and the logarithm of hydraulic conductivity (r^2=0.78). This indicates the importance of continuous pores for root growth.

The hydraulic conductivity in May 1991 of the subsoil loosened treatment in this trial was significantly greater (134 mm h^{-1}) at the 20-40 cm depth compared to the nil cultivation treatment (35 mm h^{-1}). This provides evidence of an increase in the so-called functional porosity following soil loosening. This development of a continuous pore system is due to the disruption of the compacted layers and has allowed the development of an increased root length below 50 cm in the subsoil loosened treatment. Although the large mass of soil or distinct peds may have a high strength, roots may still be able to penetrate these layers if a network of sufficiently large voids exists (Wiersum, 1980). Voids allow the rapid penetration of roots and a greater proliferation of roots in each horizon (Braim *et al.*, 1984; Hipps and Hodgson, 1988; Barbosa *et al.*, 1989; Greenwood, 1989).

In this trial a decrease in soil bulk density and an increase in soil porosity following subsoil loosening led to significantly greater root lengths and a higher percentage of the total roots present below the 30 cm depth in the subsoil loosened treatment compared to the nil cultivation treatment.

Soil moisture.

Under field conditions soil moisture as well as soil structure and porosity determine the depth of penetration by roots (Haak, 1981). In this trial the better drainage of the subsoil loosened treatment resulted in a significantly drier soil profile (0-70 cm) during August 1991. The subsoiled treatment had a more rapid root penetration and root proliferation below 50 cm than in the nil cultivation treatment. Mengel and Kirkby (1982) state that over the spring period roots proliferate more freely in a drier soil.

The subsoil loosened treatment had a drier A-horizon over the spring period (1-Aug-91 to 28-Nov-91). This created an environment that was warmer, thus encouraging the earlier onset of root activity and root growth in the subsoil loosened treatment compared to the nil cultivation treatment.

Higher soil moisture contents are often related to poor soil aeration and lower soil temperatures which will reduce root growth rates (Wiersum, 1980). De Nobili *et al.* (1990) reported that deep plant roots grew eight times faster when the surface soil was maintained at 20% saturation than when it was maintained at 50% saturation. In this trial the drier topsoil of the loosened soil treatments aided the root growth below 30 cm during the spring period.

Aeration.

An important factor restricting root development is the aeration status of the soil. Poor soil aeration will restrict root respiration and therefore root growth in the soil (Wiersum, 1980). Compacted layers located at a depth smaller than the desired rooting depth, are an obstruction for root growth as a consequence of a low porosity accompanied by an oxygen shortage (Wiersum, 1980; Ide *et al.*, 1987b).

In the trial reported here, increased porosity of the previously compacted layers in the soil profile of the loosened treatments suggests an increased aeration status of the loosened soil profiles. This increase in aeration status was especially apparent below the 50 cm depth where the largest increases in root length occurred in the subsoil loosened treatment. Chapman and Allbrook (1987) also related the increased pasture root length after subsoiling (45 cm) to the increased aeration of the soil profile, caused by an increased macroporosity.

The poorer aeration status of the nil cultivation treatment during spring was also indicated by the higher micronutrient concentrations of plants grown in that treatment compared with those of the drier subsoil loosened treatment.

Spring root growth.

Root length (cm cm^{-2}) of the pasture showed no response to cultivation at the end of winter (1-Aug-91). However by the end of spring (28-Nov-91) significant differences were apparent in root length (36%, increase) and the relative vertical distribution (49%, increase) below the 30 cm depth of the subsoil loosened treatment compared to the nil cultivation treatment.

The spring root growth of a perennial ryegrass pasture in temperate regions is rapid, while there can be virtually no growth through the warm dry summers (Davidson, 1978; Atkinson, 1990). In this trial, spring root growth was increased from 0.05 mm cm^{-2} d^{-1} to 0.11 mm cm^{-2} d^{-1} by subsoil loosening. Subsoil loosening created favourable water and aeration conditions for root growth earlier in the 1991/1992 season in both the A and B horizons.

By 18-Jan-92 this earlier root growth had led to a greater and more evenly distributed root length pattern to be present in the loosened treatments compared to the nil cultivation treatment.

Delroy and Bowden (1986) and Marks and Soane (1987) both found subsoil loosening of crops enabled faster root penetration and a higher root growth rate early in the growing season. Deep cultivated maize maintained a higher root growth rate of 20 mm d^{-1} compared with 11.8 mm d^{-1} for the conventionally tilled treatments during the period of vegetative growth. The net result of deep ripping maize was a deeper rooting system (Bennie and Botha, 1986).

Summary.

1. Soil loosening (aerated and subsoiled loosened treatments) led to favourable conditions for root growth through a reduction in bulk density and through increases in porosity and the aeration status of the soil profile.

2. Soil loosening led to increased rates of root growth over spring (1-Aug-91 to 28-Nov-91).

3. The increased root growth rates created a more extensive pasture root system for continued pasture growth over the drier summer months on the loosened treatments compared to the nil cultivated treatment.

6.3 The Effect of Soil Loosening on Nutrient Uptake.

The reaction of pasture to soil loosening (aerated and subsoiled cultivations) in the uptake of various nutritive elements is different for each nutrient, dependent upon the way in which the nutrient is absorbed by the pasture roots. By the creation of soil physical conditions favourable for root growth soil loosening has been shown to increase the size of the pasture root zone and the root length present within the root zone. This has led to an increase in the accessibility of nutrients and moisture for the pasture. In the trial reported here there were no differences in water use following soil loosening, suggesting that the increased pasture production was due to an increase in nutrient availability.

Sulphur and Nitrogen.
Soil loosening (aerated and subsoiled cultivations) greatly increased sulphur uptake by the pasture compared to the nil cultivation treatment, which was in agreement with Bowden (1986) who also observed a sulphur response in wheat following soil loosening.

In December 1990 fertiliser sulphur (30 kg S ha^{-1}) was applied to one third of the plots (Section 3.2.3) but no significant cultivation/fertiliser interaction occurred. Bowden (1986) explained his lack of interaction between soil ripping and nitrogen application when nitrogen was limiting, because the nitrogen rates where not high enough. In the present trial, soil loosening led to an increase in pasture sulphur concentrations which was thought to be large enough to mask the effects of sulphur fertiliser application.

Sulphur was found to be present at a higher concentration at depth (30-50 cm) compared with the topsoil (Figure 6.1). Sulphur is thought to accumulate within the B-horizon of the Templeton silt loam by leaching and subsequent absorption processes (M^cLaren *et al.*, 1992). In many cases sulphur retained in the subsoil horizons has been reported to be recovered by deep plant roots (Freney, 1986).

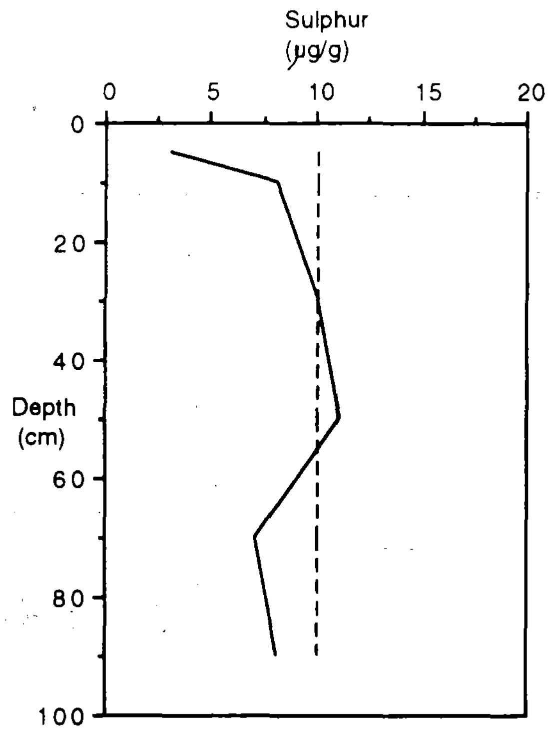

Figure 6.1: Distribution of sulphur in the soil profile of the Templeton silt loam, '-----' indicates a 'low nutrient level' (Cornforth and Sinclair, 1984).

Any roots present below 30 cm depth in this soil would therefore have ready access to the accumulated sulphur. In this trial the subsoiled cultivation treatment had a larger root length below 30 cm depth from 28-Nov-91 to 18-Jan-92 compared with the nil cultivation treatment. Thus plants in the subsoiled cultivation treatment had a greater opportunity for uptake than the plants in nil cultivation treatment.

The increased sulphur uptake by plants in the subsoil loosened treatment compared to the nil cultivation treatment was also marked over spring (1-Aug-91 to 28-Nov-91) when pasture roots began to penetrate below the 30 cm depth of the loosened treatments.

The large response to soil loosening in sulphur uptake was because the soil profile above 25 cm where the roots of the nil cultivation treatment are concentrated had a very low sulphur status (Cornforth and Sinclair, 1984). One of the factors limiting pasture production during this trial was therefore thought to be sulphur nutrition.

The ability of the loosened treatments to access sulphur below 30 cm caused an increase in pasture production, sulphur concentration and sulphur uptake. Bowden (1986) states that one of the consequences of increased root growth following soil loosening is that the uptake of nutrients will be higher on the loosened treatments when nutrient stress occurs, such as for sulphur in the trial reported here.

Nitrogen, like sulphur, can leach to below the normal pasture rooting depths. However in this trial, nitrogen uptake showed little response to soil loosening. It is suggested that due to above average rainfall over the winter of 1991, the nitrate present would have been leached below any plant roots in the soil profile. Chaney and Kamprath (1982) and Reeves and Trouchton (1986) both attributed greater crop yields in subsoiled over nonsubsoiled treatments to extraction of leached nitrogen below the tillage pan. The extraction of the nitrogen was possible due to increased root growth below the tillage pan of the subsoiled treatments. Delroy and Bowden (1986) found that the greater rooting depth on the ripped plots increased nitrogen uptake efficiency to the extent that twice as much nitrogen was taken up on the ripped versus non-ripped plots.

In the trial reported here during the summer months (Dec-91 and Jan-92) the loosened treatments showed a trend for higher pasture herbage nitrogen concentrations. However these increases were not large enough to overcome the nitrogen deficiency to a sufficient extent to increase pasture production on the loosened treatments. These increased nitrogen concentrations are thought to be due to the higher root lengths and deeper roots of the loosened treatments having access to the nitrogen leached from the topsoil during the spring (1-Aug-91 to 28-Nov-91). This trend was particularly evident when the pasture was taking it s water and nutrients predominantly from lower in the soil profile because the topsoil had dried out cver the summer months (Dec-91 and Jan-92).

Phosphorus and Potassium.

The absorption of phosphate and potassium is mainly by diffusion mechanisms and is therefore strongly influenced by the development of an extensive root system. Uptake by diffusion is limited by the soil diffusivity for the nutrient, and the length of time since the root grew into the new soil area (McCaskill and Blair, 1990). Root surface area is most likely to be the limiting factor in phosphate adsorption.

The value of soil loosening in optimising root development in the soil profile to increase phosphorus and potassium uptake is often supported by increases in plant phosphorus and potassium concentrations and uptakes following soil loosening (Haak, 1981; Atkinson, 1990). Table 6.2 shows the value of increases in root length and improvements to root morphology in the increased uptake of phosphorus and potassium.

Property	Change in Property	Estimated Consequence for P or K Uptake
Root length density	Increase by 10^3 for a 500-μm-diam. root with 0.275-mm zone of exploitation, which thus increased the exploitable soil volume from 0.067 mm^{-3} cm^{-3} (Lv = 0.1 cm cm^{-3}) to 67 mm^3 cm^{-3} (Lv = 10 cm cm^{-3})	P:access to an additional 45 μg P cm^{-3} soil
	Increase from 2.4 to 5.6 m cm^{-2}	K:possible increased uptake of 1.6 mg cm^{-2}
	Increase from 1 to 3 cm cm^{-3}	K:possible increased uptake of 130 mmol $plant^{-1}$
Root depth	Increase by 10 cm for a single root, diameter + zone exploited as above	P:Access to an additional 0.45 μg P and 20 mm of water
Specific root length	Increase from 100 to 200 m g^{-1} for a root wt. of 1.4 mg cm^{-2}, an increase of La from 14 to 28 cm cm^{-2} in 15 cm of soil depth	K:a potential increase in uptake of 60 mmol $plant^{-1}$ but in perennial species a probable decrease in root survival and so a loss of around 4 cm cm^{-2} yr^{-1} in root length density

Table 6.2: The consequences of measured variation in root system properties on water and nutrient uptake (Atkinson, 1990).

In the trial reported here the loosened (aerated and subsoiled) treatments tended to have a slightly larger total uptake of phosphorus. It is suggested that this increase was due to the larger root length present in the loosened treatments compared to the nil cultivation treatment. Haak (1981), Ide *et al.* (1987b) and Barbosa *et al.* (1989) state that the increase in root length as a result of subsoil cultivation often leads to an increase in foliar phosphorus concentration and increased total uptake of phosphorus.

The distribution of phosphorus in the Templeton silt loam used in this field trial reached a peak concentration at approximately 30-50 cm (Figure 6.2). At this depth pasture in the subsoil loosened treatment had a significantly higher root length on 18-Jan-92 than the nil cultivation treatment. Therefore on 16-Jan-92 phosphorus concentration of the pasture herbage from the loosened treatments (0.30%) was significantly higher than from the nil cultivation treatment (0.20%). At this date the moisture content of the soil profile was only 12% (v/v) (0-70 cm) and diffusion, the main transport mechanism for phosphorus is known to decrease sharply as soil water content diminishes (Wiersum, 1980).

As surface soil drying enhances phosphorus uptake from lower soil horizons (Pinkerton and Simpson, 1986) it would would be expected that the deeper more extensive root system of the loosened treatments would have a higher phosphorus pasture concentration and phosphorus uptake at this time (16-Jan-92).

