TILLAGE AND NO-TILLAGE EFFECTS ON PHYSICAL CHARACTERISTICS OF A SILT LOAM UNDER 5 YEARS OF CONTINUOUS OATS-MAIZE CROP ROTATION

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Abstract

Conservation tillage is one of the conserving practices recognized worldwide despite its empirical benefits still largely undergoing continuous research. This research is part of a sequence of studies carried out at Massey University tillage trial. The soil type is Ohakea silt loam representing youngest yellow-grey earth with poor natural drainage on fine texture material, and topsoil moderately to strong acid enleached soils. Selected soil physical properties under different tillage systems i.e. no-tillage (NT), moldboard plough (MP) and permanent pasture (PP) (as control) were measured and compared. The important soil properties considered were soil aggregate stability, soil penetration resistance, water infiltration rate, soil bulk density, soil water content, crop dry matter, water runoff and leachate and soil pH (H_2O), total C and N. Results from both the field and laboratory experiments suggested that 5 years of continuous no-tillage have improved soil characteristics relative to conventional tillage.

Soil penetration resistance was significantly lower in the MP plots soon after cultivation and at the early oats growing season, compared to the NT and PP plots. However, this trend was reversed within six months, following winter grazing and spring fallow when soil was recompacted.

Bulk density measured during early oats growing season indicated a remarkably higher density at the top 0-5 cm soil layer under the NT compared to the MP treatment suggesting that NT plots' soils were more compacted at the time of planting and had lower total porosity than soils in the MP plots. On the other hand, water infiltration rates measured over one year period indicated an average value significantly higher under the NT and PP treatments than the MP plots. These results suggest that macropore continuity, water-filled porosity and other hydraulic properties were improved under NT.

A substantially higher level (11%) of water content was found in the NT plots compared to that in the MP plot. These suggested that although the NT soils were more resistant to penetration and had high levels of bulk density, these soils retained more water. These further suggested that the water-filled porosity under the NT soil was higher, thus helped increase the water availability for plant growth. The results also demonstrated that the

NT soil produced comparable winter oats and summer maize DM to those under MP treatment.

Regression analysis results indicated, not unexpectedly, a strong linear relationship between bulk density and soil penetration resistance with R^2 values of 0.97, 0.99, and 0.73 for the PP, MP, and NT treatments respectively. Similar analyses between soil water content and soil penetration resistance demonstrated a strong, moderate, and no correlations under the NT, MP and PP treatments respectively.

The NT soils were substantially more stable than the MP soils but were similar to the PP soils. The surface soil (0-10 cm soil depth) water-stable aggregates remaining on sieve for the PP, MP, and NT were 75.2, 26.2 and 70.8 % respectively. The macroaggregates (> 2 mm diameter) made up a large proportion of the pasture soil (54.7 %) and the un-tilled soil (37.4%), whereas the ploughed soils had macroaggregates at 4.8%. The ploughed soil was consisted of 73.8% of 0.5 mm water-stable aggregates. Prolonged sieving for 60 minutes also confirmed the above results that the detachment of soils by water in the continuously ploughed land was much easier as compared to the NT and PP management. Thus making the MP soils most vulnerable to water erosion.

Runoff and leachete experiments had produced rather inconclusive results as compared to the results on the same plots three years ago. However the trend was obvious that the MP treatment had caused more surface runoff than the other two treatments. By contrast, water runoff was lower in NT plots, which was also reflected by the occurrence of more water leaching under this treatment compared to the MP treatment.

The NT soils were relatively more acidic (lower pH) both at 0-10 and 10-20 cm soil layers. Both the MP and NT had resulted in a marked decline in total C level compared to PP at the 0-10 cm soil layer. The decline of total C content after 5 years of continuous double cropping in the 0-20 cm soil layer was about 12% in the MP plots and 2.65% in the NT plots. At the 10-20 cm soil depth, total C and N showed no differences among all treatments. Total N at the 0-10 cm soil layer was significantly lower under MP treatment compared to the other two treatments.

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Chapter 1

General Introduction

1.1 Introduction

Sustainability of the agriculture management system and its capacity to continue producing on a long term basis is a problem when human activities cause ecological changes that undermine agroecosystem function (Barrow, 1995). In agricultural systems, tillage is the principal agent resulting in soil perturbation and subsequent modification in soil structure. From an ecological point of view, such perturbations strongly influence the distribution of energy-rich organic substances within the soil and thus impact on energy flow and the dynamics of soil geochemical cycles (Carter, 1994).

In recent decades, the possible adverse effects of conventional tillage have become increasingly apparent and attention has been devoted to alternative management methods. Many of these alternatives have been based upon the principle of reducing the number and intensity of tillage operations (minimal tillage or reduced cultivation), which are commonly known as conservation tillage practices (Briggs and Courtney, 1985). The most obvious advantage of conservation tillage from an environmental viewpoint is its role in minimizing the risk of erosion. Surface residues protect soil structural conditions at the surface from the energies of raindrop impact and surface flow. Aggregate breakdown, surface sealing and crusting, and clogging of worm holes or voids between structural units is reduced (Bradford and Huang, 1994).

Riley et al. (1994), suggested that many of the changes caused by conservation tillage practices are interrelated, and their consequences may be of greater or lesser importance, depending on the soil type and on the external constraints of the climate. These changes can be summarized as follows:

- accumulation of available nutrients (phosphorus and potassium) and organic matter near the soil surface;
- increased bulk density and penetration resistance in upper and central topsoil layers;

- lower air-filled porosity and gaseous exchange and, sometimes, higher water-holding capacity;
- lower surface infiltration rates, but in some cases, increased hydraulic conductivity between topsoil and subsoil; and
- greater aggregate stability, greater earthworm activity, and more favourable conditions for promoting pore continuity.

No-till is the most extreme form of conservation tillage (Gish and Coffman, 1987). This involves no seedbed preparation at all, and crops are sown into the untilled soil by a machine that cuts a narrow seed-slot. Crop residues are normally allowed to decompose *in situ*, herbicides are used to control weeds and pests, and rooting and drainage conditions by encouraging earthworm activity. This practice is also known as direct-drilling in Britain or zero tillage in the USA (Briggs and Courtney, 1985).

Massey University is one of the leading advocates of conservation tillage in New Zealand and internationally. Research and development of the direct-drilling practice as well as studying its effects on soil and crops has been continuing since 1970's. To mention some of the studies which were conducted more than two decades ago, were those concerning the effects of no-till on soil properties conducted by Hughes and Baker (1977) and Choudhary (1979) regarding the drilling equipment performance and its relationship to seed emergence and soil micro-environment. In 1995, an experimental site was established, over which a series of specific studies on soil characteristics in regard to different mechanical treatments have been carried out (Guo, 1997; Aslam , 1998; Hou, 1999).

This research is part of a sequence of studies on the experimental site mentioned above. The experiments cover measurements of selected soil physical parameters, which in fact, will be the core of discussion. Soil physical characteristics such as soil penetration resistance, bulk density, water infiltration rate, soil aggregation stability, and organic matter content are assessed through both field and laboratory experiments. Changes in these properties may help characterize the effects on soil structure due to tillage practices and pasture management. As background of the whole study, chapter two which contains a review of literature, reflects the efforts to view the topic of this research in a broader spectrum of agricultural sustainability, especially in regard with conservation of soil and water resources. This implies also the literature research on interactions of tillage, cropping systems and pesticides, which attract increasing concern lately in the case of no-tillage practice. In short, attempts of this enlarged literature study, were to partly enrich the discussion of the results and to some extent fill the gaps on some other soil physical parameters not able to be covered by this research. Chapter three describes the methodology of the research, and the consequent results are presented in chapter four. It is recognized that the results based on the experiments are limited and specifically related to soil physical properties. Therefore, to enhance a comprehensive outlook of no-till and tillage performance on the experimental site, analysis will also cover some results previously obtained from other studies. Lastly, chapter five points out the conclusions of the study and recommendations for further researches.

1.2 Rationale

Changes in soil physical properties that occur as a result of changing from moldboard ploughing and permanent pasture to conservation tillage might be expected to develop slowly after the initiation of conservation tillage. In this context, a time period of 5 years after the implementation of conservation tillage, is viewed as an appropriate time frame for the comparison among mechanical treatments of the soil being studied in this research.

The hypothesis underlying the attempts of this study is that under conservation tillage some important soil properties are enhanced, although as a method, conservation tillage has a number of advantages and disadvantages. Particular focus of this study would be on soil physical properties as there is very limited information concerning tillage-induced changes and documentation on long-term tillage effects on soil physical properties.

1.3 Objectives

The specific objectives of this research are :

(a) To measure selected soil physical properties under different tillage systems i.e. no-tillage, moldboard plough and permanent pasture (as control treatment). The important soil properties considered in this research are soil penetration resistance, water infiltration rate, soil bulk density, soil water content, crop dry matter, soil aggregation stability, water and sediment runoff, leachate, and selected soil chemical properties such as soil pH, total C and N.

(b) To examine the relationship between soil physical characteristics mentioned above. Furthermore, the investigation would focus on the extension of improvement of such soil properties in the untilled plots relative to the conventionally cultivated plots.

Chapter 2

Literature Review

2.1 Agricultural Sustainability

2.1.1 Introduction

The sustainability of agricultural production is a question of major concern for the human race because agriculture is the prime source of food for an increasing world population (Prasad and Power, 1997). On a global scale, agriculture has been very successful in meeting a growing demand for food production during the later half of the 20^{th} century. According to Gliessman (1998), this has been due mainly to scientific advances and technological innovations, including the development of new plants varieties, the use of fertilizers and pesticides, and the growth of extensive infrastructures for irrigation.