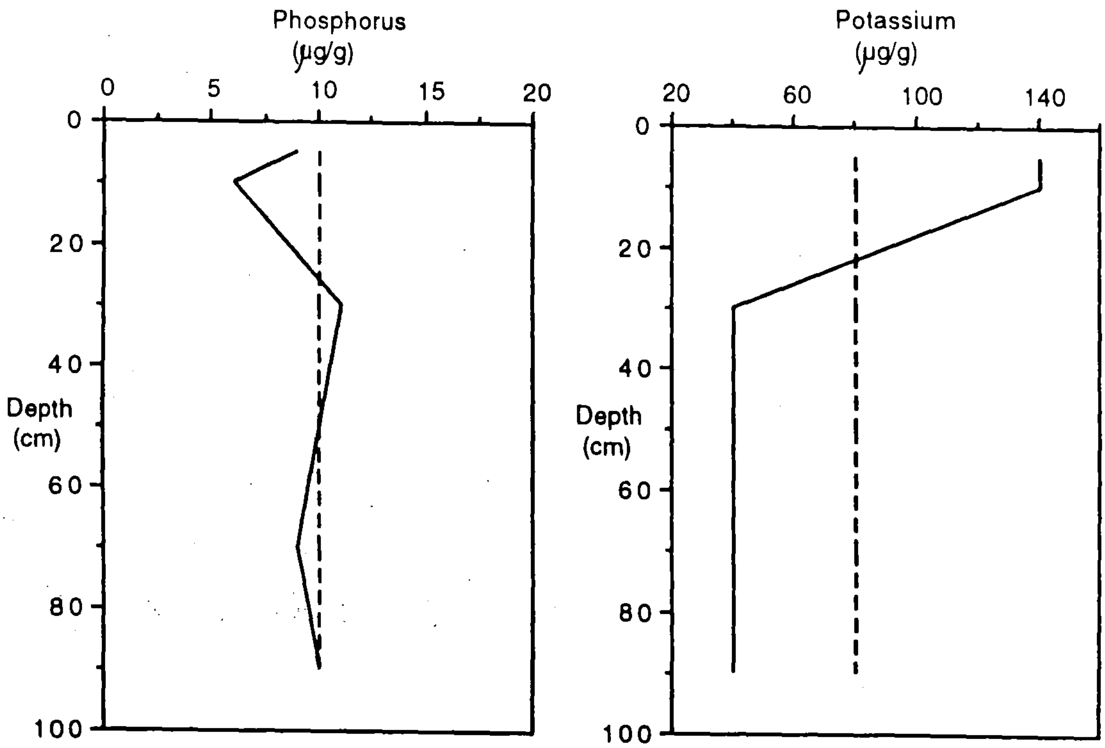

Figure 6.2: Distribution of phosphorus and pota°°ium in the soil ,profile of the Templeton silt loam, '-----' indicates a 'low nutrient level' (Cornforth and Sinclair, 1984).

In this trial over early spring (5-Sep-91 t(26-Sep-91) the uptake of phospho' .s was significantly higher on the loosened treatments than the nil cultivation treatmen. The pasture production over this time on the loosened treatments was higher than the nil cultivation treatment.

All of the research work reported thus far used annual crops as indicators of the effect of subsoil loosening on root growth and phosphorus and potassium uptake. In the present field trial established pasture (8 years old) was loosened and less noticeable results occurred.

The limited response in potassium uptake following soil loosening can be explained by examination of the soil profile distribution of potassium. Below 30 cm the potassium content of the soil was very low (Figure 6.2) (Cornforth and Sinclair, 1984). Therefore extra root length or root growth below 30 cm would not result in a higher uptake of potassium.

De Nobili *et al.* (1990) found that potassium uptake in particular was improved by subsoiling. Root growth of winter barley increased significantly after subsoiling of a hard pan. At the flowering stage, total root weight between 50-70 cm depth was 325% higher in the subsoiled plots than in the control. Potassium concentration in the roots and green mass was increased by 30% following subsoiling.

In this field trial sulphur and nitrogen are the nutrients most limiting pasture production, therefore responses to soil loosening in the uptake of phosphorus and potassium are less likely, and are due to increased pasture production resulting from the increased sulphur and nitrogen nutrition created by the soil loosening.

Davies *et al.* (1989) also used established pasture (26 years) and found slitting to 15 cm gave increased net uptakes by above ground plant material of phosphorus (83%) and potassium (107%). However in the study conducted by Davies *et al.* (1989) the major restriction to pasture root growth occurred at the 10-12 cm depth. The compacted layer offered a large restriction to pasture growth with the compacted treatment having 97% of its root length above 10 cm. Once the compacted layer was removed the roots grew at an improved rate due to the removal of the compacted layer and the reduction in water logging.

Calcium.

The higher root elongation rate present in the loosened treatments compared to the nil cultivation treatment resulted in a larger surface area of young roots. This led to an increased uptake of calcium, since calcium is passively absorbed by the growing tips of roots (Wiersum, 1980). In the trial reported here this effect was noticeable at two times. Firstly in spring (Sep-91 to Oct-91), when the loosened treatments had faster pasture growth, faster root growth and therefore a greater calcium uptake than the nil cultivation treatment.

In spring the loosened treatment had a higher percentage of its root growth below the 30 cm depth in the soil profile where an increase in soil calcium content was detected (Figure 6.3) thus leading to a larger calcium uptake. It is reported in these soils that calcium accumulations occur within the subsoil (Cox, 1978) (Figure 6.3).

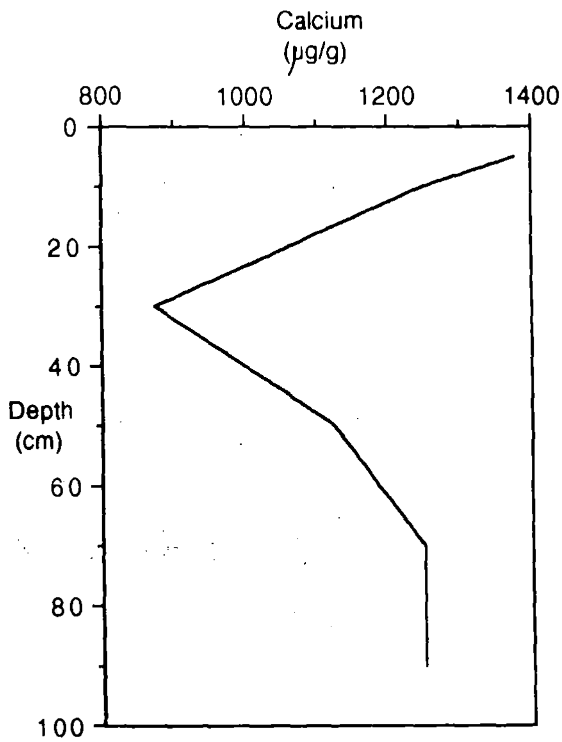

Figure 6.3: Distribution of calcium in the soil profile of the Templeton silt loam.

The second date when this effect was noticeable was in January 1992, when the soil profile was dry (10-12%, v/v) and the loosened treatments already had in place a more extensive root system below 40 cm than the nil cultivation treatment. Therefore even at low root growth rates more young root surfaces would be present in the loosened treatments at the depth of high calcium concentration (i.e. >40 cm) resulting in a larger calcium uptake from the loosened treatments than the nil cultivation treatment.

Magnesium and Sodium.

Subsoil loosening tended to increase the pasture herbage concentration of sodium compared to the nil cultivation treatment. The sodium content within the soil profile of the Templeton silt loam was found to increase from below 30 cm (Figure 6.4).

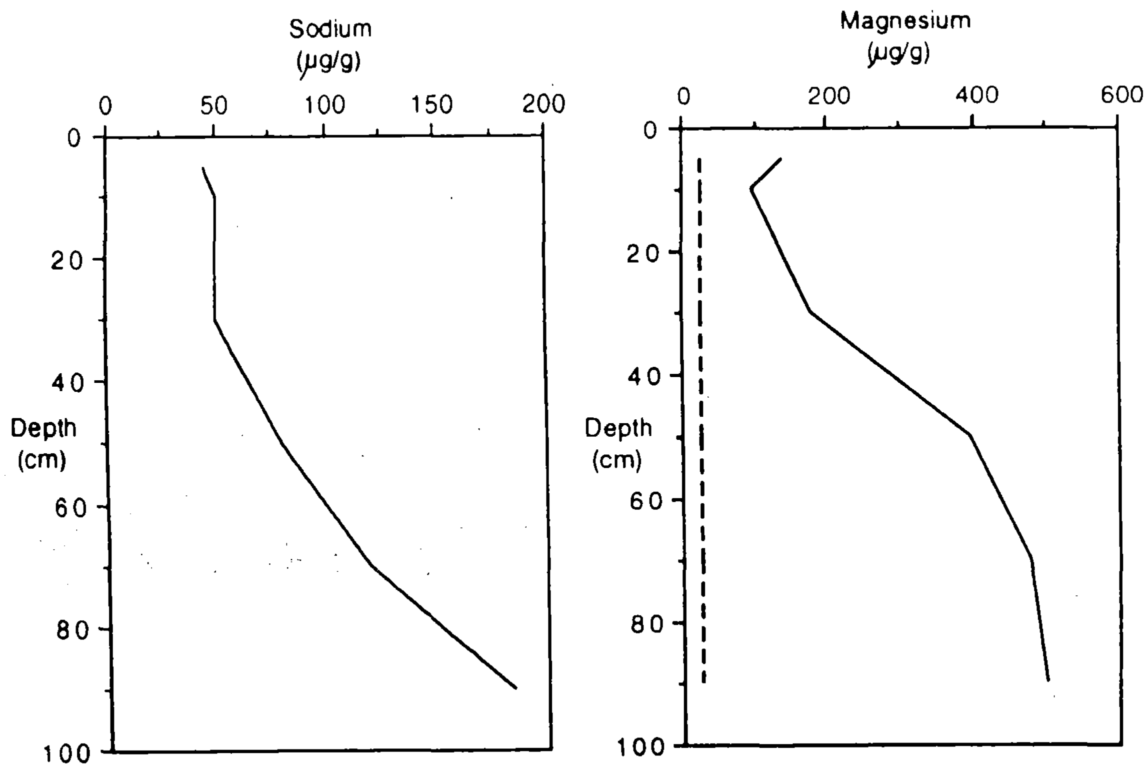

Figure 6.4: Distribution of sodium and magnesium in the soil profile of the Templeton silt loam, '——' indicates a 'low nutrient level' (Cornforth and Sinclair, 1984).

The increased root length below 30 cm of the subsoil loosened treatment therefore resulted in an increase in sodium concentration of the pasture. Indeed, this increased sodium concentration in pasture grown in the subsoiled plots may be a useful indicator of root activity at depth in this particular soil.

A trend of increased magnesium concentration in the pasture of the subsoil loosened treatment is also apparent. The distribution of magnesium in the soil profile like sodium increases below 30 cm (Figure 6.4). This in combination with the higher root lengths below 30 cm in the subsoil loosened treatment resulted in higher magnesium concentrations of the pasture from the subsoil loosened treatments compared with the nil cultivation treatment.

Aeration status.

Much nutrient uptake is believed to take place across membranes and against gradients of chemical and electrical potential energy. Energy must therefore be expended to move the nutritive ions thermodynamically 'up hill'. Since the source of the energy, ATP, is derived mainly from aerobic respiration it is not surprising that in the absence of oxygen nutrient absorption is curtailed (Arkin and Taylor, 1981).

Over the spring of 1991 (1-Aug-91 to 28-Nov-91) the loosened treatments of this trial had larger macronutrient uptakes (P, K, S, Ca, Mg, and Na) than the nil cultivation treatment. This is believed to be due in part to the loosened treatments having a lower water content and a higher aeration status than the nil cultivation treatment.

Micronutrients.

In a freely drained aerobic soil micronutrients occur predominantly in their higher oxidation states and are relatively insoluble. As the water content of soils increase and the redox potential decreases, transformation to the more soluble reduced forms of micronutrients takes place (M^c^Laren and Cameron, 1990). In the trial reported here the wetter soil profile of the nil cultivation treatment resulted in higher micronutrient concentrations being present in the pasture herbage of the nil cultivation treatment than the pasture herbage of the drier subsoil loosened treatment.

Summary.

1. Soil loosening (aeration to 27 cm, and subsoiling to 47 cm) created soil physical conditions that over the spring period led to greater rates of pasture root growth than those rates present in the nil cultivation treatment.

2. Soil loosening reduced soil bulk density and increased soil porosity, thus increasing the soil aeration status. These increases in aeration status aided the higher uptake of nutrients by the loosened treatments compared with the nil cultivation treatment.

3. The faster root growth rate of plants in the loosened treatments created a more extensive rooting system and increased macronutrient uptake during the spring. Over the summer the more extensive rooting system allowed higher uptakes of most macronutrients by the pasture of the loosened treatments.

4. Sulphur, sodium and calcium were found to be more abundant within the B-horizon than in the A-horizon of the Templeton silt loam. The increased uptake of these nutrients by pasture in the subsoil loosened treatment was probably a result of this treatment having a more extensive rooting system below 20 cm.

5. Sulphur and nitrogen were the nutrients most limiting pasture production at this site. The improved access of plant roots in the subsoil loosened treatment to accumulated subsoil sulphur caused large responses in pasture production and sulphur uptake.

7.0 CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK.

The main conclusions from the research results reported in this thesis are:

(i) Soil loosening (aeration to 27 cm depth and subsoiling to 47 cm depth) led to increased pasture production over the second season (1991/1992) of the trial, with the increases being most notable during mid-spring and mid-summer. The reasons for this trend were mostly attributed to improved plant nutrition.