Despite its success, the system of global food production has overdrawn and degraded the natural resources upon which agriculture depends - soil, water resources, and natural genetic diversity. So far, the global agricultural system is not environmentally benign. Scientific agriculture and conventional farming tended 'to drive ecology out of the input-output equation' (Pesek, 1994). In short, modern agriculture is unsustainable - it cannot continue to produce enough food for the global population over the long term because it deteriorates the conditions that make agriculture possible (Gliessman, 1998).

In New Zealand, the protection of soils, the reduction of adverse impacts on water quality and the maintenance of biological diversity are especially important. This has been confirmed by the public response in submissions to *Environment 2010: A Statement of the Government's Strategy on the Environment* and the agreement by the government through its over-arching strategic statement *Investing in Our Future* (Anon, 1995).

2.1.2 Soil degradation

Soil management encompasses the diverse areas of cropping and tillage systems, fertilization, conservation, and pest management, and how these practices influence the soil and its properties. In the formation of a new conventional agriculture, it will be necessary to scrutinize current management systems to determine those practices that sustain the soil resource and those that degrade it (Robinson et al., 1994).

Soil degradation is a resultant of a wide variety of interacting factors. Blum (1998) suggested two types of soil degradation: (i) natural degradation (without human interference) and (ii) soil degradation caused by anthropogenic activities, especially by the competition between the various types of land use. Lal (1998) further specified the soil degradation by anthropogenic activities into: (a) industrial (b) urban, and (c) agricultural. A soil is agriculturally degraded when its functions of direct concern to human well-being, agricultural productivity and environmental regulatory capacity have been lost or reduced (Blum, 1998; Lal, 1998). It implies a decline in soil's inherent capacity to produce economic goods and perform environmental regulatory functions, which is very much dependable on soil quality and relevant properties. Therefore, soil degradation involves adverse changes in its properties that limit or reduce soil's ability to perform the above mentioned functions.

In New Zealand, the removal of indigenous forest to make way for pasture has left some 10 million hectares of North Island hill country at risk of erosion (Anon, 1995). Also, serious soil degradation has occurred on approximately 2 per cent (300,000 hectares, mainly in the semi-arid inland zones) of the South Island, the result of 150 years of pastoral use (OECD, 1998). Declining levels of soil fertility and organic matter, and increasing soil acidification are issues that have been apparent for some time. Also recently concerns have increased over issues such as chemical contamination, soil compaction, loss of soil structure and contamination of ground water (Anon, 1995).

Agricultural productivity is strongly influenced by management such as fertilizer use, water management, and tillage methods. Resilient soils are productive and respond positively to management. Inappropriate management in agriculture is often the main cause of soil degradation. The most severe form of agricultural degradation according to

Lal (1998) is that caused by accelerated erosion and non-point source pollution. Key soil properties, such as soil structure, soil organic carbon content, clay and clay minerals, available water capacity are, among others, properties being affected by these degradative mechanisms. The net effect would be the degradation of soil quality which in turn adversely affects the agriculture productivity and sustainability. However, judicious land use and choice of appropriate crop management systems would reverse these degradative trends.

On agricultural activities alone, the degradation is divided into chemical, physical, and biological mechanisms (Lal, 1998). It is not within the scope of this study to discuss the details of such degradative activities. Rather, this brief outlook of soil degradation will serve as an introductory piece of analysis for the whole research and the discussion in the next sections.

2.1.3 Soil erosion

Soil erosion is a serious threat to the quality of soil, land, and water resources as a basis for a sustainable agriculture and land use. The problem with erosion is found in its consequences. Problems and prospects associated with soil erosion by wind and water were reviewed at length by Lal (1994). Although it is recognised as part of natural landscape-forming processes, it is the extensive acceleration of the soil erosion processes induced by human activities that is of concern (Rose, 1998). Soil erosion, accelerated by human activities relative to natural rates, reduces crop productivity and causes soil damage resulting sediment transport and deposition (Pierce and Lal, 1994).

According to Lal (1998), one of the main difficulties related to erosion control is the reliability and the precision of erosion assessment in terms of extension, magnitude, and rate of soil erosion and its economic and environmental consequences. Many studies have been continuously undertaken for this purpose. Laflen and Roose (1998) have suggested some methodologies for assessment of soil degradation due to water erosion. Measurement and estimation techniques for both interril and channel (rill and gully) erosion were described. Also mathematical models of water and wind erosion have been widely developed and reviewed (Nearing et al., 1994; Skidmore, 1994; Rose, 1998).

The Universal Soil Loss Equation (USLE), is the empirical erosion model which has been used most widely for predicting soil erosion (Nearing et al., 1994). The basic structure of USLE is given by:

$$A = RKLSCP$$

where A is the computed soil loss, R is the rainfall-runoff erosivity factor, K is the soil erodibility factor, L is the slope length factor, S is the slope steepness factor, C is the cover-management factor, and P is the supporting practices factor. This empirically-based equation, derived from a large mass of field data, computes sheet and rill erosion using values representing the four major factors affecting erosion. These factors are climate erosivity represented by R, soil erodibility represented by K, topography represented by LS, and landuse represented by CP (Renard et al., 1994). Despite its wide acceptance, this model has shown to be ineffective when applied outside the range of conditions for which it was developed. This fact has lead to the emergence of new models, among them the revised USLE (RUSLE) and the USDA-Water Erosion Prediction Project (WEPP) models. The latter, categorised by Nearing et al. (1994) as physically-based models, are intended to represent synthesis of the individual components which affect erosion, the complex interaction between various factors, and their spatial and temporal variabilities.

The susceptibility of a soil to erosion is influenced by diverse factors. These include physical and hydrologic, chemical and mineralogical, and biological and biochemical properties as well as its soil profile characteristics (Lal, 1998). In regard to soil physical properties that affect the resistance of a soil to erosion, texture, structure, water retention and transmission properties, and unconfined compressive and shear strength are those relevant to be mentioned. The importance of these properties has been reviewed, among others, by Briggs and Courtney (1985), Quirk and Murray (1991), and Hillel (1998). Moreover, the effects on these properties caused by agricultural activities such as tillage practices with respect to water runoff and soil losses are continuously under research. Long-term tillage effects on physical properties of eroded soils (Hussain et al., 1998) ; quantification (Montgomery et al., 1999), assessment (Thapa et al., 1999), and modelling (Lobb and Kachanoski, 1999) of soil tillage erosion and translocation are among the studies recently carried out. More details of the effects of tillage on selected soil properties will be described in section 2.3 of this chapter.

2.1.4 Nonpoint source pollution: soil and water quality

Sources of water pollution are recognized as either of point or nonpoint origin (Schwab et al., 1996). Point sources include animal feedlots, chemical dumpsites, storm drain and sewer outlets, acid mine outlets, and other identifiable points of origin. Nonpoint source (NPS) pollution originates from diffuse land areas that intermittently contribute pollutants to surface and groundwater. Poincelot (1986) suggested that the major cause of NPS pollution is agriculture. Storm runoff, because of present agricultural practices, carries pesticides, particles of soil, nutrients, and organic wastes. Irrigation water return is also a nonpoint source pollutant, when it is saline and contains nutrients.

According to Schwab et al. (1996) water quality is determined by the presence of biological, chemical, and physical contaminants. Most water pollution is the result of human activities. Biological contaminants result from human and animal wastes plus some industrial processes. Chemicals enter the water supply from industrial processes and agricultural use of fertilizers and pesticides. Physical contaminants result from erosion and disposal of man-made objects. Poincelot (1986) suggested that sediment from erosion forms the largest agricultural pollutant. In fact, according to this source, the number one pollutant of water by volume is sediment.

The most troublesome agriculture pollutants in terms of soil quality are pesticides. Certain toxic wastes, if used as fertilizers or organic amendments can also be harmful. An area in need of research is whether the use of pesticides damages the soil ecosystem to the extent that the crop productivity is lessened over a long period of time (Poincelot, 1986). The lack of soil mixing and heavy herbicide usage with no-till and minimal till systems suggests a potential problem needing research. Another major threat to soil quality is soil erosion (Lal, 1998). The threat is more serious for the soils of the tropics that are highly susceptible to erosion and other degradative processes. Erosion influences soil properties, e.g. topsoil depth (TSD), soil organic carbon (SOC) content, nutrient status, soil texture and structure, available water holding capacity (AWC) and water transmission characteristics that regulate soil quality and determine crop yield.

Extensive research and model development in the area of NPS pollution has been widely reported. The most recent studies on NPS have been reviewed by Line et al. (1998). More than a decade earlier, Overcash and Davidson (1980) in their book "Environmental Impact of Nonpoint Source Pollution", have presented a number of important studies related to agricultural nonpoint pollution sources such as: pesticides, pathogens, nitrogen and phosphorus, sediment, and land use. In a paper presented at the USEPA, Baker (1980) has largely discussed the issue of agricultural areas as nonpoint sources of pollution. Some data on loads and time-concentration trends for nutrients such as N and P, and pesticides in surface runoff from agricultural areas as affected by management practices (i.e. cropping, tillage, and chemical application methods) were presented. More specifically on tillage impacts on groundawater quality, Logan et al. (1987) indicated a number of resource studies, covering aspects of soil physical, chemical, and biological processes as well as the fate and transport of applied pesticides and fertilizers. Further review of recent studies on the interaction between tillage practices and pesticide transport will be given later in the next sections.

As has been mentioned earlier, the major share of agricultural pollution, sediment, arises from erosion. Poincelot (1986), suggested that this fact can be prevented or controlled. By prevention or controling the erosion, two purposes would be accomplished i.e. sustainability of an agricultural resource and reduction of pollution.

2.1.5 Agricultural management

2.1.5.1 Soil and water conservation

One of the key inputs to any agricultural system is water. For agricultural systems to be both productive and sustainable in the long term, management of the water resource is required to ensure that sufficient water is available for the plant growth and excess water is not allowed to contribute to land degradation. According to Sadler and Turner (1994), water is not only important because it contributes to plant growth, but also because it is a transporting agent for dissolving materials, nutrients, chemicals and solids. Although its ability to transport nutrients, pesticides, and phytohormones is fundamental to plant growth and protection, excess water can lead to pesticides, salts, and nutrients entering the ground water or surface water and to soil particles being moved down-slope, resulting in soil erosion and land degradation.

Erosion adversely affects crop productivity by reducing the availability of water, nutrients, and organic matter, and, as the topsoil thins, by restricting rooting depth (Pimentel, 1993). In present time, there is a variety of conservation technologies available and effective in preventing soil erosion. The principal method of controlling erosion and its accompanying rapid water runoff is maintenance of adequate vegetative cover. Stocking (1994) has pointed out some key elements in assessing the vegetative cover and management effects in erosion control. However, management of conservation practices can be beneficial or detrimental to the environment (Schwab et al., 1996). Terracing cultivated land can be beneficial by reducing erosion and sedimentation. Minimum tillage, which provides greater cover but reduces erosion, may increase pesticide requirements. Irrigation also can be detrimental by increasing drainage water salinity (Poincelot, 1986).

In principle, according to Schwab et al. (1996), soil and water conservation are those measures that provide for the management of water and soil in such a way as to ensure the most effective use of each, while preserving or improving the environment. Three main interrelated components are involved in conservation practices: the soil, the plant, and the climate. An inventory of the soil, quantitative measurements of its physical characteristics, and information on soil response to various treatments are the requirements for the soil phase conservation. The plant phase conservation concerns (i) questions of adequate, but not excessive, water for plant growth and (ii) optimum utilization of the plant as a means of preventing erosion and increasing the movement of water into and through the soil. The climate phase, according to this source, is an overwhelming aspect. This phase involves water that can be partly controlled by humans, with appropriate drainage and irrigation practices. Other climate factors involved such as temperature, wind, humidity, chemical constituents in the air, and solar radiation are those over which humans have little or no control.

It is important, however, to recognise that soil and water conservation requires a workable, continuing program, not a single effort, but as an integral part of crop production. Also, by simply saving the soil from further erosion is not sufficient to sustain a growing population, because soil, however, can deteriorate naturally, in many other ways. For example, excessive aeration leads to loss of organic matter, and compaction affects runoff, soil drainage, rooting habits, and plant growth. Damaged and depleted soils need to be rebuilt, improved, and used more efficiently if they are to support a permanent agriculture (Sprague, 1986). The tillage systems discussed later in the next sections are designed for specific sites and situations and promise to contribute much toward rebuilding and retaining soil productivity.

2.1.5.2 Towards a sustainable agriculture

The agricultural system must be both sustainable and highly productive in the future if it is to feed the growing human population. For this twin challenge to be overcome, Poincelot (1986) recommended a new approach to agriculture and agricultural development that builds on resource-conserving aspects of traditional, local, and small-scale agriculture while at the same time drawing on modern ecological knowledge and methods. Traditional agriculture, despite its market limitations, can provide models and practices valuable in developing sustainable agriculture. The mainstream approach to modernizing agriculture on the other hand, apart from its successes promoted by scientific advances and technological innovations cited by Gliessman (1998), has led to dependency on external inputs, e.g. seed, fertilizer, pesticides, machinery and fossil fuels (Kotschi et al., 1990).

In recent years, concern with both resources limitations and the ecological repercussions of modern technology has led to a growing awareness of the need for environmental protection and ecologically sound practices, in agriculture as well as other forms of resource use and management (Kotschi et al., 1990). Specifically in agricultural development, a specific management is required so that production and productivity are enhanced while sustaining a healthy ecological balance within the agricultural ecosystem (Sadler and Turner, 1994). A need is being gradually recognised to find ways of meeting production requirements without excessive strain on nonrenewable natural resources. In various parts of the world, concepts of this new approach are being promoted, e.g. ecologically sound agriculture, biological husbandry, organic farming, conservation agriculture, sustainable agriculture, which Kotschi et al. (1990) referred to as 'ecofarming'. In a broader category, these practices are embodied in the science of agroecology, which is defined as the application of ecological concepts and principles to the design and management of sustainable agroecosystems (Poincelot, 1986).

The precision farming (site-specific management) is another contributing pathway to sustainable agriculture which has been getting considerably attention lately. Some studies on the promises and pitfalls of SSM have been reported by Yule et al. (1996), Nowak (1998), and Schepers and Francis (1998). It is a knowledge-based system that enables farmers to apply precise amounts of fertilizers, pesticides, water, seed, or other inputs to specific areas and when they are needed for optimal crop growth (Lu, et al., 1997). The adoption of precision farming is enhanced by the increased profitability it could provide, environmental concerns over the occurrence of agrichemicals and fertilizers in surface and groundwater, and the availability of new technologies such as global positioning system (GPS), geographical information system (GIS), and monitoring and control sensors.

In New Zealand, the Resource Management Act (RMA) 1991 embodies the principle of sustainable management. In 1993 the New Zealand Government released a position paper on sustainable agriculture, as part of a wider policy to promote sustainable land management. The Ministry of Agriculture and Fisheries (MAF) has undertaken a facilitation program designed to encourage the adoption of sustainable agricultural practices, and regional councils are also promoting sustainable agriculture as part of their responsibilities under the RMA. According to OECD, (1998), in the meantime, over 60 farmed-based community groups have formed to address issues connected with sustainable agriculture in New Zealand.

In this vast array of discussion regarding sustainable agriculture, conservation tillage, specifically direct-drilling or no-tillage is one of the recent technologies being promoted in New Zealand and getting recognition world-wide. Particular studies on interrelationships between direct-drilled seeds with soil microenvironment, and the interactions between conservation tillage machines, soil and climate were reported by Choudhary (1979; 1981). Also, the development of direct drilling equipment in Europe and North America and its relation to New Zealand has been reviewed among others by Baker (1981). In a later publication Choudhary and Baker (1994) discussed the development of conservation tillage in New Zealand along with its progress and constraints.

2.2 Tillage Systems

2.2.1 Introduction

Tillage, or soil surface management to prepare a desired seedbed, is a major input in agricultural production. Lal (1991) indicated that judiciously used tillage can be a powerful tool to alleviate some soil-related constraints to crop production, e.g. compaction, crusting, low infiltration, poor drainage, unfavourable soil moisture and temperature regimes, disposal of undesirable biomass and wastes, and pest management. Improperly used, tillage can lead to deterioration of soil structure, reduced infiltration, accelerated runoff and erosion, water pollution, and degradation of soil and environment.

According to Hillel (1980), there are no universal prescriptions for what constitutes efficient tillage. Some soils have suitable tilth quite naturally and require little, if any, tillage to serve as favourable media for crop growth. Others, exhibit pans or barriers which inhibit root penetration and hence can be improved by appropriate tillage. Appropriate tillage systems, thus, are soil-specific and crop-specific, and their adaptation is governed by both biophysical and socioeconomic factors. In addition to increasing crop yields, tillage methods must also facilitate soil and water conservation, improve root system development, maintain a favourable level of soil organic matter content, and reverse degradation trends in the soil's life-support processes.

Under some conditions of soil and climate, whether or not tillage has been carelessly undertaken, soil deterioration has been excessive, most weedy species have been inadequately controlled, moisture management has been less than desired and time and energy requirements have been inefficiently high (Sprague, 1986). An alternate means of providing an optimum environment for crop growth has been needed to improve production, conserve and recharge our soil and water resources, and add greater permanency to agricultures throughout the world. Conservation tillage, is one of the means which may offer opportunities to attain these objectives. The purpose of this section is to briefly describe and examine the differing principles and practices of conventional and conservation tillages.

2.2.2 Principles of tillage

Tillage can be described as a method of mechanically modifying structural units of soil for the purpose of improving plant and soil productivity (Smucker et al. 1988). Numerous passes by tillage tools are required to prepare soil, plant seeds, and control weeds. In contrast, contemporary power and implement systems can excessively till and compact many soil types with few passes. According to Hadas (1997), soil tillage drastically changes soil structure and at the same time destabilizes it. The induced changes in soil structure evolve, and the derived physical properties deteriorate in the course of time, because of climatic variations and human activities.

Three primary aims are generally attributed to tillage: (i) control of weeds, (ii) incorporation of organic matter into the soil, and (iii) improvement of soil structure (Hillel, 1980). An auxiliary function of tillage, still insufficiently well understood, is the conservation of soil moisture, where the processes of rain infiltration, runoff, and evaporation are involved. Also, by burying the plant residues and loosening the soil surface, it enhances the surface energy and water exchange, permitting relatively rapid drying and warming in the spring (Robinson et al., 1994). This advantage can be critical for early spring planting, which is an important factor influencing crop yields.