Root pruning by the loosening operation was however suspected to have reduced pasture production during the first season (1990/1991).

(ii) Loosening by cultivation of the compacted soil layers significantly reduced bulk density (11%) and significantly increased porosity (8%) compared to the nil cultivation treatment.

(iii) The subsoil loosened treatment had a significantly drier soil profile (0-70 cm) over the 1991/1992 season. This was considered to be due to higher soil drainage rates particularly in late winter/early spring.

In the trial reported here the drier soil profile of the subsoil loosened treatment resulted in lower micronutrient concentrations (Fe, Cu, Co and Zn) being present in the pasture herbage than in the pasture herbage of the wetter nil cultivation treatment. It was explained that this was due to the influence of the water content on the redox potential and subsequent transformations of micronutrients to more insoluble forms.

(iv) By decreasing the soil water content and thus increasing the soil aeration status, soil loosening created a soil environment that favoured the earlier onset of root activity in the topsoil, and root growth into the B-horizon during spring.

(v) Through the creation of soil physical conditions which were more favourable for root growth, for example lower bulk density, lower soil water content in spring and a higher soil aeration status, soil loosening allowed root growth to a greater depth in the soil profile and the creation of a significantly more extensive pasture root system, compared to the nil cultivation treatment.

(v_a) Surface applied fertiliser was not applied at high enough rates to compensate for the nutrient deficiency arising from shallower rooting in the nil cultivation treatment.

(vi) In this field trial, contrary to previous workers (eg. Reid *et al.*, 1987; Greenwood, 1989) no differences in plant water use were detected between the three cultivation treatments. Therefore water use was not regarded as the main reason for increased pasture production on the loosened treatments.

(vii) Soil loosening was found to significantly increase the uptake of sulphur by pasture plants. The Templeton silt loam at the trial site was found to be sulphur deficient, with very low concentrations ($< 3\ \mu g\ g^{-1}$) of SO_4^{2-}-S occurring in the topsoil. However between the 30-50 cm depth, the soil SO_4^{2-}-S concentrations rose to 10 $\mu g\ g^{-1}$. The deeper and more extensive pasture root system at this depth in the loosened treatments had greater access to this sulphur, and resulted in an increase in the uptake of sulphur by the plants and increases in pasture production.

(viii) Pasture grown on the loosened treatments tended to have higher concentrations of several macronutrients (S, Ca, Mg, and Na) particularly during spring and mid-summer. The concentration of these four macronutrients in this Templeton silt loam were found to increase below a depth of approximately 30 cm. The larger root lengths present below 30 cm in the loosened treatments allowed the pasture roots greater access and consequently higher uptakes of these nutrients.

It is suggested that in field trials such as the one reported here, that the examination of relationships between profile distributions of macronutrients and pasture nutrient concentrations are useful indicators of root activity at different depths.

(ix) A method was developed to calculate root densities from root length measurements that has the potential to produce useful, accurate results from limited destructive sampling. This method should allow seasonal trends in root growth to be quantified. In the experiment reported here, however not enough root density samples were taken to accurately calibrate root density/length relationships.

(x) The tracer injection technique which was developed for use in the Microplot Trial was reasonably successful for labelling of indigenous soil sulphur with ^{35}S. This enabled a useful estimate to be made of the activity of plant roots at different depths in the soil profile, and allowed comparison between the root activity of the pasture components. Even though ^{35}S has seen limited use as a nutrient tracer, it is particularly suited for use as a tracer in field trials. This is because it has a sufficiently long half life to allow the study of seasonal trends. It is also adequately mobile within the soil-root continuum that it does not need to be injected in large amounts or banded within the soil profile.

The successful use of ^{32}P in field root studies would require a larger number of injection points and higher activities than were used in this trial. The practical difficulties involved however may limit it's use.

Suggestions for future research.

The lack of research on pasture plant root systems in New Zealand, limits the usefulness of some past agronomic research when predicting the effect of various management strategies on pasture production. Because of the overriding effect of the soil/root system on pasture production these relationships need to be fully defined to be able to predict pasture production.

The limited research on pasture root systems may be due to the problems involved in the time consuming and inaccurate techniques used to measure pasture root systems. The development of a method that overcomes these problems would allow agronomic research to include root data, therefore making the research more widely applicable.

Tracer techniques are widely used in pot trials or similarly confined experiments. The further development of techniques to place tracers at various depths in a field soil could provide accurate data on root activity in the field situation.

The positive effect of soil loosening on dryland pasture production seen in this trial, suggests that further attention to the subject is warranted, as soil loosening may prove to be a useful management tool for farmers. Increased pasture production depends on the interactions between soil, plants and climate to provide adequate nutrients and water. These factors need to considered when deciding if soil loosening will be beneficial. Further research defining the situations for which soil loosening would be a beneficial option is necessary to improve the economic use of soil loosening.

Soil loosening as described in this thesis would be beneficial in a dry land farming situation where there was an increase in macronutrients with depth, thus allowing a higher macronutrient uptake with increased root growth. Soil loosening would have to be approached more cautiously if contemplated in an area of higher rainfall where soil drainage may be more beneficial.

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APPENDIX 3.1

Templeton silt loam soil profile description at the trial site.

Ap 1-7 cm	2.5Y 3/1 brownish black; slightly sticky; fine sandy loam; slightly plastic; firm. Moderately developed, medium nutty and moderately fine nutty. Boundary indistinct.
Ah_2 7-27 cm	10YR 4/2; greyish yellow brown; strongly developed; fine nutty structure; friable; slightly sticky; fine sandy loam. Boundary distinct.
AB 27-36 cm	2.5Y 6/4 and also 10YR 4/2 (50% : 50% greyish yellow brown colour and dull yellow); common 2-5 mm pores; worm mixing; strongly developed medium and fine nutty; fine sandy loam. Boundary indistinct.
B_w 36-48 cm	2.5Y 6/4 dull yellow (75%) and 10YR 3/1 brownish black (25%); moderate medium blocky structure; firm; macropores; sandy loam. Boundary diffuse.
2BC 48-91 cm	2.5Y 5/6 yellowish brown; very friable; loamy sand. Few fine indistinct 7.5YR bright brown 5/6 mottles. Very fow indistinct 10YR 7/1 mottles; light grey towards depth (unweathered sand). Single grain - not structured. Boundary distinct.
$3BC_{1b}$ 91-95 cm	7.5YR 5/4 (dull brown) friable; loamy sand. Boundary distinct.
$3BC_{2b}$ 95-102 cm	Weakly developed fine blocky structure; very friable; 2.5Y 4/4 olive brown; loamy sand. Boundary indistinct.
$3C_g$ 102-120 cm	2.5Y 4/3 olive brown; loose; single grain; sand.

APPENDIX 3.2

Soil Profile Class descriptions:

(1) Silt loam or fine sandy loam texture below the A horizon to a depth of 100 cm.

(2) Same as Class 1, but including up to 30 cm of sandy loam or loamy sand to a depth of 100 cm.

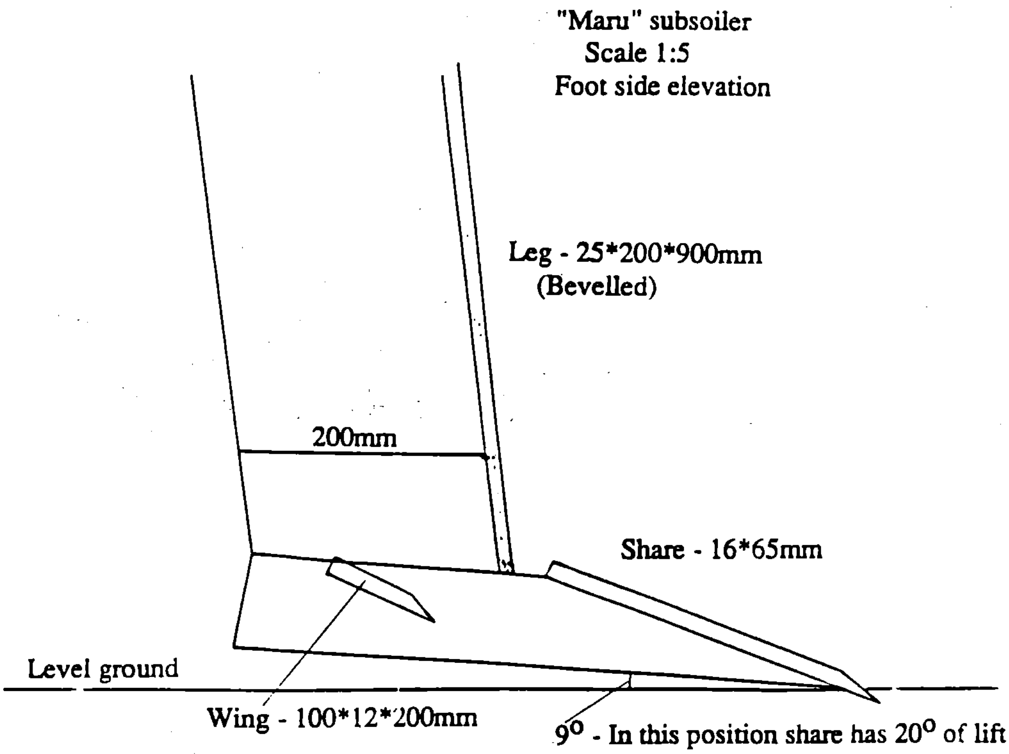
(3) Same as Class 1, including over 30 cm of sandy loam or loamy sand to a depth of 100 cm.

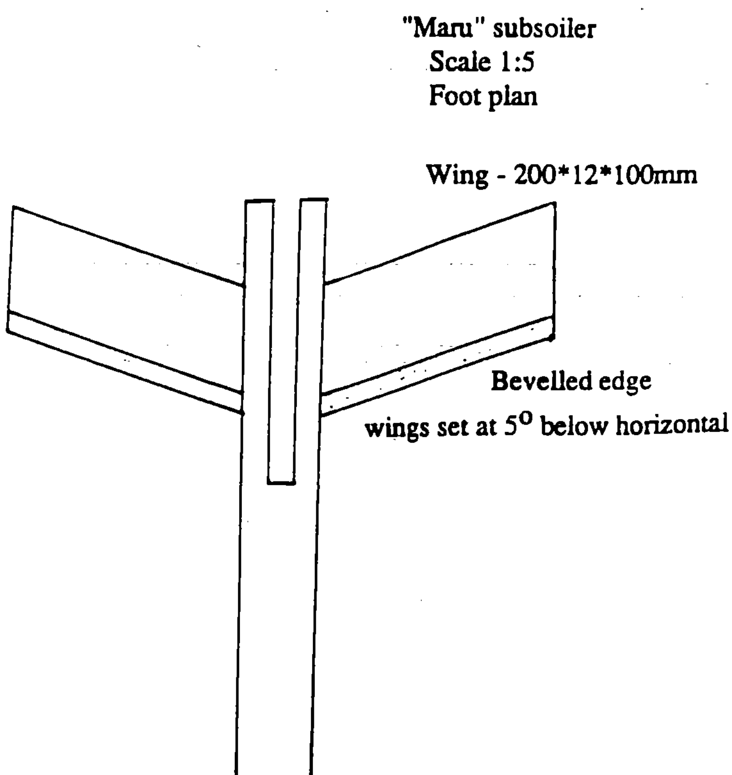
(4) Same Class 1, including a clay loam texture to a depth of 100 cm.

(5) Sandy loam or loamy sand texture to a depth of 100 cm.

APPENDIX 3.3

Plan of the "Maru" subsoiler foot.





APPENDIX 3.4

The manual and Gamma Probe bulk densities (g/cm3).

Manual sampling bulk densities.

Depth (cm)	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)	CV (%)
5.0	1.186	1.162	1.615	<0.001	0.1928	30.3
10.0	1.266	1.155	1.611	<0.001	0.1800	27.8
15.0	1.349	1.253	1.590	0.010	0.1848	27.4
20.0	1.264	1.241	1.572	<0.001	0.1248	19.0
25.0	1.271	1.191	1.626	<0.001	0.1521	23.1
30.0	1.197	1.292	1.712	<0.001	0.1750	25.9
35.0	1.307	1.144	1.616	<0.001	0.1571	24.0
40.0	1.298	1.239	1.683	<0.001	0.1639	24.2
45.0	1.282	1.225	1.676	<0.001	0.1519	22.6
50.0	1.348	1.210	1.672	<0.001	0.1950	28.7
55.0	1.268	1.185	1.664	<0.001	0.1623	24.5
60.0	1.301	1.209	1.609	<0.001	0.1668	25.2

Gamma Probe bulk density results.

Depth (mm)	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)	CV (%)
5.0	1.271	1.287	1.271	NS	-	2.8
10.2	1.348	1.309	1.314	0.021	0.0240	2.2
15.2	1.382	1.330	1.352	0.002	0.0217	2.0
20.3	1.339	1.244	1.273	0.008	0.0473	4.5
25.4	1.358	1.173	1.161	0.004	0.1002	10.0
30.5	1.421	1.219	1.079	<0.001	0.1033	7.7
35.6	1.531	1.403	1.237	<0.001	0.0795	7.1
40.6	1.631	1.558	1.418	<0.001	0.1657	5.3
45.7	1.687	1.672	1.616	0.084	0.0540	4.0
50.9	1.635	1.728	1.715	NS	-	5.1
55.9	1.652	1.741	1.761	0.076	0.0824	5.9
61.0	1.648	1.745	1.754	NS	-	6.5
66.0	1.657	1.762	1.705	NS	-	6.8
71.1	1.662	1.732	1.664	NS	-	7.3

APPENDIX 3.5

Description of the Gamma Density Probe.

Density measurements are made with the MC-3 PORTAPROBE set to one of the transmission mode depths. Measurements performed on soils require no special preparation other than preparing a surface that is level and relatively smooth, and drilling a hole for inserting the source rod.