2.2.2.1 Conventional tillage

Conventional agriculture has long been based on the practice of cultivating the soil completely, deeply, and regularly (Gliessman, 1998). This cultivation practice, referred to here as conventional tillage, involves a combination of primary and secondary tillage operations normally performed in preparing a seedbed for a given crop grown in a given geographical area (Mannering et al., 1987). Fawcett (1987) mentioned that the systems under conventional tillage are those which totally disturb the soil surface and bury residue from the previous crop.

Traditionally, the moldboard plough has been used world-wide as the *primary tillage* tool. Another common primary tillage tool is the disk plough, comprising a hardened steel round concave disk of 50 to 95 cm in diameter (McKyes, 1985). Chisel plough, subsoilers, and rotary ploughs also find use in many areas; they break and loosen the soil without inverting it (Hillel, 1980). *Secondary tillage*, performed after primary treatment, aims to improve seedbed levelness and structure, increase soil pulverization, conservation of moisture, destruction of weeds, chopping of crop residues and the like. Disk harrows, spike harrows, spring-tooth harrows, sweeps, drags, and cultipackers are among the common implements used to refine coarse soil conditions during secondary tillage (McKyes, 1985; Hillel, 1980).

Apart from the aims of tillage, Hillel (1980) cited above, a good and simple reasoning for ploughing was given by Sprague (1986) as follows:

(i) weed control; two plants growing in the same place at the same time compete for space and raw materials. Thus, the unwanted plant must be kept out. This is common for establishment and maintenance of monocropping systems.

(ii) plant residue incorporation; this creates a neat and orderly appearance in the field. Also, it allows shallow cultivation and planting equipment to perform more uniformly by removing obstacles.

(iii) soil mixing; by mixing the lower horizons with surface layers through deep tillage, deep placement and distribution of fertilizer is permitted. Rooting and availability of minerals and moisture may improve.

(iv) soil loosening; this is to encourage water absorption, aid precision in seed placement, and encourage plant emergence.

(v) good hygiene; by interrupting weed, insect, and diseases cycles.

Apparently, two contradicting effects generally occur in the soil during tillage e.g. soil loosening as the effect from the tillage implement and soil compression by the tractor while it is pulling the implement. Following tillage, the soil structure tends to readjust back towards its original state as rainfall, the burrowing of worms, pressures exerted by roots, the cause of frost and wetting-and-drying combine to cause changes in the arrangement of the particles (Briggs and Courtney, 1985). When these readjustments are incomplete, repeated tillage may result in a progressive change in soil structure. In some cases this leads to long-term damage to the soil. Moreover, the change in structural conditions has implications for other soil properties, such as the chemical status and the organic activity. In the long term these effects may significantly influence crop yields.

2.2.2.3 Conservation tillage

Recent trends in tillage research have been aimed at minimizing tillage operations and travel (both to reduce costs and to avoid soil compaction) while tailoring each operation to its specific zone and objective (Hillel, 1980). This approach underlies various tillage methods under the term of conservation tillage, as commonly known world-wide. There are many, somewhat different definitions for the term 'conservation tillage'. According to *Resource Conservation Glossary* (Mannering and Fenster, 1983), conservation tillage is "*any* tillage system that reduces loss of soil or water relative to conventional tillage; often a form of noninversion tillage that retains protective amounts of residue mulch on the surface." More specifically, it is commonly defined as any tillage system that maintains at least 30% residue cover on the soil surface after planting to reduce water erosion, or small grain residue equivalent on the surface during the critical erosion period to reduce wind erosion (Mannering et al., 1987; Unger, 1996).

Due to its broad definition, conservation tillage was further defined as an umbrella term used for tillage intensity ranging from zero-tillage (no-tillage) to other forms of non-inversion soil tillage practices that have the potential to increase (or at least maintain) crop yield, and reduce soil water runoff relative to conventional tillage. Within this range of definition emerge several types of conservation tillage systems described by Mannering et al. (1987) such as: no-till or slot planting; ridge-till; strip-till; mulch-till; and reduced-till. Space will not permit a detailed elucidation of each of these conservation tillage practices. Rather, for convenience of the discussion, conservation tillage is broadly divided into two categories (Willocks, 1984) as cited below:

1. No-tillage - where vegetation is controlled using a herbicide and the seed is direct drilled into the undisturbed seedbed using specialised drilling equipment. No-tillage is the most recognised category of conservation tillage.

2. Minimum-tillage - where vegetation is controlled using a herbicide, followed by a light cultivation or reduced cultivation prior to establishing the seed using conventional drilling equipment.

For simplification in regards with terminologies, no-tillage as the main focus of this research will be used interchangeably with reduced tillage, minimum tillage, and conservation tillage.

No-tillage farming is a relatively new concept made possible through the development of chemical herbicides that can provide good weed control without using tillage. Where conditions suit, no-tillage is the ideal method of crop establishment in terms of minimal inputs and maximizing opportunities (Willocks, 1984). This fact has led to the rapidly growing interest in and adoption of no-tillage systems of crop production throughout the world. A comprehensive description of no-tillage along with its principles and practices has been provided by Phillips and Phillips (1984). Earlier, Allen (1981), in his publication *Direct drilling & reduced cultivations*, has pointed out the concept, and described early trials and the experiments, the development and the economics of direct drilling (no-tillage), both in the UK and overseas. A wide range of studies on conservation tillage has been carried out and reported through seminars and publications in New Zealand (Monsanto, 1981; 1984) and Australia (Conacher and Conacher, 1986). Recent studies about conservation tillage and its effects on specific soil properties will be discussed in the next part of this chapter.

In summary, it is not inappropriate to suggest that for considerations of conservation tillage adoption, the interaction between soil type and climate is of prime importance. Suffice it to say in present context that conservation tillage practices developed in one location may not be suitable for another location, where conditions can differ greatly. Various constraints to conservation tillage as concluded by Carter (1994) were characterized by: soil tillage requirement, soil and climatic interactions, and biological constraints. According to this author, plant performance for example, is governed by the environment created by tillage and is not directly related to the tillage implement used. This environment is dynamic, being subject to both temporal and spatial changes in soil properties and soil climate.

2.2.3 Tillage systems and the environment

The inevitable use of pesticides during conservation tillage, and the increased use of fertilizer is recognized as a potential source of environmental pollution, specifically with respect to water quality (Lal, 1991). Pesticides in particular, are a major concern because of their toxicity even at low concentrations (Watts and Hall, 1996). While conservation tillage practices may conserve energy as well as the soil, little is known of how these practices effect solute transport through the soil and reach the underlying ground water (Gish and Coffman, 1987). In contrast, plough-based tillage methods may enhance risks of soil erosion, increase rates of mineralisation of soil organic matter, and accentuate emission of radiatively active gases from soil related processes (Watts and Hall, 1996).

One basic thrust in research dealing with tillage systems is to define the best management practice for pesticide application which maintain a high level of chemical efficacy without accentuating non-point source pollution on non-target areas. There is a tendency to use the more persistent types for better long-term weed control; these are more likely to be persistent long enough to move into waters (Miller and Donahue, 1990). According to this source, it is typical to require 15 - 40 percent more pesticides in reduced tillage compared to needs in conventional tillage. Higher pesticides addition increase solubilized pesticides. Any eroded soil sediment has higher amounts of both pesticides and phosphorus adsorbed to it. The reduction of fossil fuels burned while using reduced tillage will probably be insignificant in its effect on the environmental air pollution. Crop rotations would reduce the amounts of pesticides required and would be a logical consideration to help reduce environmental pollution from croplands.

2.2.3.1 Interaction of pesticides with tillage systems

Conservation tillage (no-till) is believed to be a palliative for pesticide contamination of surface water. A study conducted by Malone et al. (1996) has demonstrated the decrease in pesticide loss via surface water by reducing runoff and its attendant erosion. Surface-applied metribuzin transport has been investigated under three different soil treatments: compost amendments (CA), no-tillage (NT) and conventional tillage (CT). The results indicated that the runoff water and sediment were lower in the NT compared to the CA and CT. Also the metribuzin load from sediment was less in the NT compared to the CA and CT. Table 1 shows part of the study results.

Table 2.1 Runoff parameters, KSU Research Farm (Malone et al., 1996)

Trt	Rain (cm)	Runoff Water			Sediment		
		Total water (cm)	Mean* metr. Conc. (ppm)	Metr. load (g/ha)	Mean load (kg/ha)	Mean metr. conc. (ppm)	Metr. load (g/ha)
CA	29.4	1.431	0.069	12.44	153.1	0.234	0.297
			125.0**		145.6	77.8	
NT	29.4	0.073	0.072	0.19	9.2	0.631	0.004
			140.3		173.1	103.7	
CT	29.4	4.383	0.016	8.86	668.9	0.096	0.707
			98.5		57.5	103.2	

CA: compost amendments; NT: no-tillage; CT: conventional tillage

* all mean values are calculated using only runoff dates where data is available from all the plots

** coefficient of variation (%)

However, the mean concentration of metribuzin both in runoff and sediment were higher. Similar studies carried out by Baker et al. (1978) and Kenimer et al. (1987) also found that pesticide concentration increased with an increase in residue cover. This may be attributed to the higher soluble organic matter in the runoff which could affect the solubility of metribuzin in runoff water (Baker et al., 1978) or to foliar washoff (Kenimer et al., 1987).

Little difference in metribuzin concentrations was found between the NT and CA treatments. Kenimer et al. (1987) found no-till to have higher pesticide concentration than conventionally-tilled plots with organic residue added after tillage. The CA should partition more metribuzin compared to the NT due to the higher organic content of the CA, therefore, the concentration was expected to be less on the CA than NT. This did not occur because the NT had less than half the runoff of CA on each runoff occurrence therefore metribuzin may have infiltrated prior to runoff. The metribuzin load in runoff was less for the NT compared to both the CA and CT. This is consistent with Kenimer et al. (1987). The reduction was due to reduced runoff volume in the NT compared to both the CA and CT.

Bandaranayake et al. (1998) in a study on chemigated solute movement under flood irrigation in tilled and untilled soil found that bromide leaching was most rapid in flood irrigated, untilled soil with chemigation. On the other hand, bromide leaching losses were reduced by sprinkler irrigation, tillage, and pre-application of the solute. The study also found a large lateral variability in the bromide concentration, particularly in the non-tilled soil, and suggested that water flow in preferred pathways funnelled the nearly uniformly applied solute into localized regions creating area of high and low concentration.

At one of the MSEA (Management Systems Evaluation Area) research sites in Iowa, Kanwar et al. (1991) found four different pesticides: atrazine (2-chloro-4 -(ethylamino)-6-(isopropylamino)-s-triazine); cyanazine (2-(4-chloro-6-ethylamino-s-triazin-2-ylamino)-2-methylpropionitrile); alachlor (2-chloro-2',6'-diethyl-N-(methoxymethyl)acetanilide); and metribuzin in the tile drain water at concentrations less than 1 to 19 ppb immediately after rainfall. In the few tile water samples in 1989, atrazine and alachlor concentrations of more than 18 ppb were observed. The rapid appearance of pesticides in drainage water may be due to direct transfer from the soil surface to tile depth by macropore flow. The relative potential for pesticide leaching to groundwater in chisel plough and no-till soils is largely unknown, but one study at Iowa State University, USA, suggests that more leaching may occur in no-till relative to conventional tillage systems (Kanwar et al., 1991). Hall et al. (1989) found similar results, more water leached through the 1.2 m profile under no-till. The amounts of atrazine, cyanazine, simazine (2-chloro-4,6-bis(ethylamino)-s-triazine), and metolachlor (2-chloro-N (2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl) acetamide) leached through the soil profile were also greater in the no-till system.

2.2.3.2 Tillage and cropping systems

While conventional tillage is mostly associated with monoculture, planting crops in a designated sequence and rotation has found new parameters with no-tillage. With no-tillage system, harvesting can be followed immediately by planting of the succeeding crop, thus reducing the time lag between crops. Phillips and Thomas (1984) indicated some advantages of no-tillage, and the most important ones include: (i) labor and cost reduction; (ii) soil moisture conservation, ensuring stands of second and third crops under restricted rainfall patterns; (iii) less soil structure disturbance by elimination of ploughing and land preparation; (iv) time saved in planting the second and third crops when timeliness of planting is very important; (v) allow interseeding of legumes into grass pastures with minimum reduction of grass stands.

a. Crop rotation

Double cropping is one of the most common rotational cropping patterns. No-tillage practices are helpful in making double-cropping systems successful. By not tilling the soil, the succeeding crop can be planted more quickly. Crop rotations of forage legumes followed by grain crops represent a practical means of maintaining crop productivity before inexpensive fertilizer nitrogen became widely available (Triplett, 1986). A common sequence in low or middle latitudes in U.S. involves a winter small grain crop (oats, wheat, or barley), followed by soybeans planted in the stubble immediately after harvest (Phillips and Thomas, 1984).

As far as crop yields are concerned, it is difficult to establish any clear and major advantages of no-tillage, since the results to date have been variable over different soil types, seasonal conditions and types of management. Long-term trials undertaken in Western Australia concluded that conservation tillage, after some initial problems, performed well on the heavier soils but was less successful on light sandy soils. On average, conservation tillage practices outyielded conventional practice over an eight year period (Conacher and Conacher, 1986). The outyield results under no-tillage practices were also confirmed by other overseas studies (Dickson and Ritchie, 1996; Barber, et al., 1996). Janson (1984), investigating an intensive arable cropping in two different soil types under direct-drilling (DD) and conventional tillage (CT) in New Zealand concluded his results in a slightly different statement. The study found out that reliability in crop yield under direct-drilling on light free-draining soils was easier to achieve. By contrast, on the heavy, slow-draining soils, despite the greater problems imposed by DD, the yield comparability with CT was achieved relatively quickly.

Contrasting results were found by other studies in terms of yield resulted from conservation tillage. Hughes et al. (1992) in a study on a 10-year maize/oats rotation in a fine silt loam soil, found lesser maize forage yields under reduced tillage as compared to fully tilled seedbeds. Two reduced tillage treatments (minimum tillage and no-tillage) gave depressed maize yields 7 years out of 10. A major reason for this was likely to be differences in number of plants. Seedling establishment was often low and variable in no-tilled crops. The winter-grown oats showed no statistically differences among treatments. Less yield results under no-tillage practices were also found by Acharya and Sharma (1994) in a study on maize/wheat rotation. Variable yield results were also reported by Lindwall et al. (1994) on continuous wheat, wheat-fallow, and wheat-barley-fallow rotations sumperimposed by conventional and no-tillage.

Despite the contradicting results cited above, it can be said that, generally, given adequate soil water, favourable precipitation, good drainage, reasonable soil fertility and good weed control, crop yields under conservation tillage can be equal to or higher than under conventional systems. Concerning sustainability, whilst yield and short-term economic differences between these tillage systems may not be all that great, this needs to be weighed against some obvious advantages, particularly in the more fragile or degraded agricultural areas.

b. Pasture-based cropping and pasture renovation

New Zealand has quite a long experience in pasture production since its export income is heavily dependent on animal products. Efforts have been put through in either renewal or renovation of the existing pasture lands. Surface reseeding of poor pastures on steep land by aerial methods and resowing of pastures into crop rotations on flatter land using cultivation have become common practice in temperate New Zealand (Choudhary and Baker, 1994). Traditionally, this has been achieved by using conventional means of tillage prior to grass seeding. In recent decades, however, direct drilling has gained major attraction due to its obvious advantages already mentioned before. Allen (1981), in his publication partly discussed the advantages of direct-drilling with regard to pasture renewal and renovation and provided some practical guidelines as well.

Two major attractions of direct-drilling related to pasture were that (i) the whole process of renewal is more rapid and streamlined and (ii) the consolidation of the surface is not affected, so that shortly after the new seeds have been sufficiently established, the old grass can be grazed (Allen, 1981). The New Zealand pattern of using a pasture-crop rotation on arable land means that the renewal or restoration of pasture without cultivation is an integral part of the total low energy input system. The advent of glyphosate in particular has had a major impact on pasture renovation programs (Choudhary and Baker, 1994). Apart from that, a number of pasture seed drills commercially available such as 'Cross Slot'™ and 'Original Baker Boot'™, provide favourable microenvironments and are suitable for operations in contouring and trash-free pastureland (Choudhary and Baker, 1993). Presently on experimental stage, attempts were also made to promote ecologically sound techniques such as triple disc drill and strip seeder drill. A study conducted by Lowther et al. (1996) demonstrated the agronomic superiority of the strip seeder direct drill for pasture establishment.

c. Legume grain crops in rotation with rice

Legumes, with their adaptability to different rice-based cropping systems, offer opportunities to increase and sustain productivity and income of rice farmers. In the irrigated lowland areas, legumes (soybean, peanut and mungbean) are generally grown in rotation with rice (rice-rice-legume rotation) or (rice-legume-legume rotation) with two or more irrigations during the season (Adisarwanto et al., 1996). Rotation of rice-cowpea, is also believed to be suitable for the humid tropic soils (Benites and Ofori, 1993).

In lowland areas, the growing conditions required for rice are entirely different from those required for legumes. Rice is grown best under puddled and reduced conditions, legumes require un-puddled and oxidised conditions. The two conditions are associated with large differences in physical, chemical and biological properties of the soil (Adisarwanto et al., 1996). A study by Cass et al. (1994) indicates that a rotation of rice-soyabean over a period of 21 years, tends to deteriorate soil structural quality, thus it is unsustainable. Instead, as part of the comparison study, they suggested that a rotation of rice and grass fallow would probably restore the soil structure to a favourable state. In humid tropic soils, where soils are mainly acidic, rotation of acid-tolerant crops such as upland rice and cowpea under no-tillage practice was recommended by Benites and

Ofori (1993). This was viewed as part of solution addressing the problems associated with shifting cultivation in transition to continuous cultivation.

The puddled condition of the soil is a major cause of the poor stand and performance of secondary crops after rice. Early sowing and minimum tillage systems appear to be more reliable than conventional tillage systems (Adisarwanto et al., 1996). Overcoming weed problems in relation with rice production under minimum tillage, paraquat-assisted minimum tillage techniques were found effective and being widely developed in the tropics (Allen, 1981). Experiments on soils of heavy structure in the tropics cited by Lal (1986) suggested that no-tillage can be adopted successfully for both seeded and transplanted rice. Satisfactory yields of paddy rice are obtainable provided weeds are properly controlled.

2.3 Tillage Effects on Selected Soil Properties

2.3.1 Introduction

A large volume of information can be found in literature on the effects of tillage practices on soil properties under various soil types, cropping regimes and climatic conditions. As a result, the specific effects of various tillage operations also vary. Thus, effects of changes in soil properties due to tillage must be interpreted differently for regions, localities within a region, and often for soils on a farm, when they differ appreciably in drainage, texture, depth, and topographic characteristics.