The guide plate can be used to smooth loose soil on an uneven surface. The holes can be drilled with the drill pin and a hammer or mallet, using the guideplate as a template.

After drilling the transmission hole:

1. Tilt the PORTAPROBE slightly using the cast lip on the front of the bottom casting.

2. Lower the source rod and the detector rod until the handles are between 50 and 100 mm.

3. Grasp the guide tube above the handle and raise the MC-3 until the source rod and detector rod are visibly going into the hole.

4. Lower the MC-3, source rod and detector rod into the hole.

5. Set the handles to depth position desired and start test.

APPENDIX 4.1
Porosity (%) as affected by cultivation treatment.

Depth (mm)	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
50.8	50.34	50.45	50.36	NS	-
101.6	47.35	48.88	48.67	0.021	0.936
152.4	46.02	48.05	47.18	0.002	0.845
203.2	47.70	51.41	50.26	0.008	1.847
254.0	46.94	54.16	54.66	0.004	3.904
304.8	44.48	52.37	57.85	<0.001	4.023
355.6	40.20	45.19	51.68	<0.001	3.099
406.4	36.31	39.15	44.60	<0.001	2.560
457.2	34.11	34.67	36.86	0.084	2.107
508.8	34.19	32.51	33.00	NS	-
558.8	35.45	31.98	31.20	0.076	3.216
609.6	35.64	31.85	31.47	NS	-
660.4	35.28	31.17	33.40	NS	-
711.2	35.09	32.36	35.01	NS	-

APPENDIX 4.2

Cumulative Pasture Growth (kg/ha) (Cultivation Treatment)

Date	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
07-Nov-90	983	1122	1227	NS	-
05-Dec-90	2289	2572	2587	NS	-
15-Jan-91	3728	3492	3422	NS	-
25-Feb-91	5167	4681	4667	NS	-
22-Apr-91	5756	5239	5175	NS	-
01-Aug-91	6240	6466	6409	NS	-
05-Sep-91	7006	7658	7317	NS	-
26-Sep-91	7782	8397	8320	NS	-
11-Oct-91	7919	8939	8737	NS	-
24-Oct-91	9006	10132	9932	NS	-
28-Nov-91	10563	11524	11621	NS	-
20-Dec-91	10627	11745	11836	NS	-
16-Jan-92	11180	11960	12010	NS	-
16-Feb-92	11339	12693	12518	NS	-

Cumulative Pasture Growth (kg/ha) (summed from August 1991)

Date	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
01-Aug-91	994	1260	1285	0.073	223.42
05-Sep-91	1760	2452	2192	0.038	420.08
26-Sep-91	2536	3191	3196	NS	
11-Oct-91	2674	3733	3613	0.081	825.62
24-Oct-91	3761	4927	4807	NS	
28-Nov-91	5319	6318	6496	NS	
20-Dec-91	5330	6539	6712	NS	
16-Jan-92	5953	6755	6885	NS	
16-Feb-92	6094	7487	7393	NS	

APPENDIX 4.2 CONTINUED

Cumulative Pasture Growth (kg/ha) (Fertiliser Treatment)

Date	Nil	P	P&S	FProb	L.S.D(10%)
07-Nov-90	1063	1152	1117	NS	-
05-Dec-90	2470	2398	2580	NS	-
15-Jan-91	3455	3394	3794	NS	-
25-Feb-91	4601	4833	5081	NS	-
22-Apr-91	5024	5388	5758	NS	-
01-Aug-91	6015	6154	6936	0.085	710.86
05-Sep-91	6749	7215	8017	0.036	762.58
26-Sep-91	7456	8112	8930	0.042	906.98
11-Oct-91	7761	8523	9312	0.069	1061.26
24-Oct-91	8961	9587	10522	NS	-
28-Nov-91	10376	11163	12169	NS	-
20-Dec-91	10532	11498	12178	NS	-
16-Jan-92	10615	11559	12347	NS	-
16-Feb-92	11100	12340	13110	NS	-

Cumulative Pasture Growth (kg/ha) (summed from August 1991)

Date	Nil	P	P&S	FProb	L.S.D(10%)
01-Aug-91	1115	1196	1227	NS	-
05-Sep-91	1849	2247	2309	NS	-
26-Sep-91	2557	3144	3222	NS	-
11-Oct-91	2862	3555	3603	NS	-
24-Oct-91	4062	4619	4814	NS	-
28-Nov-91	5477	6195	6450	NS	-
20-Dec-91	5632	6530	6468	NS	-
16-Jan-92	5716	6591	6638	NS	
16-Feb-92	6201	7372	7401	NS	

APPENDIX 4.3

Growth rate of pasture (kg/ha/day) (Cultivation Treatment)

Date	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
05-Dec-90	40.8	45.3	42.5	NS	-
15-Jan-91	35.1	22.5	29.5	0.002	5.32
25-Feb-91	35.1	29.0	30.4	NS	-
22-Apr-91	23.5	22.3	20.4	NS	-
01-Aug-91	10.0	12.7	13.0	0.073	2.26
05-Sep-91	21.9	34.1	25.9	0.039	7.47
26-Sep-91	36.9	35.2	47.8	NS	-
11-Oct-91	9.2	36.2	27.8	0.033	16.11
24-Oct-91	83.6	91.8	91.9	NS	-
28-Nov-91	44.5	39.8	48.3	NS	-
20-Dec-91	9.7	8.5	13.0	NS	-
16-Jan-92	1.8	12.3	4.8	0.023	4.84
16-Feb-92	19.8	25.4	23.1	NS	-

Growth rate of pasture (kg/ha/day) (Fertiliser Treatment)

Date	Nil	P	P and S	FProb	L.S.D(10%)
05-Dec-90	44	38.9	45.7	NS	-
15-Jan-91	24	24.3	29.6	NS	-
25-Feb-91	27.9	35.1	31.4	NS	-
22-Apr-91	17	22.2	27.1	0.063	5.34
01-Aug-91	11.27	12.08	12.4	NS	-
05-Sep-91	21	30	30.9	0.066	7.47
26-Sep-91	33.7	42.7	43.5	NS	-
11-Oct-91	20.3	27.4	25.4	NS	-
24-Oct-91	92.3	81.9	93.1	NS	-
28-Nov-91	40.4	45	47.1	NS	-
20-Dec-91	11.1	13.8	6.4	NS	-
16-Jan-92	5	7.5	6.4	NS	-
16-Feb-92	20.8	27.5	20.1	NS	-

APPENDIX 4.4
Total Profile Root Length (cm/cm2) (0-80 cm)

Date	Nil	Aerated	Subsoiled	FProb
05-Aug-91	4.9321	4.6782	4.9630	NS
04-Sep-91	4.7230	5.6951	5.2152	NS
03-Oct-91	4.3750	5.0083	5.9464	NS
30-Oct-91	5.5226	5.5347	5.2426	NS
29-Nov-91	4.8646	6.2784	6.2541	NS
18-Dec-91	5.3270	6.0470	5.6820	NS
18-Jan-92	4.8539	5.5178	6.2680	NS

APPENDIX 4.5
Root length (cm/cm2)

05-Aug-91	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
0 - 10cm	1.990	1.940	1.890	NS	-
10 - 20cm	1.480	1.540	1.320	NS	-
20 - 30cm	0.653	0.797	0.906	NS	-
30 - 40cm	0.423	0.262	0.611	NS	-
40 - 50cm	0.159	0.101	0.144	NS	-
50 - 60cm	0.078	0.027	0.040	NS	-
60 - 70cm	0.065	0.008	0.035	NS	-
70 - 80cm	0.085	0.004	0.017	NS	-

04-Sep-91	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
0 - 10cm	1.780	2.100	1.680	NS	-
10 - 20cm	1.460	1.740	1.700	NS	-
20 - 30cm	0.890	1.250	1.010	NS	-
30 - 40cm	0.333	0.352	0.590	NS	-
40 - 50cm	0.151	0.120	0.142	NS	-
50 - 60cm	0.052	0.064	0.042	NS	-
60 - 70cm	0.039	0.045	0.035	NS	-
70 - 80cm	0.018	0.024	0.016	NS	-

03-Oct-91	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
0 - 10cm	1.671	1.966	1.925	NS	-
10 - 20cm	1.260	1.460	1.770	NS	-
20 - 30cm	0.777	1.074	1.196	NS	-
30 - 40cm	0.371	0.364	0.807	0.012	0.246
40 - 50cm	0.142	0.105	0.179	NS	-
50 - 60cm	0.071	0.025	0.042	NS	-
60 - 70cm	0.041	0.013	0.015	NS	-
70 - 80cm	0.042	0.001	0.013	NS	-

30-Oct-91	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
0 - 10cm	1.992	1.970	1.654	NS	-
10 - 20cm	1.550	1.603	1.476	NS	-
20 - 30cm	1.029	1.123	1.098	0.093	0.669
30 - 40cm	0.573	0.537	0.674	NS	-
40 - 50cm	0.214	0.210	0.263	NS	-
50 - 60cm	0.076	0.065	0.048	0.063	0.035
60 - 70cm	0.063	0.020	0.025	0.006	0.018
70 - 80cm	0.026	0.007	0.005	NS	-

APPENDIX 4.5 CONTINUED
Root length (cm/cm2)

29-Nov-91	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
0 - 10cm	1.929	1.957	1.834	NS	-
10 - 20cm	1.567	1.898	1.517	NS	-
20 - 30cm	0.842	1.478	1.464	0.093	0.669
30 - 40cm	0.310	0.660	0.930	NS	-
40 - 50cm	0.141	0.188	0.309	NS	-
50 - 60cm	0.047	0.068	0.097	NS	-
60 - 70cm	0.020	0.025	0.060	0.063	0.035
70 - 80cm	0.009	0.004	0.043	0.006	0.0175
18-Dec-91	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
0 - 10cm	2.300	2.000	1.870	NS	-
10 - 20cm	1.470	1.830	1.520	NS	-
20 - 30cm	0.851	1.227	1.203	NS	-
30 - 40cm	0.393	0.542	0.677	NS	-
40 - 50cm	0.213	0.203	0.260	NS	-
50 - 60cm	0.072	0.125	0.063	NS	-
60 - 70cm	0.021	0.078	0.053	NS	-
70 - 80cm	0.007	0.042	0.036	NS	-
18-Jan-92	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
0 - 10cm	1.760	1.890	1.650	NS	-
10 - 20cm	1.510	1.700	1.660	NS	-
20 - 30cm	0.871	1.267	1.397	NS	-
30 - 40cm	0.403	0.434	1.002	0.035	0.449
40 - 50cm	0.161	0.153	0.388	0.085	0.238
50 - 60cm	0.086	0.037	0.095	0.062	0.00621
60 - 70cm	0.056	0.025	0.052	NS	-
70 - 80cm	0.007	0.012	0.024	NS	-

APPENDIX 4.6
Relative Vertical Distribution of Root Length (%).

05-Aug-91	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
0 - 10cm	40.50	42.30	38.10	NS	-
10 - 20cm	30.13	32.41	26.90	NS	-
20 - 30cm	13.62	16.72	18.24	0.067	2.959
30 - 40cm	8.20	5.70	12.00	NS	-
40 - 50cm	3.05	2.09	2.86	NS	-
50 - 60cm	1.59	0.57	0.82	NS	-
60 - 70cm	1.270	0.140	0.760	NS	-
70 - 80cm	1.590	0.100	0.320	NS	-

04-Sep-91	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
0 - 10cm	38.30	37.60	32.30	NS	-
10 - 20cm	31.00	31.20	32.60	NS	-
20 - 30cm	18.90	21.60	19.20	NS	-
30 - 40cm	6.60	5.60	11.20	NS	-
40 - 50cm	2.96	1.89	2.74	NS	-
50 - 60cm	1.04	1.01	0.84	NS	-
60 - 70cm	0.900	0.710	0.730	NS	-
70 - 80cm	0.378	0.390	0.332	NS	-

03-Oct-91	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
0 - 10cm	38.09	39.23	32.53	0.011	2.6394
10 - 20cm	28.81	29.10	29.44	NS	-
20 - 30cm	17.89	21.49	20.12	NS	-
30 - 40cm	8.56	7.31	13.64	0.003	1.65
40 - 50cm	3.20	2.08	3.07	-	-
50 - 60cm	1.59	0.52	0.73	-	-
60 - 70cm	0.930	0.260	0.260	-	-
70 - 80cm	0.930	0.020	0.220	-	-

30-Oct-91	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
0 - 10cm	36.26	35.74	31.63	0.092	3.565
10 - 20cm	28.17	29.07	28.27	NS	-
20 - 30cm	18.52	20.28	20.89	NS	-
30 - 40cm	10.26	9.63	12.64	0.003	1.65
40 - 50cm	3.84	3.69	5.07	NS	-
50 - 60cm	1.38	1.15	0.99	NS	-
60 - 70cm	1.14	0.33	0.44	NS	-
70 - 80cm	0.43	0.11	0.07	NS	-

APPENDIX 4.6 CONTINUED

Relative Vertical Distribution of Root Length (%).