Well-developed soils have a good balance between voids and particles and have a high water storage capacity; accordingly, these types of soils offer the most favorable conditions for crop growth. They are also less susceptible to erosion. Tillage (Hillel, 1980), in various practices, is primarily defined as the mechanical manipulation of the soil structure aimed at improving soil conditions affecting crop production. Studies have indicated that soils which have long been continuously direct drilled are different to conventionally cultivated soils in a number of ways. A description of the main differences between soils under these two tillage systems has been made by McLaren and Cameron (1996, pp. 133). However, because of the many factors involved and the complexity of interactions encompassed, the tillage investigations must necessarily be long-term undertakings. In some situations, variability is such that a long run of experiments is necessary to determine a clear and consistent result.

The importance of the management and the maintenance of a stable soil structure under cropping regimes and tillage practices has been the subject of many studies. The results of some studies, partly experiments carried out at the Massey University experimental site will be briefly reviewed. Selected soil properties, mainly those of physical characteristics are discussed. These include aggregation stability, soil compaction and density, surface water and sediment runoff, soil water content, soil infiltrability, soil organic matter, and pH.

2.3.2 Soil structure and aggregate stability

Soil structure can be characterized through measurable indicators such as aggregate stability, bulk density, and soil penetrability (Kemper and Rosenau, 1986; Hillel, 1998). Soil aggregation effects on soil physical and chemicals properties of structured soils have been reviewed at length by Horn et al. (1994). Kemper and Rosenau (1986) defined aggregate as a group of primary particles that cohere to each other more strongly than to other surrounding soil particles. The stability of aggregates is measured as a function of whether the cohesive force between particles withstand the applied disruptive force. Most frequently, this concept is applied in relation to the destructive action of water (Hillel, 1998). This is probably the main reason for using the wet-sieving procedure to determine the water-stable aggregates (WSA) and mean weight diameter (MWD) of a given sample of soil as suggested by Yoder (1936) and Kemper and Rosenau (1986).

Apart from the disruptive force of water and wind, Conacher and Conacher (1986) mentioned that the clearing of natural vegetation, loss of organic matter, repeated tillage, excessive working speeds, passage of heavy machinery and trampling by stock all contribute to a reduction in the number and size of stable aggregates in the soil. By any measure, the degree of aggregation is a time-variable property, as aggregates form, disintegrate, and re-form periodically (Hillel, 1998). In other words, Lal (1998) stated that agriculturally stable soils are dynamic and always changing in response to management and weather.

Intensive cultivation can cause excessive breakdown of soil aggregates. Robinson et al. (1994) stated that the more intensive the tillage practices used, the more reliant the soil becomes on tillage practices to maintain physical conditions favorable to crop production. In essence, soil becomes "addicted" to tillage. As has been cited before, conservation tillage offers opportunity to reverse this trend. A number of studies on soil physical properties (Hill, 1990; Karlen et al., 1994; Chan and Heenan, 1996; Guo, 1997; Hussain, et al., 1998) and specially on aggregate stability (Hughes and Baker, 1977; Beare et al., 1994; Franzluebbers and Arshad, 1996) under conventional and conservation tillages have been carried out in New Zealand and overseas. Some of these studies will be referred to in details later in chapter 4.

The decrease in aggregate water stabilities after 10 years of continuous maize/oats rotation in a silt loam were found greatest in the fully tilled plots as compared to the no-tilled plots (Horne et al., 1992). In a similar study, Franzluebbers and Arshad (1996) found that the distribution of water-stable aggregates (WSA) were only secondarily affected by tillage. The primary affecting factor was due to the clay content. Comparing two soils with different texture, this study also concluded that at a depth of 0 - 50 mm, macroaggregation (> 0.25 mm) was found significantly higher under no-tillage than under conventional tillage in coarse-textured soils, but similar, less or not significant in fine-textured soils. Similar results were also reported by Beare et al. (1994). This study found that at the 0 - 50 mm soil depth the total sand-free C and N were significantly higher in all WSA of no-tillage than of conventional tillage. These studies, in general, confirm that no-tillage causes less damage to soil structure. Also, the greatest WSA found at the topsoil under NT is believed to be closely associated with more organic matter retained at this specific soil layer as compared to conventional tillage.

2.3.3 Soil compaction and density

Surface compaction may be created as a result of either traffic and/or treading when the soil is too wet or excess use of tillage implements (Allen, 1981; Briggs and Courtney, 1985; Robinson et al., 1994). Soil compaction is usually characterized by high bulk density and soil strength. This means that some basic soil properties such as pore volume, pore size distribution, macropore continuity, and soil strength are altered. These properties, according to Hakansson and Voorhees (1998), have a large influence on elongation of plant roots, and on storage and movement of water, air and heat in the soil.

Studies cited by Allen (1981) found that following ploughing to 25-30 cm subsequent wheel traffic caused very large recompaction effects through the depth of cultivation. In contrast, where direct drilling is adopted the soil rapidly builds up to an equilibrium level of reformation of aggregates and it then has a high enough strength to resist further compaction. However, latest study by Hakansson and Voorhees (1998) concluded that compaction effects tend to accumulate and be more persistent under reduced tillage than in a system with ploughing. According to this source these conditions may still be adequate for clay soils due to improved continuity of macropore system. In contrary, for unloosened sandy soils the compaction effects usually accumulate with little natural alleviation. Consequently, compaction may prevent continuous use of reduced tillage or direct drilling, especially for sandy soils.

Repeated tillage at the same depth may result in the formation of a plowpan, a soil layer of increased bulk density and strength just below the tilth layer (Briggs and Courtney, 1985; Robinson et al., 1994). Consequences are that in wet periods plants may suffer from waterlogging in the root zone; and during dry periods the shallow depth of the roots may mean that they are unable to exploit water reserves deeper in the soil and may suffer from moisture deficiencies. In short, compaction of soils adversely affects crop performance by limiting the availability of soil oxygen, restricting root penetration, and reducing the ability of roots to take up water and nutrients (Conacher and Conacher, 1986; Robinson et al., 1994; Hakansson and Voorhees, 1998).

2.3.3.1 Penetration resistance

Cone penetrometer as an indirect method of measuring soil compaction is described in the next chapter. There are several soil factors influencing penetration resistance. These, according to Bradford (1986), include matric potential (or water content), bulk density, soil compressibility, soil strength parameters, and soil structure. The changes in such soil compaction affecting properties induced by tillage systems are of the most concern of many studies.

Horne et al. (1992), in a study on maize/oats rotation in a silt loam under full-tillage, minimum tillage, and zero-tillage found that penetration resistance was substantially lower in the full tillage compared to the other two treatments. Pasture plots gave the greater penetration resistance. Two months after sowing maize the difference in penetration resistance was significant at 95% probability among the tillage treatments between 100-200 mm soil depth. A significant difference (P<0.01) among the tillage treatments was also observed after maize harvest between 30-300 mm soil depth. In their study, the seasonal variations in soil water content did not contribute to the difference in soil strength. Another study in a sandy loam by Braim et al. (1992) also concluded that within the topsoil (0-230 mm) of the direct drilled treatments, resistances to cone penetrometer were 7 - 9 times greater than those of the ploughed soils. Different results from the above were reported by Guo (1997). In a trial at Massey University, Palmerston North, New Zealand, he found the fully cultivated plots to have significantly higher soil strength than the no-tillage and permanent pasture plots. This may partly coincide with the results later shown by Hakansson and Voorhees (1998).

2.3.3.2 Bulk density

Bulk density, ρ_b, the ratio of the mass of dry solids to the bulk volume of the soil, is not invariant for a given soil. It varies with structural condition of the soil, particularly that related to packing. For this reason it is often used as a measure of soil structure (Blake and Hartge, 1986). The latest review of the usefulness of relative bulk density values in studies of soil structure and compaction was presented by Hakansson and Lipiec (2000). Damage to soil physical structures under continuous tillage (ploughing and disking in particular), reduction of soil porosity, compaction and pulverisation by machines and stock, and cultivation of very wet to dry soils, all contribute to increases in bulk density (Conacher and Conacher, 1986). This consequently leads to the soil suffering effects such as increased resistance to mechanical cultivation, incurring greater wear and tear of parts and increased fuel consumption; impedance to root penetration; reduced water infiltration; increased waterlogging and surface water runoff, and accelerated erosion.

Numerous studies have so far been attempted to investigate changes in soil properties affected by tillage practices, inclusively bulk density. Horne et al. (1992) found the increase in bulk density in a similar pattern as the one reported for penetration resistance for tillage treatments cited above. After 10 years of continuous cropping, there was a significant difference (*P*<0.05) in bulk densities among all the tillage treatments with the top 100 mm of the zero-tilled plots being consistently more compact than the corresponding layer on the other two treatments. Contrastingly, Guo (1997) in his second experiment suggested conventional tillage to result in higher bulk density than no-tillage and permanent pasture (Table 2.2).

Table 2.2 Effects of tillage practices and permanent pasture on soil bulk density ($Mg\ m^{-3}$) (Guo, 1997)

Treatments*	First experiment (March 1996)	Second experiment (August 1996)
MP	1.27 a	1.21 a
NT	1.24 a	1.10 b
PP	1.22 a	1.02 c
$LSD_{0.05}$	0.07	0.012

*) *MP=moldboard plough, NT= no-tillage, PP= permanent pasture*
Values followed by the same letter are not significantly different ($P \leq 0.05$)

Braim et al. (1992) and Unger (1996), on the other hand, found that bulk density was not significantly affected by tillage practices. These contradicting results may reflect the specificities of the circumstances and the nature of each study, primarily related to site characteristics, cropping regimes involved, and the timing and duration of the trials.