29-Nov-91	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
0 - 10cm	39.60	31.60	32.90	NS	-
10 - 20cm	32.17	30.29	26.90	NS	-
20 - 30cm	17.29	23.45	21.30	0.01	2.518
30 - 40cm	6.40	10.30	11.54	0.078	5.351
40 - 50cm	2.95	2.82	4.61	NS	-
50 - 60cm	0.97	1.05	1.15	NS	-
60 - 70cm	0.422	0.398	0.920	0.063	0.3772
70 - 80cm	0.183	0.067	0.650	0.007	0.2155

18-Dec-91	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
0 - 10cm	43.40	33.30	32.90	NS	-
10 - 20cm	27.30	30.20	26.90	NS	-
20 - 30cm	15.90	20.30	21.30	NS	-
30 - 40cm	7.38	8.96	11.54	NS	-
40 - 50cm	4.08	3.29	4.61	NS	-
50 - 60cm	1.38	2.01	1.15	NS	-
60 - 70cm	0.360	1.260	0.920	NS	-
70 - 80cm	0.120	0.660	0.650	NS	-

18-Jan-92	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
0 - 10cm	36.30	34.20	26.60	0.072	6.609
10 - 20cm	31.10	30.50	26.70	NS	-
20 - 30cm	18.14	22.83	22.23	0.079	3.401
30 - 40cm	8.38	8.22	15.76	0.011	3.157
40 - 50cm	3.21	2.91	6.10	0.1	2.565
50 - 60cm	1.69	0.69	1.48	0.012	0.3899
60 - 70cm	0.990	0.440	0.780	NS	-
70 - 80cm	0.128	0.221	0.347	NS	-

APPENDIX 4.7
Maximum Rooting Depth (cm)

Date	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
05-Aug-91	73.3	45.0	63.6	0.007	9.17
04-Sep-91	60.0	60.0	51.7	NS	-
03-Oct-91	71.7	45.0	51.7	0.004	7.68
30-Oct-91	61.7	51.7	51.7	NS	-
29-Nov-91	55.0	50.0	66.7	NS	-
18-Dec-91	53.3	66.7	66.7	NS	-
18-Jan-92	58.3	50.0	61.7	NS	-

APPENDIX 4.8
Root Density (cm/cm3)

DATE:	05-Aug-91				
DEPTH	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
0-10	0.880	0.880	0.880	NR	-
10-20	0.740	1.034	0.447	0.090	0.1568
20-30	0.557	0.698	0.471	NS	-
30-40	0.379	0.484	0.359	NS	-
40-50	0.414	0.369	0.146	0.019	0.1034
50-60	0.158	0.274	0.042	0.003	0.0290
60-70	0.140	0.230	0.050	NR	-
70-80	0.200	0.200	0.200	NR	-
DATE:	04-Sep-91				
DEPTH	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
0-10	1.040	1.040	1.040	NR	-
10-20	1.030	1.110	0.094	NS	-
20-30	0.756	0.882	0.512	NS	-
30-40	0.305	0.515	0.352	NS	-
40-50	0.131	0.380	0.144	0.019	0.1034
50-60	0.183	0.326	0.040	0.003	0.0290
60-70	0.190	0.320	0.050	NR	-
70-80	0.310	0.310	0.310	NR	-
DATE:	03-Oct-91				
DEPTH	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
0-10	1.680	1.680	1.680	NR	-
10-20	0.900	0.900	0.840	NS	-
20-30	0.653	0.796	0.603	NS	-
30-40	0.348	0.536	0.434	0.031	0.0660
40-50	0.132	0.383	0.168	<.001	0.0404
50-60	0.159	0.273	0.044	0.005	0.0292
60-70	0.110	0.220	-	NR	-
70-80	0.100	0.100	0.100	NR	-

APPENDIX 4.8 CONTINUED
Root Density (cm/cm3)

DATE:	30-Oct-91				
DEPTH	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
0-10	1.280	1.280	1.280	NR	-
10-20	0.935	1.016	0.854	NS	-
20-30	0.898	0.815	0.551	0.073	0.2050
30-40	0.499	0.605	0.384	NS	-
40-50	0.210	0.452	0.000	0.013	0.0919
50-60	0.192	0.331	0.054	0.026	0.0848
60-70	0.080	0.240	-	NR	-
70-80	0.230	0.230	0.230	NR	-
DATE:	28-Nov-91				
DEPTH	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
1.17	1.170	1.170	1.170	NR	-
10-20	0.930	0.131	0.550	NS	-
20-30	0.710	0.909	0.770	NS	-
30-40	0.295	0.649	0.491	0.065	0.1929
40-50	0.135	0.436	0.233	0.020	0.1149
50-60	0.223	0.340	0.106	0.039	0.0885
60-70	0.140	0.260	0.030	NR	-
70-80	0.200	0.200	0.200	NR	-
DATE:	18-Dec-91				
DEPTH	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
0-10	1.590	1.590	1.590	NR	-
10-20	1.002	1.169	0.834	NS	-
20-30	0.746	0.852	0.592	NS	-
30-40	0.363	0.608	0.384	NS	-
40-50	0.210	0.450	0.216	0.004	0.0649
50-60	0.231	0.393	0.069	0.009	0.0562
60-70	0.220	0.300	0.140	NR	-
70-80	0.140	0.140	0.140	NR	-
DATE:	18-Jan-92				
DEPTH	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
0-10	1.000	1.000	1.000	NR	-
10-20	0.960	1.200	0.720	NS	-
20-30	0.733	0.874	0.716	NS	-
30-40	0.372	0.564	0.516	NS	-
40-50	0.146	0.421	0.272	0.042	0.1298
50-60	0.201	0.296	0.106	0.005	0.0243
60-70	0.140	0.280	0.010	NR	-
70-80	0.220	0.220	0.220	NR	-

APPENDIX 4.9
Volumetric Water Content of Each Depth.

Depth (cm)	Nil	Aerated	Subsoiled	FProb	L.S.D (10 %)
18-Apr-91					
0-20	26.2	25.5	21.7	NS	-
20-30	NR	NR	NR	-	
30-35	30.5	43.7	18.3	NS	-
35-40	NR	NR	NR	-	
40-50	22.8	26.0	22.4	NS	-
50-70	NR	NR	NR	-	
27-Apr-91					
0-20	29.1	29.2	27.0	NS	
20-30	NR	NR	NR	-	
30-35	31.5	42.1	18.9	NS	-
35-40	NR	NR	NR	-	
40-50	23.6	26.2	26.2	NS	-
50-70	NR	NR	NR	-	
17-May-91					
0-20	28.5	29.6	24.6	0.01	1.0979
20-30	NR	NR	NR	-	
30-35	27.2	28.2	18.0	NS	-
35-40	NR	NR	NR	-	
40-50	21.9	26.6	33.3	NS	-
50-70	NR	NR	NR	-	
31-May-91					
0-20	28.5	30.7	25.5	0.002	0.4768
20-30	NR	NR	NR	-	
30-35	29.3	35.2	18.3	NS	-
35-40	NR	NR	NR	-	
40-50	27.8	28.3	31.0	NS	-
50-70	NR	NR	NR	-	
19-Jun-91					
0-20	36.2	37.8	32.7	NS	-
20-30	NR	NR	NR	-	
30-35	35.6	48.6	27.2	0.059	3.7172
35-40	NR	NR	NR	-	
40-50	27.7	24.0	35.7	NS	-
50-70	NR	NR	NR	-	

(N.B.: NR = No Result due to excess missing values)

APPENDIX 4.9 CONTINUED
Volumetric Water Content of Each Depth.

Depth (cm)	Nil	Aerated	Subsoiled	FProb	L.S.D (10 %)
31-Jul-91					
0-20	31.4	31.7	30.0	NS	-
20-30	NR	NR	NR	-	
30-35	36.8	55.1	43.5	0.055	2.9930
35-40	NR	NR	NR	-	
40-50	34.5	28.5	37.0	NS	-
50-70	NR	NR	NR	-	
14-Aug-91					
0-20	27.6	27.2	28.2	NS	-
20-30	29.3	30.2	31.0	NS	-
30-35	33.9	22.2	27.7	NS	-
35-40	30.7	42.7	20.6	0.028	11.9136
40-50	34.4	32.8	32.1	NS	-
50-70	*	*	*		
23-Aug-91					
0-20	32.0	28.6	29.8	NS	-
20-30	25.7	30.7	31.4	NS	-
30-35	32.4	24.7	26.5	NS	-
35-40	31.7	44.8	20.2	NS	-
40-50	35.2	31.2	31.6	NS	-
50-70	*	*	*		
29-Aug-91					
0-20	25.7	23.8	38.2	NS	-
20-30	26.9	29.7	33.8	NS	-
30-35	28.7	25.1	29.7	NS	-
35-40	28.6	36.1	19.0	0.097	14.9504
40-50	34.7	31.8	31.9	NS	-
50-70	*	*	*		
05-Sep-91					
0-20	28.5	27.1	26.3	NS	-
20-30	28.5	30.3	31.4	NS	-
30-35	30.4	16.4	22.1	NS	-
35-40	28.0	39.0	22.2	0.044	10.8916
40-50	35.5	30.8	32.8	NS	-
50-70	*	*	*		

APPENDIX 4.9 CONTINUED
Volumetric Water Content of Each Depth (%, v/v)

Depth (cm)	Nil	Aerated	Subsoiled	FProb	L.S.D (10 %)
q					
0-20	28.4	26.4	26.5	NS	-
20-30	29.1	31.2	29.6	NS	-
30-35	27.8	14.9	23.1	NS	-
35-40	23.4	37.6	23.4	NS	-
40-50	33.1	29.7	31.9	NS	-
50-70	*	*	*		
23-Sep-91					
0-20	28.1	25.6	24.9	NS	-
20-30	27.9	28.5	27.6	NS	-
30-35	24.1	25.7	24.8	NS	-
35-40	29.1	30.7	22.9	NS	-
40-50	27.4	24.6	24.9	NS	-
50-70	30.8	30.6	26.9	NS	-
30-Sep-91					
0-20	26.4	23.4	23.2	NS	-
20-30	26.2	25.6	27.3	NS	-
30-35	25.4	26.5	23.2	NS	-
35-40	29.6	31.0	36.1	NS	-
40-50	27.5	24.2	12.3	NS	-
50-70	31.0	30.8	26.3	NS	-
14-Oct-91					
0-20	19.7	17.2	16.4	NS	-
20-30	23.0	25.0	22.1	NS	-
30-35	20.2	23.7	20.4	NS	-
35-40	21.8	24.9	15.0	NS	-
40-50	27.3	21.5	19.7	NS	-
50-70	34.1	31.7	25.8	NS	-
18-Oct-91					
0-20	16.6	14.1	16.0	NS	-
20-30	18.4	17.4	18.4	NS	-
30-35	20.7	27.1	17.5	NS	-
35-40	18.9	24.4	12.3	NS	-
40-50	27.3	20.1	15.9	0.094	7.0387
50-70	33.9	32.1	25.2	NS	-

APPENDIX 4.9 CONTINUED
Volumetric Water Content of Each Depth (%, v/v).

Depth (cm)	Nil	Aerated	Subsoiled	FProb	L.S.D (10 %)
25-Oct-91					
0-20	13.8	12.1	12.1	NS	-
20-30	15.8	14.8	18.1	NS	-
30-35	16.6	23.7	5.9	0.007	10.3660
35-40	16.8	19.3	20.1	NS	-
40-50	25.3	20.4	14.2	0.098	6.8921
50-70	33.4	31.3	22.5	NS	-
01-Nov-91					
0-20	14.0	8.4	9.7	NS	-
20-30	14.5	10.5	15.7	0.035	4.5289
30-35	14.0	22.0	9.6	0.073	12.7020
35-40	17.9	18.2	13.8	NS	-
40-50	20.4	20.8	11.6	NS	-
50-70	33.2	29.8	23.2	NS	-
07-Nov-91					
0-20	24.6	24.2	23.6	NS	-
20-30	14.4	15.7	13.8	NS	-
30-35	16.8	24.4	7.3	NS	-
35-40	18.5	35.7	13.7	0.063	12.7550
40-50	20.8	15.2	18.2	NS	-
50-70	35.4	29.1	20.2	NS	-
21-Nov-91					
0-20	15.1	15.2	16.6	NS	-
20-30	11.0	13.0	9.1	NS	-
30-35	14.1	17.6	10.3	NS	-
35-40	18.7	18.1	8.0	NS	-
40-50	19.9	20.1	18.4	NS	-
50-70	33.6	29.9	19.2	NS	-
04-Dec-91					
0-20	19.5	17.6	18.1	NS	-
20-30	10.1	11.1	6.5	NS	-
30-35	15.3	22.1	8.5	NS	-
35-40	14.8	20.7	7.7	NS	-
40-50	13.5	20.4	20.5	NS	-
50-70	32.3	27.0	16.6	NS	-

APPENDIX 4.9 CONTINUED
Volumetric Water Content of Each Depth (%, v/v).

Depth (cm)	Nil	Aerated	Subsoiled	FProb	L.S.D (10 %)
10-Dec-91					
0-20	15.3	14.2	14.4	NS	-
20-30	9.1	11.2	10.5	NS	-
30-35	8.9	19.7	10.8	NS	-
35-40	24.6	20.6	4.2	0.07	14.1453
40-50	18.7	17.1	18.1	NS	-
50-70	31.3	28.6	19.3	NS	-
19-Dec-91					
0-20	11.5	10.9	12.8	NS	-
20-30	16.7	11.6	12.7	NS	-
30-35	16.2	16.2	4.5	NS	-
35-40	9.3	21.4	7.0	NS	-
40-50	20.4	18.6	18.4	NS	-
50-70	29.0	27.4	18.7	NS	-
23-Dec-91					
0-20	11.1	9.5	11.9	NS	-
20-30	10.7	9.7	11.7	NS	-
30-35	19.0	16.9	5.3	NS	-
35-40	14.5	18.5	10.3	NS	-
40-50	16.2	18.2	17.3	NS	-
50-70	27.8	27.1	17.2	NS	-
13-Jan-92					
0-20	14.7	14.9	13.7	NS	-
20-30	14.9	7.1	12.3	NS	-
30-35	13.5	16.0	8.8	NS	-
35-40	18.7	21.3	11.0	NS	-
40-50	18.9	16.8	16.7	NS	-
50-70	23.7	25.9	17.4	NS	-
17-Jan-92					
0-20	11.6	9.3	9.3	NS	-
20-30	10.9	12.9	12.5	NS	-
30-35	14.2	10.6	6.1	0.095	5.8484
35-40	12.1	19.1	7.5	NS	-
40-50	16.6	16.2	15.6	NS	-
50-70	23.0	24.5	16.2	NS	-

APPENDIX 4.9 CONTINUED
Volumetric Water Content of Each Depth (%, v/v).