2.3.4 Surface water runoff and leachate

Soil erosion research must be based on experimental results of some form. Often, laboratory and field plots are used to obtain experimental data for predicting and evaluating soil erosion and sediment yield (Mutchler et al., 1994). Soil erosion in the context of soil degradation and soil and water conservation has been discussed in the earlier sections. General information in literature regarding tillage practices previously reviewed was also partly concerned with the importance of controlling and preventing erosion. However, details of some recent studies would be valuable in enhancing a better understanding of soil erosion in relation with tillage systems.

Guo (1997) in his study on the effects of tillage practices on non-point source pollution obtained results which reflected earlier data by Malone et al. (1996). Tables 2.3 shows the surface runoff, soil sediment in runoff, and leachate under different tillage practices.

Table 2.3 Effects of tillage practices and cropping regime on surface water runoff, soil sediment, and leachate under rainfall simulation (Guo, 1997)

Treatment *	Surface runoff (mm)	Soil sediment in runoff (kg/m^3)	Leachate (mm)
MP	8.5 a	6.28 a	14.6 b
NT	2.5 b	0.19 b	24.8 a
PP	3.6 b	0.14 b	24.7 a
$LSD_{0.05}$	2.6	0.52	5.9

*) *MP=moldboard plough, NT= no-tillage, PP= permanent pasture*
Rainfall intensity of 48 ± 2 mm/hr
Values followed by the same letter are not significantly different ($P \leq 0.05$)

Moldboard plough treatment produced the highest surface water runoff among the treatments. Further effect was consistently shown by the highest amount of soil sediment found in the MP plots. The differences between runoff and sediment results in the MP and other two treatments were statistically significant. Less water runoff had occurred in no-tillage plots which eventually meant that the simulated rainfall water mostly went downward through the soil profile, clearly shown by the highest occurrence of leachate. These results were later confirmed by Hou (1999), who conducted his study at the same experimental site using natural rainstorm to measure water runoff and soil sediment. Choudhary et al. (1997), comparing moldboard plough (MP), chisel plough (CP), and no-till (NT) also reported that soil erosion and surface runoff were markedly affected by tillage methods. The order in which the runoff resulted was MP > CP > NT. The reverse order was obtained for leachate. This study also found the soil splash to be 2.5-fold higher in MP than in CP and NT.

In a study by Myers and Wagger (1996) in a 2-year experiment, runoff and sediment losses under conventional tillage (CT) for corn grain production, no-tillage grain production (NTG) with surface residue, and no-tillage silage production (NTS) without residue cover were compared. The sediment losses found in this study were in the order of NTG<NTS<CT and this was clearly associated with the residue cover. Rather surprisingly, the average first event runoff in both years was higher in the NT practices (40 % and 44% for NTG and NTS respectively) compared to CT (22%). The surface roughness that existed immediately after tillage operations in CT may have aided in more rainfall water catchment and infiltration leading to decreased surface water runoff. However, in the second event each year, the runoff loss was doubled with CT suggesting that soil surface seal development has taken place thus decreasing water retention and infiltration.

Erosion, as widely recognised, involves a complexity of interacting factors. Still in relation with tillage practices, some studies found no significant differences among tillage practices relative to no-tillage in terms of water runoff and soil loss. In other words, no-tillage was not primarily a major factor contributing to reduced runoff and enhanced water infiltration. Recent researches found that surface amendments (Rao, et al., 1998a; 1998b), watershed characteristics (Shipitalo and Edwards, 1998), and landscape features (Lobb and Kachanoski, 1999) were the leading factors to contribute significantly in the differences of soil erosion and runoff among tillage treatments.

2.3.5. Soil infiltration rate and hydraulic conductivity

Because ploughing is minimized under conservation tillage there are more continuous macropores and other preferential paths reaching directly from the soil surface deep into the subsoil. Conventional tillage destroys the structure of the surface soils, mixing the plough layer and covering the macropore's connection to the surface. These macropores are capable of increasing the infiltration of water and dissolved chemicals (Andreini and Steenhuis, 1990). Maule and Reed (1993) suggested that both the final rain and final ponded infiltration rates were the lowest for conventional tillage (CT) field although significant differences did not occur as shown in Table 2.4. The saturated hydraulic conductivities of the CT field also had lower values for all depths than the other fields under the NT practices.

Guo (1997) while confirming such infiltration results (Table 2.5) also suggested that higher volumes of leachate was found in the NT compared to the CT as shown previously in Table 2.3. Other studies also suggest similar results with those cited above. Chan and Mead (1989) did a study on water movement and macroporosity using a rainfall simulator to compare the effects of different tillage practices. The decrease in macropore density and continuity was evident according to their study. Similarly, Lal and Vandoren (1990) also reported higher cumulative infiltration and infiltration rate under no-tillage treatment than moldboard plough and chisel plough treatments. Latter, Benjamin (1993) also found out no-tillage to have a better impact on hydraulic conductivity.

Table 2.4 Infiltration and hydraulic conductivity values of field sites (Maule and Reed, 1993)

Property	Depth	NT5	NT10	NT13	SF	CT
Cumulative rain infiltration (mm at 60 min.)	surface	55.8 b	63.2 a	69.3 b	38.0 a	73.6 b
Rain final infiltration rate (x 10^{-6} m/s)	surface	13.2 b	13.0 b	12.7 b	3.8 a	11.6 b
Ponded final infiltration rate (x 10^{-6} m/s)	surface	13.7 a	16.7 a	11.4 a	-	8.6 a
Saturated hydraulic conductivity (x 10^{-6} m/s)	0-100	18.6 a	16.4 a	7.0 bc	10.8 c	3.1 b
	100-200	7.5 ab	20.3 a	8.1 ab	4.7 b	4.6 b
	200-300	6.3 a	6.6 a	5.0 a	7.5 a	4.7 a

SF: conventional, spring wheat-fallow, 2 yr rotation;
CT: conventional tillage, continuous wheat;
NT5: no-till, 5 years continuous crop;
NT10: no-till, 10 years continuous crop;
NT13: no-till, 13 years continuous crop.
Each number is an average of 3 samples.
Row numbers followed by similar letters are not significantly different at ($P \leq 0.05$)
Ponded infiltration rate data for the SF field were not taken.

Table 2.5 Effects of tillage practices and cropping regime on soil water infiltrability (Guo, 1997)

Treatment *)	Infiltration rate (mm/hr)	
	1st experiment (March 1996)	2nd experiment (August 1996)
MP	22.5 c	10.5 b
NT	35.5 b	16.7 a
PP	41.5 a	17.2 a
$LSD_{0.05}$	0.9	0.5

*) *MP=moldboard plough, NT= no-tillage, PP= permanent pasture*
Values followed by the same letter are not significantly different $(P \leq 0.05)$

The results of the studies mentioned above will be elaborated while digesting the findings of this research later in the next chapter. In short, it can be suggested that these infiltration and hydraulic conductivity studies show that although no-till soils may have high bulk densities and penetration resistance, they seem to have enhanced water conductivities enhancing water conservation and plant growth.

2.3.6 Organic matter

Miller and Donahue (1990) described the importance of organic matter in such a way that reflects its close relationships with the other soil parameters previously discussed as follow :

"... soil organic matter, from living or dead plant and animal residue, is a very important and active portion of the soil. It is the nitrogen reservoir; it furnishes large portions of the soil phosphorus and sulphur; it protects soils against erosion; it supplies the cementing substances for desirable aggregation formation; and it loosens up the soil to provide better aeration and water movement. For maximum benefit, organic matter must be readily decomposable and continuously replenished with fresh residues - roots, tops, and manures."

In a study at Massey University experimental site, Aslam (1998) found greater amount of microbial biomass C, N, and P in the no-tilled plots than conventionally tilled plots. Significant differences were found mainly at the 0 - 50 mm soil surface. The study, which spanned two cropping seasons with continuous conventional tillage, resulted in a significant decline in soil biological status and organic matter. Similar influence on biological status was found between no-tillage treatment and the adjacent permanent pasture control treatment. In a study on pasture and maize cropping following pasture conversion at four different soils in Manawatu, New Zealand, Sparling et al. (1992) found a markedly decline in both organic C and microbial C under continuous cultivation following conversion from pasture.

Similar results were reported by recent studies from other parts of New Zealand (Beare et al., 1994; Haynes, 1999; 2000) and from overseas (Campbell et al., 1996). Generally their findings suggested that with increasing period under pasture, soil organic content increased. By contrast, intensive cultivation mainly caused organic carbon decline partly due to enhanced decomposition of the existing organic matter by tillage. More details of the above studies will be referred to during the discussion in chapter 4.

2.4 Summary

Scientific advances and technological innovations in agriculture had contributed quite successfully in meeting a growing demand for food production. Adversely, the global food production system has at the same time overdrawn and degraded the natural resources upon which agriculture mostly depends.

The most severe form of agricultural degradation is that caused by erosion and non-point source pollution. Judicious land use and choice of appropriate crop management would help reverse these degradative trends.

Numerous studies suggest soil tillage to play an important role in agricultural sustainability. It influences crop yields through its effects on soil properties that regulate nutrient and water supply, competition with pests, and co-restrictive biophysical and socio-economic constraints. Appropriate tillage methods differ among soils, crops, and climatic regions, and the choice depends on a range of interacting factors.