Depth (cm)	Nil	Aerated	Subsoiled	FProb	L.S.D (10 %)
22-Jan-92					
0-20	11.4	12.4	10.6	NS	-
20-30	10.1	7.0	10.8	NS	-
30-35	11.9	7.9	7.3	NS	-
35-40	14.1	19.0	11.1	NS	-
40-50	15.2	15.8	14.9	NS	-
50-70	22.4	23.8	18.3	NS	-
03-Feb-92					
0-20	9.3	8.9	8.5	NS	-
20-30	11.3	10.5	14.9	NS	-
30-35	11.0	5.8	3.2	NS	-
35-40	10.7	15.6	9.4	NS	-
40-50	13.5	12.3	14.6	NS	-
50-70	21.0	24.3	14.7	NS	-
10-Feb-92					
0-20	14.5	9.9	9.5	NS	-
20-30	12.1	10.1	11.9	NS	-
30-35	18.8	7.9	9.4	0.052	7.1891
35-40	13.0	10.7	2.8	NS	-
40-50	21.5	17.7	14.0	NS	-
50-70	21.0	21.4	15.0	NS	-
18-Feb-92					
0-20	15.0	11.5	10.7	NS	-
20-30	12.3	6.4	12.1	NS	-
30-35	14.1	9.0	4.5	NS	-
35-40	15.5	19.7	4.1	NS	-
40-50	21.0	13.6	13.8	NS	-
50-70	20.6	22.7	15.5	NS	-

APPENDIX 4.10
Macronutrient Concentration as affected by cultivation treatment (%).

01-Aug-91	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
Nitrogen	2.817	2.656	2.838	NS	-
Phosphorus	0.3208	0.3217	0.3133	NS	-
Sulphur	0.2483	0.2483	0.2417	NS	-
Magnesium	0.1933	0.1717	0.1833	0.012	0.0123
Calcuim	0.581	0.492	0.586	0.049	0.06912
Sodium	0.249	0.263	0.271	NS	-
Potassium	1.859	2.085	1.928	NS	-
05-Sep-91	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
Nitrogen	3.063	2.896	2.936	NS	-
Phosphorus	0.3508	0.3717	0.3708	NS	-
Sulphur	0.2267	0.2358	0.2283	NS	-
Magnesium	0.2108	0.1967	0.205	NS	-
Calcuim	0.655	0.668	0.659	NS	-
Sodium	0.325	0.359	0.438	0.063	0.07973
Potassium	2.268	2.24	2.192	NS	-
26-Sep-91	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
Nitrogen	3.363	3.151	3.145	NS	-
Phosphorus	0.4583	0.465	0.4408	NS	-
Sulphur	0.2542	0.2683	0.2533	NS	-
Magnesium	0.21	0.2125	0.2158	NS	-
Calcuim	0.695	0.739	0.778	NS	-
Sodium	0.467	0.44	0.471	NS	-
Potassium	2.864	2.703	2.575	0.022	0.16511
11-Oct-91	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
Nitrogen	2.888	2.818	2.791	NS	-
Phosphorus	0.4058	0.4067	0.395	NS	-
Sulphur	0.2358	0.2575	0.2342	NS	-
Magnesium	0.1917	0.1925	0.2058	NS	-
Calcuim	0.602	0.623	0.702	0.029	0.06296
Sodium	0.482	0.415	0.463	NS	-
Potassium	2.68	2.4899	2.493	NS	-
24-Oct-91	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
Nitrogen	2.643	2.643	2.827	NS	-
Phosphorus	0.3967	0.3983	0.395	NS	-
Sulphur	0.2458	0.2492	0.2475	NS	-
Magnesium	0.205	0.2067	0.215	0.067	0.0074429
Calcuim	0.708	0.752	0.77	NS	-
Sodium	0.392	0.378	0.412	NS	-
Potassium	2.359	2.102	2.11	0.053	0.19403

APPENDIX 4.10 CONTINUED

Macronutrient Concentration as affected by cultivation treatment (%).

28-Nov-91	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
Nitrogen	1.437	1.68	1.656	NS	-
Phosphorus	0.2808	0.3008	0.3083	NS	-
Sulphur	0.1692	0.1917	0.185	NS	-
Magnesium	0.1883	0.1967	0.2008	NS	-
Calcuim	0.663	0.719	0.735	NS	-
Sodium	0.306	0.273	0.325	NS	-
Potassium	1.784	1.692	1.717	NS	-
20-Dec-91	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
Nitrogen	1.795	1.935	2.066	NS	-
Phosphorus	0.2967	0.2967	0.305	NS	-
Sulphur	0.1858	0.2	0.195	NS	-
Magnesium	0.2025	0.2067	0.2125	NS	-
Calcuim	0.802	0.847	0.932	0.022	0.07546
Sodium	0.2575	0.2658	0.2683	NS	-
Potassium	1.767	1.753	1.67	NS	-
16-Jan-92	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
Nitrogen	1.951	2.102	2.177	NS	-
Phosphorus	0.2742	0.2958	0.2908	0.8	0.01637
Sulphur	0.1908	0.2058	0.78	0.085	0.01896
Magnesium	0.225	0.2308	0.2375	NS	-
Calcuim	0.802	0.859	0.973	0.02	0.09821
Sodium	0.262	0.27	0.286	NS	-
Potassium	1.798	1.698	1.723	NS	-
12-Feb-92	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
Nitrogen	1.96	2.003	2.067	NS	-
Phosphorus	0.2592	0.2408	0.2458	NS	-
Sulphur	0.22	0.21	0.2	NS	-
Magnesium	0.2308	0.225	0.24	NS	-
Calcuim	0.967	0.969	1.069	NS	-
Sodium	0.1783	0.2133	0.2283	0.15	0.03585
Potassium	1.092	1.123	1.213	NS	-

APPENDIX 4.10 CONTINUED
Macronutrient Concentration as affected by fertiliser treatment (%).

01-Aug-91	Nil	P	P&S	FProb	LSD(10%)
Nitrogen	2.76	2.788	2.763	NS	-
Phosphorus	0.3	0.3317	0.3242	NS	-
Sulphur	0.2425	0.2392	0.2567	NS	-
Magnesium	0.18	0.1867	0.1817	NS	-
Calcuim	0.533	0.577	0.548	NS	-
Sodium	0.24	0.259	0.284	NS	-
Potassium	1.955	1.957	1.961	NS	-
05-Sep-91	Nil	P	P&S	FProb	L.S.D (10%)
Nitrogen	2.97	2.977	2.947	NS	-
Phosphorus	0.3392	0.3742	0.38	0.009	0.02575
Sulphur	0.2208	0.2283	0.2417	NS	-
Magnesium	0.0992	0.2133	0.2	NS	-
Calcuim	0.678	0.703	0.659	NS	-
Sodium	0.29	0.417	0.415	0.016	0.07973
Potassium	2.267	2.272	2.16	NS	-
26-Sep-91	Nil	P	P&S	FProb	L.S.D (10%)
Nitrogen	3.39	3.079	3.189	NS	-
Phosphorus	0.4325	0.4575	0.4742	0.034	0.0225
Sulphur	0.2558	0.2417	0.2783	0.043	0.02358
Magnesium	0.2192	0.2125	0.2067	NS	-
Calcuim	0.73	0.735	0.747	NS	-
Sodium	0.417	0.482	0.478	NS	-
Potassium	2.808	2.626	2.708	NS	-
11-Oct-91	Nil	P	P&S	FProb	L.S.D (10%)
Nitrogen	2.767	2.738	2.992	NS	-
Phosphorus	0.3975	0.405	0.405	NS	-
Sulphur	0.235	0.23	0.2625	0.038	0.021883
Magnesium	0.195	0.2017	0.1933	NS	-
Calcuim	0.67	0.655	0.602	NS	-
Sodium	0.393	0.466	0.501	0.072	0.07802
Potassium	2.644	2.418	2.6	0.073	0.16956
24-Oct-91	Nil	P	P&S	FProb	L.S.D (10%)
Nitrogen	2.661	2.669	2.784	NS	-
Phosphorus	0.3825	0.4067	0.4008	NS	-
Sulphur	0.23	0.245	0.2675	0.035	0.02505
Magnesium	0.21	0.2108	0.2058	NS	-
Calcuim	0.746	0.754	0.729	NS	-
Sodium	0.36	0.401	0.422	NS	-
Potassium	2.22	2.137	2.215	NS	-

APPENDIX 4.10 CONTINUED
Macronutrient Concentration as affected by fertiliser treatment (%).

28-Nov-91	Nil	P	P&S	FProb	L.S.D (10%)
Nitrogen	1.512	1.574	1.687	0.036	0.1915
Phosphorus	0.2708	0.3167	0.3025	0.018	0.0301136
Sulphur	0.1642	0.1783	0.2033	0.005	0.0188
Magnesium	0.19	0.1958	0.2	NS	-
Calcuim	0.71	0.684	0.723	NS	-
Sodium	0.274	0.308	0.322	NS	-
Potassium	1.732	1.685	1.776	NS	-
20-Dec-91	Nil	P	P&S	FProb	L.S.D (10%)
Nitrogen	1.771	2.033	1.993	NS	-
Phosphorus	0.2733	0.3025	0.3225	0.006	0.02732
Sulphur	0.1825	0.1917	0.2067	NS	-
Magnesium	0.1967	0.2158	0.2092	0.034	0.011892
Calcuim	0.817	0.904	0.859	NS	-
Sodium	0.2192	0.2808	0.2917	0.007	0.03788
Potassium	1.626	1.764	1.773	NS	-
16-Jan-92	Nil	P	P&S	FProb	L.S.D (10%)
Nitrogen	2.11	2.098	2.021	NS	-
Phosphorus	0.2733	0.2975	0.29	0.052	0.01637
Sulphur	0.1775	0.1917	0.2075	0.041	0.01896
Magnesium	0.2333	0.225	0.235	NS	-
Calcuim	0.879	0.867	0.888	NS	-
Sodium	0.272	0.28	0.267	NS	-
Potassium	1.603	1.768	1.751	0.036	0.08795
12-Feb-92	Nil	P	P&S	FProb	L.S.D (10%)
Nitrogen	1.955	1.996	2.079	NS	-
Phosphorus	0.223	0.255	0.2475	NS	-
Sulphur	0.1992	0.2108	0.22	NS	-
Magnesium	0.22	0.2383	0.2375	0.034	0.01271
Calcuim	0.974	1.059	0.972	NS	-
Sodium	0.1683	0.2275	0.2242	0.069	0.03585
Potassium	1.085	1.188	1.156	NS	-

APPENDIX 4.11

Macronutrient uptake (kg/ha) as affected by cultivation and fertiliser treatment.

Nitrogen					
Date	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
07-Nov-90	23.97	26.43	28.27	NS	-
05-Dec-90	29.93	33.67	28.80	NS	-
15-Jan-91	32.10	20.30	18.60	0.0050	6.895
25-Feb-91	25.97	29.37	31.77	NS	-
22-Apr-91	14.37	13.13	13.10	NS	-
01-Aug-91	29.53	34.17	36.70	NS	-
05-Sep-91	23.27	34.37	25.97	0.0780	8.172
26-Sep-91	27.27	24.03	30.00	NS	-
11-Oct-91	3.30	14.63	10.90	0.0370	6.930
24-Oct-91	29.93	30.20	33.77	NS	-
28-Nov-91	25.43	23.67	29.00	NS	-
20-Dec-91	3.70	0.51	6.07	NS	-
16-Jan-92	0.82	7.24	3.24	0.0300	3.894
13-Feb-92	10.87	13.70	12.97	NS	-
Date	Nil	P	P & S	FProb	L.S.D (10%)
07-Nov-90	24.93	28.07	25.67	NS	-
05-Dec-90	31.00	30.07	31.33	NS	-
15-Jan-91	21.23	21.97	27.80	NS	-
25-Feb-91	18.43	35.80	32.87	NS	-
22-Apr-91	9.70	13.90	17.00	0.053	4.860
01-Aug-91	30.30	34.87	35.23	NS	-
05-Sep-91	22.33	29.97	31.30	NS	-
26-Sep-91	23.27	28.13	29.90	NS	-
11-Oct-91	8.03	9.87	10.93	NS	-
24-Oct-91	31.23	26.90	35.77	NS	-
28-Nov-91	21.17	26.50	30.43	NS	-
20-Dec-91	4.97	5.93	2.90	NS	-
16-Jan-92	2.79	4.56	3.96	NS	-
13-Feb-92	10.93	14.83	11.77	NS	-

APPENDIX 4.11 CONTINUED

Macronutrient uptake (kg/ha) as affected by cultivation and fertiliser treatment.

Phosphorus					
Date	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
07-Nov-90	3.68	3.81	4.36	NS	-
05-Dec-90	4.22	4.42	3.97	NS	-
15-Jan-91	4.54	2.75	2.54	0.0030	0.951
25-Feb-91	4.53	3.56	3.57	NS	-
22-Apr-91	1.67	1.56	1.47	NS	-
01-Aug-91	3.34	3.98	4.28	NS	-
05-Sep-91	2.85	4.63	3.37	0.0330	1.067
26-Sep-91	3.65	3.53	4.56	NS	-
11-Oct-91	0.68	2.27	1.62	0.0550	1.036
24-Oct-91	4.33	4.75	4.79	NS	-
28-Nov-91	4.87	4.10	5.32	NS	-
20-Dec-91	0.59	0.51	0.92	NS	-
16-Jan-92	0.12	1.03	0.39	0.02	0.524
13-Feb-92	1.44	1.64	1.53	NS	-
Date	Nil	P	P & S	FProb	L.S.D (10%)
07-Nov-90	3.75	4.10	4.01	NS	-
05-Dec-90	4.33	3.90	4.38	NS	-
15-Jan-91	2.59	3.44	3.80	NS	-
25-Feb-91	3.08	4.66	3.92	0.032	0.960
22-Apr-91	1.07	1.61	2.02	0.021	0.550
01-Aug-91	3.27	3.97	4.35	NS	-
05-Sep-91	2.56	4.07	4.22	0.033	1.067
26-Sep-91	3.16	4.20	4.38	NS	-
11-Oct-91	1.29	1.70	1.57	NS	-
24-Oct-91	4.63	4.42	4.82	NS	-
28-Nov-91	3.79	5.02	5.49	0.06	1.163
20-Dec-91	0.68	0.90	0.45	NS	-
16-Jan-92	0.37	0.64	0.53	NS	-
13-Feb-92	1.35	1.89	1.37	NS	-

APPENDIX 4.11 CONTINUED

Macronutrient uptake (kg/ha) as affected by cultivation and fertiliser treatment.

Sulphur					
Date	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
07-Nov-90	2.26	2.40	2.57	NS	-
05-Dec-90	2.93	3.00	2.58	NS	-
15-Jan-91	3.10	2.03	1.74	0.0110	0.739
25-Feb-91	3.12	2.55	2.54	NS	-
22-Apr-91	1.24	1.21	1.07	NS	-
01-Aug-91	2.43	3.10	3.21	0.0680	0.577
05-Sep-91	1.49	2.82	2.17	0.0170	0.691
26-Sep-91	1.81	1.89	2.63	NS	-
11-Oct-91	0.29	1.42	1.04	0.0320	0.666
24-Oct-91	2.74	2.85	3.43	NS	-
28-Nov-91	2.58	2.53	3.32	0.0870	0.645
20-Dec-91	0.34	0.51	0.59	NS	-
16-Jan-92	0.09	0.72	0.28	0.0240	0.375
13-Feb-92	1.16	1.46	1.28	NS	-
Date	Nil	P	P & S	FProb	L.S.D (10%)
07-Nov-90	2.32	2.52	2.39	NS	-
05-Dec-90	2.87	2.67	2.97	NS	-
15-Jan-91	1.88	2.00	2.99	0.032	0.740
25-Feb-91	2.20	2.87	3.14	0.082	0.710
22-Apr-91	0.82	1.09	1.61	0.007	0.390
01-Aug-91	2.60	2.81	3.33	NS	-
05-Sep-91	1.61	2.39	2.48	0.088	0.691
26-Sep-91	1.75	2.05	2.53	NS	-
11-Oct-91	0.77	0.96	1.02	NS	-
24-Oct-91	2.73	2.56	3.75	NS	-
28-Nov-91	2.24	2.71	3.48	0.17	0.645
20-Dec-91	0.43	0.54	0.31	NS	-
16-Jan-92	0.24	0.44	0.41	NS	-
13-Feb-92	1.12	1.59	1.19	NS	-

APPENDIX 4.11 CONTINUED
Macronutrient uptake (kg/ha) as affected by cultivation and fertiliser treatment.

Calcium					
Date	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
07-Nov-90	7.59	8.51	8.44	NS	-
05-Dec-90	13.58	14.56	14.63	NS	-
15-Jan-91	15.63	10.57	9.89	0.0140	3.360
25-Feb-91	15.08	13.61	14.69	NS	-
22-Apr-91	4.89	4.40	3.84	NS	-
01-Aug-91	7.27	5.97	7.22	NS	-
05-Sep-91	4.89	7.88	6.05	0.0490	1.907
26-Sep-91	6.31	5.62	7.53	NS	-
11-Oct-91	0.74	3.27	2.67	0.0280	1.500
24-Oct-91	8.10	8.64	8.96	NS	-
28-Nov-91	11.69	10.35	12.40	NS	-
20-Dec-91	1.76	0.51	2.70	NS	-
16-Jan-92	0.34	2.86	1.17	0.0240	1.482
13-Feb-92	5.39	6.82	7.02	NS	-
Date	Nil	P	P & S	FProb	L.S.D (10%)
07-Nov-90	8.02	8.44	8.08	NS	-
05-Dec-90	14.91	12.50	15.36	NS	-
15-Jan-91	11.62	10.74	13.74	NS	-
25-Feb-91	12.83	16.40	14.16	NS	-
22-Apr-91	3.51	4.60	5.01	NS	-
01-Aug-91	5.93	6.77	7.76	0.07	1.259
05-Sep-91	4.96	7.19	6.68	NS	-
26-Sep-91	5.42	6.98	7.06	NS	-
11-Oct-91	1.97	2.56	2.14	NS	-
24-Oct-91	9.09	7.79	8.82	NS	-
28-Nov-91	10.24	11.17	13.02	NS	-
20-Dec-91	2.27	2.69	1.29	NS	-
16-Jan-92	1.09	1.87	1.40	NS	-
13-Feb-92	5.59	8.00	5.63	NS	-

APPENDIX 4.11 CONTINUED
Macronutrient uptake (kg/ha) as affected by cultivation and fertiliser treatment.

Magnesium					
Date	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
07-Nov-90	1.96	2.23	2.28	NS	-
05-Dec-90	3.21	3.25	3.21	NS	-
15-Jan-91	3.58	2.16	1.97	0.0010	0.700
25-Feb-91	3.33	2.78	2.95	NS	-
22-Apr-91	1.25	1.11	1.15	NS	-
01-Aug-91	2.18	2.14	2.30	NS	-
05-Sep-91	1.54	2.32	1.75	0.0400	0.490
26-Sep-91	1.68	1.53	2.08	NS	-
11-Oct-91	0.23	1.06	0.81	0.0270	0.472
24-Oct-91	2.25	2.43	2.48	NS	-
28-Nov-91	3.11	2.72	3.39	NS	-
20-Dec-91	0.44	0.51	0.62	NS	-
16-Jan-92	0.10	0.76	0.29	0.0190	0.380
13-Feb-92	1.22	1.55	1.53	NS	-
Date	Nil	P	P & S	FProb	L.S.D (10%)
07-Nov-90	2.02	2.31	2.14	NS	-
05-Dec-90	3.36	2.82	3.49	NS	-
15-Jan-91	2.49	2.44	2.77	NS	-
25-Feb-91	2.73	3.40	2.93	NS	-
22-Apr-91	0.88	1.17	1.47	0.072	0.410
01-Aug-91	2.00	2.21	2.40	NS	-
05-Sep-91	1.44	2.13	2.04	0.057	0.490
26-Sep-91	1.54	1.88	1.87	NS	-
11-Oct-91	0.59	0.81	0.70	NS	-
24-Oct-91	2.51	2.19	2.46	NS	-
28-Nov-91	2.66	3.07	3.49	NS	-
20-Dec-91	0.50	0.66	0.31	NS	-
16-Jan-92	0.29	0.47	0.39	NS	-
13-Feb-92	1.23	1.78	1.30	NS	-

APPENDIX 4.11 CONTINUED
Macronutrient uptake (kg/ha) as affected by cultivation and fertiliser treatment.

Sodium					
Date	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
07-Nov-90	3.69	4.15	4.16	NS	-
05-Dec-90	4.59	4.07	4.37	NS	-
15-Jan-91	5.19	2.99	3.04	0.007	1.223
25-Feb-91	4.13	3.21	3.51	NS	-
22-Apr-91	1.71	1.57	2.02	NS	-
01-Aug-91	3.05	3.49	3.41	NS	-
05-Sep-91	2.46	4.20	4.46	0.055	1.417
26-Sep-91	2.97	3.33	4.47	NS	-
11-Oct-91	0.84	2.31	1.78	0.088	1.081
24-Oct-91	3.98	3.99	4.83	NS	-
28-Nov-91	5.47	3.73	4.83	0.067	1.198
20-Dec-91	0.58	0.51	0.81	NS	-
16-Jan-92	0.15	0.83	0.33	0.023	0.406
13-Feb-92	0.96	1.46	1.45	NS	-
Date	Nil	P	P & S	FProb	L.S.D (10%)
07-Nov-90	3.69	4.29	4.02	NS	-
05-Dec-90	4.31	3.88	4.83	NS	-
15-Jan-91	2.81	3.42	5.00	0.015	1.220
25-Feb-91	2.44	4.31	4.10	0.009	1.040
22-Apr-91	1.16	1.76	2.38	0.030	0.740
01-Aug-91	2.55	3.19	4.21	0.052	1.072
05-Sep-91	2.12	4.16	4.83	0.014	1.417
26-Sep-91	2.73	3.93	4.12	NS	-
11-Oct-91	1.00	1.70	2.23	NS	-
24-Oct-91	4.07	3.14	5.59	0.011	1.184
28-Nov-91	3.98	4.30	5.75	0.049	1.202
20-Dec-91	0.59	0.86	0.48	NS	-
16-Jan-92	0.33	0.53	0.44	NS	-
13-Feb-92	0.88	1.72	1.28	0.037	0.520

APPENDIX 4.12

Cumulative macronutrient uptake (kg/ha) as affected by cultivation treatment (summed from 1-Aug-91).

Nitrogen	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
01-Aug-91	29.53	34.17	36.70	NS	-
05-Sep-91	52.80	68.53	62.67	NS	-
26-Sep-91	80.07	92.57	92.67	NS	-
11-Oct-91	83.37	107.20	103.57	NS	-
24-Oct-91	113.30	137.40	137.33	NS	-
28-Nov-91	138.73	161.07	166.33	NS	-
20-Dec-91	142.43	161.58	172.40	NS	-
16-Jan-92	143.26	168.82	175.64	NS	-
13-Feb-92	154.12	182.52	188.61	NS	-
Phosphorus	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
01-Aug-91	3.34	3.98	4.28	NS	-
05-Sep-91	6.19	8.61	7.65	0.081	1.731
26-Sep-91	9.83	12.14	12.21	NS	-
11-Oct-91	10.51	14.41	13.83	NS	-
24-Oct-91	14.84	19.16	18.62	NS	-
28-Nov-91	19.71	23.26	23.94	NS	-
20-Dec-91	20.31	23.77	24.86	NS	-
16-Jan-92	20.43	24.80	25.25	NS	-
13-Feb-92	21.86	26.44	26.79	NS	-
Sulphur	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
01-Aug-91	2.43	3.10	3.21	0.068	0.577
05-Sep-91	3.91	5.92	5.38	0.022	1.[illegible]26
26-Sep-91	5.73	7.81	8.01	0.062	1.692
11-Oct-91	6.02	9.23	9.05	0.034	2.126
24-Oct-91	8.76	12.08	12.48	0.082	2.919
28-Nov-91	11.34	14.61	15.80	0.094	3.414
20-Dec-91	11.68	15.12	16.39	0.064	3.481
16-Jan-92	11.77	15.84	16.67	0.047	3.655
13-Feb-92	12.93	17.30	17.95	0.074	3.712
Potassium	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
01-Aug-91	19.03	27.17	26.53	0.027	5.080
05-Sep-91	37.67	55.77	47.17	0.028	10.255
26-Sep-91	61.37	76.90	73.57	NS	-
11-Oct-91	64.90	90.33	83.53	NS	-
24-Oct-91	90.17	115.60	109.23	NS	-
28-Nov-91	119.67	140.17	138.30	NS	-
20-Dec-91	123.04	140.68	142.88	NS	-
16-Jan-92	123.91	146.26	144.96	NS	-
13-Feb-92	129.63	153.97	153.20	NS	-

APPENDIX 4.12 CONTINUED
Cumulative macronutrient uptake (kg/ha) as affected by cultivation treatment (summed from 1-Aug-91).

Calcium	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
01-Aug-91	7.27	5.97	7.22	NS	-
05-Sep-91	12.16	13.85	13.27	NS	-
26-Sep-91	18.47	19.47	20.80	NS	-
11-Oct-91	19.20	22.74	23.47	NS	-
24-Oct-91	27.30	31.37	32.43	NS	-
28-Nov-91	38.99	41.73	44.82	NS	-
20-Dec-91	40.75	42.24	47.52	NS	-
16-Jan-92	41.09	45.09	48.69	NS	-
13-Feb-92	46.47	51.91	55.72	NS	-
Magnesium	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
01-Aug-91	2.18	2.14	2.30	NS	-
05-Sep-91	3.71	4.46	4.05	NS	-
26-Sep-91	5.39	5.99	6.13	NS	-
11-Oct-91	5.62	7.05	6.94	NS	-
24-Oct-91	7.88	9.48	9.43	NS	-
28-Nov-91	10.98	12.20	12.81	NS	-
20-Dec-91	11.43	12.71	13.43	NS	-
16-Jan-92	11.53	13.47	13.71	NS	-
13-Feb-92	12.75	15.02	15.25	NS	-
Sodium	Nil	Aerated	Subsoiled	FProb	L.S.D (10%)
01-Aug-91	3.05	3.49	3.41	NS	-
05-Sep-91	5.51	7.68	7.87	NS	-
26-Sep-91	8.48	11.02	12.34	NS	-
11-Oct-91	9.32	13.33	14.12	NS	-
24-Oct-91	13.30	17.32	18.95	NS	-
28-Nov-91	18.77	21.05	23.78	NS	-
20-Dec-91	19.35	21.56	24.59	NS	-
16-Jan-92	19.50	22.38	24.91	NS	-
13-Feb-92	20.46	23.84	26.37	NS	-

APPENDIX 4.13

Micronutrient Concentration (µg/g) as affected by cultivation treatment.

Zinc	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
07-Nov-90	30.50	29.17	32.00	NS	_
05-Dec-90	36.67	34.67	35.67	NS	-
01-Aug-91	37.42	34.75	34.67	0.002	2.525
12-Feb-92	40.17	34.58	36.25	0.041	4.1868
Copper	**Nil**	**Aerated**	**Subsoiled**	**FProb**	**L.S.D(10%)**
07-Nov-90	6.08	5.67	6.00	NS	_
05-Dec-90	5.67	5.17	5.50	NS	-
01-Aug-91	5.67	4.83	5.58	0.097	0.801
12-Feb-92	5.42	4.75	5.5	0.041	0.601
Iron	**Nil**	**Aerated**	**Subsoiled**	**FProb**	**L.S.D(10%)**
07-Nov-90	411	422	456	NS	_
05-Dec-90	837	887	993	NS	-
01-Aug-91	1715	1009	1117	<0.001	249.63
12-Feb-92	500	399	484	0.032	66.44
Cobalt	**Nil**	**Aerated**	**Subsoiled**	**FProb**	**L.S.D(10%)**
07-Nov-90	0.1733	0.1758	0.1758	NS	_
05-Dec-90	0.4750	0.3880	0.4280	NS	-
01-Aug-91	0.6670	0.3420	0.3960	<0.001	0.0955
12-Feb-92	0.2380	0.1710	0.2380	0.002	0.0323
Manganese	**Nil**	**Aerated**	**Subsoiled**	**FProb**	**L.S.D(10%)**
07-Nov-90	93.5	85.3	92.3	NS	_
05-Dec-90	125.3	128.4	151.1	NS	-
01-Aug-91	127.7	108.8	114.4	NS	-
12-Feb-92	150.7	149.3	154.6	NS	-

Micronutrient Concentration (µg/g) as affected by fertiliser treatment.

Zinc	Nil	P	P & S	FProb	L.S.D(10%)
07-Nov-90	31.50	30.92	29.52	NS	-
05-Dec-90	36.00	35.42	35.58	NS	-
01-Aug-91	33.67	34.75	34.67	NS	-
12-Feb-92	37.25	37.42	36.33	NS	-
Copper	**Nil**	**P**	**P & S**	**FProb**	**L.S.D(10%)**
07-Nov-90	6.00	6.25	5.58	NS	-
05-Dec-90	5.75	5.33	5.25	NS	-
01-Aug-91	5.58	5.42	5.08	NS	-
12-Feb-92	5.08	5.42	5.17	NS	-
Iron	**Nil**	**P**	**P & S**	**FProb**	**L.S.D(10%)**
07-Nov-90	424	449	416	NS	-
05-Dec-90	992	927	797	NS	-
01-Aug-91	1371	1220	1250	NS	-
12-Feb-92	436	454	493	NS	-
Cobalt	**Nil**	**P**	**P & S**	**FProb**	**L.S.D(10%)**
07-Nov-90	0.1700	0.1825	0.1725	NS	-
05-Dec-90	0.4790	0.4590	0.3530	NS	-
01-Aug-91	0.4670	0.4450	0.4920	NS	-
12-Feb-92	0.1842	0.2433	0.2192	NS	-
Manganese	**Nil**	**P**	**P & S**	**FProb**	**L.S.D(10%)**
07-Nov-90	93.5	90.3	86.8	NS	-
05-Dec-90	130.1	148.9	125.8	NS	-
01-Aug-91	113.3	118.3	119.3	NS	-
12-Feb-92	150.5	152.9	151.6	NS	-

APPENDIX 4.14

Micronutrient uptake (kg/ha) as affected by cultivation treatment.

Iron	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
07-Nov-90	0.429	0.500	0.468	NS	-
05-Dec-90	0.971	1.340	1.459	0.068	0.3468
01-Aug-91	1.692	1.122	1.270	0.049	0.3752
16-Feb-92	0.420	0.325	0.248	0.067	0.1171
Zinc	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
07-Nov-90	0.0353	0.0349	0.0357	NS	-
05-Dec-90	0.0400	0.0490	0.0461	NS	-
01-Aug-91	0.0398	0.0399	0.0442	NS	-
16-Feb-92	0.0312	0.0250	0.0187	0.052	0.00799
Cobalt	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
07-Nov-90	0.000164	0.000205	0.000208	NS	-
05-Dec-90	0.000607	0.000607	0.000602	NS	-
01-Aug-91	0.000615	0.000403	0.000454	0.028	0.0001255
16-Feb-92	0.000197	0.000139	0.000133	0.036	0.0000423
Manganese	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
07-Nov-90	0.0949	0.1007	0.1072	NS	-
05-Dec-90	0.1474	0.1955	0.2200	0.017	0.03817
01-Aug-91	0.1215	0.1210	0.1499	NS	-
16-Feb-92	0.1244	0.1130	0.0839	NS	-
Copper	Nil	Aerated	Subsoiled	FProb	L.S.D(10%)
07-Nov-90	0.00725	0.00663	0.00732	NS	-
05-Dec-90	0.00667	0.00736	0.00714	NS	-
01-Aug-91	0.00703	0.00594	0.00698	NS	-
16-Feb-92	0.00444	0.00353	0.00290	NS	-

Micronutrient uptake (kg/ha) as affected by fertiliser treatment.

Iron	Nil	P	P & S	FProb	L.S.D(10%)
07-Nov-90	0.426	0.484	0.487	NS	-
05-Dec-90	1.377	1.151	1.242	NS	-
01-Aug-91	1.609	1.157	1.317	NS	-
16-Feb-92	0.222	0.382	0.389	0.044	0.1171
Zinc	Nil	P	P & S	FProb	L.S.D(10%)
07-Nov-90	0.0340	0.0357	0.0361	NS	-
05-Dec-90	0.0475	0.0384	0.0492	0.072	0.00803
01-Aug-91	0.0381	0.0405	0.0453	NS	-
16-Feb-92	0.0181	0.0288	0.0279	0.066	0.00799
Cobalt	Nil	P	P & S	FProb	L.S.D(10%)
07-Nov-90	0.000176	0.000203	0.000198	NS	-
05-Dec-90	0.000649	0.000580	0.000587	NS	-
01-Aug-91	0.000508	0.000423	0.005400	NS	-
16-Feb-92	0.000091	0.000200	0.000178	0.002	0.000042
Manganese	Nil	P	P & S	FProb	L.S.D(10%)
07-Nov-90	0.0973	0.1039	0.1017	NS	-
05-Dec-90	0.1832	0.1779	0.2018	NS	-
01-Aug-91	0.1259	0.1187	0.1478	NS	-
16-Feb-92	0.0742	0.1206	0.1264	0.058	0.03759
Copper	Nil	P	P & S	FProb	L.S.D(10%)
07-Nov-90	0.00672	0.00730	0.00718	NS	-
05-Dec-90	0.00737	0.00562	0.00818	0.043	0.001613
01-Aug-91	0.00613	0.00656	0.00727	NS	-
16-Feb-92	0.00252	0.00448	0.00387	0.053	0.001588

APPENDIX 5.1
35S-Sulphur concentration of the cultivation treatments and pasture components (nCi/g DM).

DATE:	28-Sep-91					
Depth of Injection: 25cm						
	Grass	Clover	Weeds		FProb	L.S.D(10%)
Nil	322.0	16.0	0.0	Cultivation	0.012	89.3
Aeration	502.0	216.0	99.0	ID	0.001	89.3
Subsoil	469.0	178.0	205.0	Cult*ID	NS	-
Depth of Injection: 40cm						
	Grass	Clover	Weeds		FProb	L.S.D(10%)
Nil	81.5	14.3	37.7	Cultivation	NS	-
Aeration	42.6	3.7	21.4	ID	NS	-
Subsoil	43.1	61.5	24.4	Cult*ID	NS	-
Depth of Injection: 55cm						
	Grass	Clover	Weeds		FProb	L.S.D(10%)
Nil	24.7	13.7	28.6	Cultivation	NS	-
Aeration	9.3	0.0	23.0	ID	NS	-
Subsoil	10.6	6.6	21.6	Cult*ID	NS	-
DATE:	23-Oct-91					
Depth of Injection: 25cm						
	Grass	Clover	Weeds		FProb	L.S.D(10%)
Nil	261.0	229.0	0.0	Cultivation	NS	-
Aeration	319.0	125.0	88.0	ID	0.011	109.68
Subsoil	388.0	169.0	166.0	Cult*ID	NS	-
Depth of Injection: 40cm						
	Grass	Clover	Weeds		FProb	L.S.D(10%)
Nil	33.1	21.7	0.0	Cultivation	NS	-
Aeration	51.8	19.0	3.6	ID	0.003	24.78
Subsoil	100.8	35.8	0.2	Cult*ID	NS	-
Depth of Injection: 55cm						
	Grass	Clover	Weeds		FProb	L.S.D(10%)
Nil	13.1	14.9	22.7	Cultivation	NS	-
Aeration	9.8	0.0	0.0	ID	NS	-
Subsoil	26.5	18.3	9.4	Cult*ID	NS	-

APPENDIX 5.1 CONTINUED
35S-Sulphur concentration of the cultivation treatments and pasture components (nCi/g DM).

DATE: 29-Nov-91						
Depth of Injection: 25cm						
	Grass	Clover	Weeds		FProb	L.S.D(10%)
Nil	181.0	95.5	8.0	Cultivation	NS	-
Aeration	178.0	80.6	52.0	ID	0.001	40.25
Subsoil	191.0	101.0	32.8	Cult*ID	NS	-
Depth of Injection: 40cm						
	Grass	Clover	Weeds		FProb	L.S.D(10%)
Nil	47.5	62.8	16.3	Cultivation	0.002	32.59
Aeration	25.7	49.7	30.0	ID	0.031	32.59
Subsoil	35.7	70.8	229.3	Cult*ID	0.001	56.42
Depth of Injection: 55cm						
	Grass	Clover	Weeds		FProb	L.S.D(10%)
Nil	25.8	24.9	12.2	Cultivation	NS	-
Aeration	7.9	20.4	7.9	ID	NS	-
Subsoil	37.5	15.7	10.2	Cult*ID	NS	-
DATE: 16-Jan-92						
Depth of Injection: 25cm						
	Grass	Clover	Weeds		FProb	L.S.D(10%)
Nil	107.7	30.1	0.1	Cultivation	0.013	27.42
Aeration	54.4	10.5	45.8	ID	0.001	27.42
Subsoil	159.8	70.2	43.6	Cult*ID	0.1	47.49
Depth of Injection: 40cm						
	Grass	Clover	Weeds		FProb	L.S.D(10%)
Nil	32.0	91.0	6.0	Cultivation	NS	-
Aeration	25.0	25.0	0.0	ID	NS	-
Subsoil	30.0	71.0	65.0	Cult*ID	NS	-
Depth of Injection: 55cm						
	Grass	Clover	Weeds		FProb	L.S.D(10%)
Nil	10.7	76.4	16.2	Cultivation	NS	-
Aeration	0.0	0.0	27.2	ID	NS	-
Subsoil	0.8	0.0	0.0	Cult*ID	NS	-

APPENDIX 5.2
Pasture composition (%) of the microplots.

28-Sep-91	Grass	Clover	Weeds
Nil	80.4	10.8	8.9
Aerated	81.3	12.1	6.6
Subsoiled	70.5	15.4	14.1
Average	77.4	12.7	9.9
+/- S.E.	2.3	1.5	1.5
23-Oct-91	Grass	Clover	Weeds
Nil	80.9	14.6	4.5
Aerated	78.5	14.4	7.1
Subsoiled	70.4	19.6	10
Average	76.6	16.2	7.2
+/- S.E.	2.6	1.9	1.5
29-Nov-91	Grass	Clover	Weeds
Nil	78	16.4	5.7
Aerated	79.7	14.7	5.2
Subsoiled	76.2	14.9	8.9
Average	77.9	15.3	6.7
+/- S.E.	2.2	2	1
16-Jan-92	Grass	Clover	Weeds
Nil	60	18.8	21.2
Aerated	58	24.4	15.9
Subsoiled	47.7	22.4	30
Average	55.2	21.9	22.9
+/- S.E.	3	2.6	3.3
Date	Grass	Clover	Weeds
28-Sep-91	77.4	12.7	9.9
23-Oct-91	76.6	16.2	7.2
29-Nov-91	77.9	15.3	6.7
16-Jan-92	55.2	21.9	22.9

APPENDIX 5.3

Recovery of 35S-Sulphur (%) as affected by cultivation treatment.

Date	Depth (cm)	Nil	Aerated (27cm)	Subsoiled (47cm)	FProb	L.S.D (10%)
28-Sep-91	25	2.620	3.890	2.300	NS	-
	40	0.600	0.340	0.310	NS	-
	55	0.198	0.075	0.059	NS	-
30-Oct-91	25	4.570	4.490	4.560	NS	-
	40	0.600	0.970	0.940	NS	-
	55	0.214	0.111	0.376	0.094	0.190
29-Nov-91	25	4.540	5.990	4.800	NS	-
	40	1.910	0.900	1.300	NS	-
	55	0.668	0.371	0.894	NS	-
18-Dec-91	25	0.806	0.493	0.589	NS	-
	40	0.510	0.300	0.060	NS	-
	55	0.000	0.079	0.057	NS	-
16-Jan-92	25	1.050	0.340	2.450	0.005	0.6396
	40	0.420	0.330	0.780	NS	-
	55	0.121	0.233	0.003	NS	-
12-Feb-92	25	0.800	0.760	0.400	NS	-
	40	1.090	0.170	0.550	NS	-
	55	0.146	0.055	0.144	NS	-
Total	25	14.386	15.963	15.099	NS	-
	40	5.130	3.010	3.940	NS	-
	55	1.347	0.924	1.533	NS	-