Literature also reveals the prevalence of soil degradation in many agricultural production and agroecology systems. To avert further degradation, the soil productivity balance must be shifted from degrading processes to conserving processes. There is an urgent need to attain agricultural sustainability essentially in fragile eco-regions and marginal lands of the tropics. Conservation tillage is one of the soil conserving practices recognised world-wide despite its empirical benefits still largely undergoing continuous research. However it is also recognised that there is no single tillage system that can be widely used for the diverse soil and climatic conditions.

Chapter 3

Methods and Materials

3.1 Introduction

Compared with conventional tillage, the use of conservation tillage may result in soils having different physical properties, because the soil matrix undergoes less disturbance. No-tillage, which exerts the least perturbation on soil, is suggested widely to have greater effects on soil physical properties which promote a better environment for plant growth.

Massey University, through its long-term experimentation on soil tillage trials, has recorded initial baseline results of the effects of tillage practices and cropping regimes on selected soil properties (Guo, 1997; Aslam, 1998; Hou, 1999). Long-term observations, experiments and records are proceeding. Variability in some parameters is such and changes are often slow that a long run of experiments is needed to draw solid conclusions on the results.

The experiments within this research were established in the context of this long-term field research programme. The purpose of the experiments was largely to measure selected soil physical parameters which were expected to change in the course of five years after the site was established. Some limitations, however, warrant to be mentioned. Firstly, not all the soil physical parameters were fully covered in this study due to time and technical constraints. Secondly, the time for sampling was randomly chosen during the course of one year, and eventually did not match, for some parameters, the time before or after the seasonal crops, summer maize and winter oats, were established. Lastly, field and laboratory experiments errors may have occurred. In the runoff-leachate experiment for instance, mishandlings during soil core extraction have led to an inadvertent lateral water leakage through the gap between the soil and corer wall. Errors such as these may have to some extent embodied and affected the results of the present study.

3.2 Experimental Site

This research was conducted in an experimental site established in 1995 at Massey University campus, Palmerston North. One of the aims was to conduct a comprehensive study of tillage effects on soil properties. The soil type is Ohakea silt loam representing youngest yellow-grey earth with poor natural drainage on fine texture material, and topsoil moderately to strong acid enleached soils (Choudhary et al., 1996).

3.3 Experimental Design

3.3.1 Treatments

Research suggest that no-tillage practice has an overwhelming effect on soil properties. Literature has provided available data of no-tillage effects on soil structure and other characteristics in comparison with other different tillage practices. However, as its effects are often site and crop specific, thus a tillage trial in a long-term basis for Massey site is required. Three different soil mechanical treatments were used in this study, as described bellow:

(i) Moldboard ploughing (MP) as a conventional tillage practice.

This treatment involved a primary tillage with moldboard plough followed by a single pass of roller to break up clods and level the surface. Secondary tillage was done after a suitable time interval by two passes of power harrowing at suitable interval for seedbed preparation. Seeding was carried out using an Aitchinson seed drill.

(ii) No-tillage (NT).

This involved no soil and residue inversion at all, and the surface soil was left intact after the previous crop was grazed by sheep. Seeding was conducted by direct seeding with an Aitchinson seed drill. Approximately two weeks prior to the seeding, weeds were controlled by herbicide spray with 4 l/ha of Roundup (360 g/l glyphosate) mixed with 1 l/ha Versatill (300 g/l clopyralid).

(iii) Permanent pasture (PP)

This was an undisturbed soil with permanent pasture grass cover [ryegrass (*Lolium perene* L.) with clover (*Trifolium repens* L.)]. In this experiment, the PP was considered as a control treatment. The grass was allowed to grow throughout the year and grazed when the grass dry matter was about 2000 kg/ha.

3.3.2 Plots

The plots were arranged in a randomised complete block (RCB) design with four blocks each of three treatments in the trial. Four replications of each treatment were considered necessary to account for any variation due to field conditions. Thus, a total of 12 plots were used in the trial.

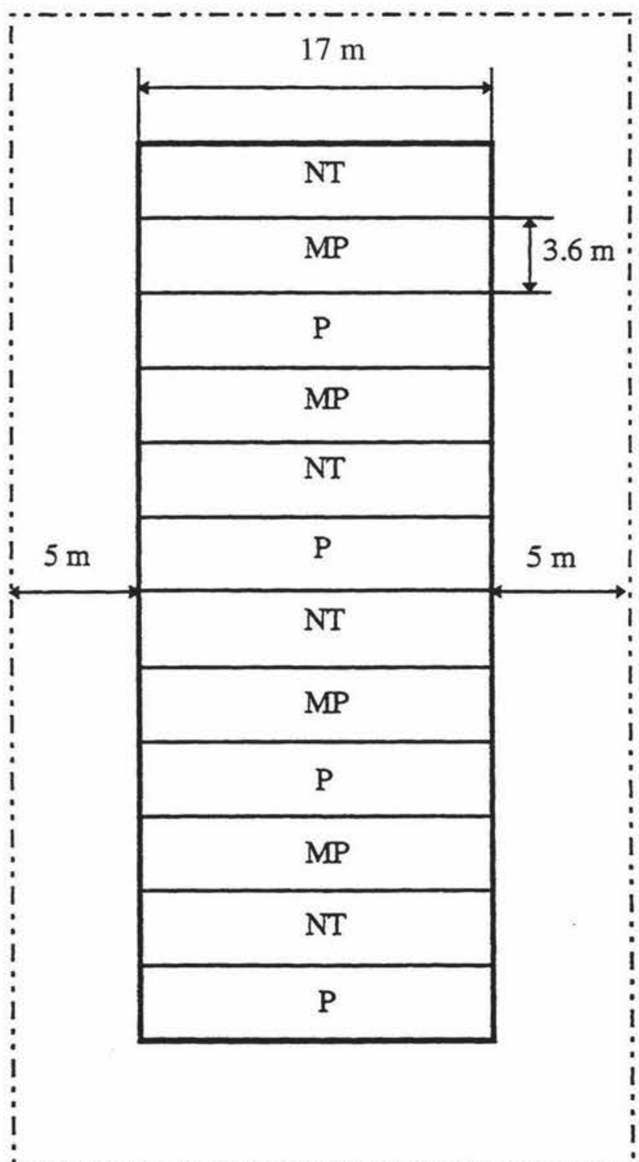
Each plot size was 7 m long and 3.6 m wide (two drills widths) with a 5 m headland for machinery operation on both sides of the field. The lay out of the plots is shown in Figure 3.1.

3.3.3 Soil sampling

There were different soil samples for different parameter measurements required in this study. Since the soil samples have to represent the field condition and reflect the variation within the area of study, considerable number, size, and methods of sampling were taken into account. Therefore, specific sampling method was used for each parameter as described below:

3.3.3.1 Runoff and leachate

A soil sample size of 300 mm long x 200 mm wide x 150 mm deep was taken from each plot for this purpose. The size was considered large enough to account for any variability in soil physical conditions on the one hand, which also allowed ease of extraction and transportation to the laboratory with little or no soil disturbance on the other. The steel corers with the above size and 3 mm wall thickness were installed manually into the soil and the soil cores were then carefully extracted avoiding soil disturbance (Figure 3.2a). The bottom end of each soil core was cut flush with the end of the core and carefully transported and placed into a laboratory at Massey University (Figure 3.2b). Any vegetative cover at the top of the soil cores was cut levelled to a height of ± 15 mm before cores being placed for experimentations. A rainfall simulator, under which, three soil cores were placed at a time, will be described later in Section 3.4. Special equipment (Figure 3.3.) was constructed to be attached to each soil core for the collection and measurement of soil and water runoff and leachate under the rainfall simulator (Guo, 1997).



PP: Permanent Pasture; MP: Moldboard Plough; NT: No-tillage

Figure 3.1 Schematic layout of the experimental plots

3.3.3.2 Bulk density

Sampling for bulk density measurement was taken for each 50 mm layer of the top soil down to 200 mm depth. Thin walled cylindrical aluminium samplers, 48 mm in internal diameter and 50 mm in length, were used. Each sampler was driven into the soil manually and the soil core carefully removed to preserve a known volume of the sample as it existed in situ. The soil cores were then transported to the laboratory for oven-drying and further calculations.

3.3.3.3 Soil water content

Samples for bulk density were also used for volumetric water content measurement. In this case, water content for four soil layers of 50 mm each from the 200 mm top soil were recorded. Sampling at different soil layers from the above were used at the time samples for aggregation stability measurement were extracted i.e. one sample for each layer of 0 - 100 mm and 100 - 200 mm. For the sake of treatments comparison, only water content determined using the same samples for bulk density were compared. There were other instances where water content measurement was required for example prior to aggregate stability and infiltration rate experiments. The values obtained in those cases were not considered for comparison among tillage treatments.

3.3.3.4 Aggregation stability

Spade slices of soil from two depths (0-100 mm and 100-200 mm) were removed from each plot. Air-dried samples from the slices were then sieved through a nest of sieves to obtain aggregate with the diameter sizes between 2 to 4 mm. These 2 - 4 mm aggregate samples were used to determine the aggregate stability by means of wet-sieving analysis. Soil samples were also taken for organic C and N analysis as these were suggested by many studies to have close relationship with soil structural stability.

Figure 3.2a A soil core soon after extracting from the field

Figure 3.2b Soil cores placed in the laboratory prior to experimentation

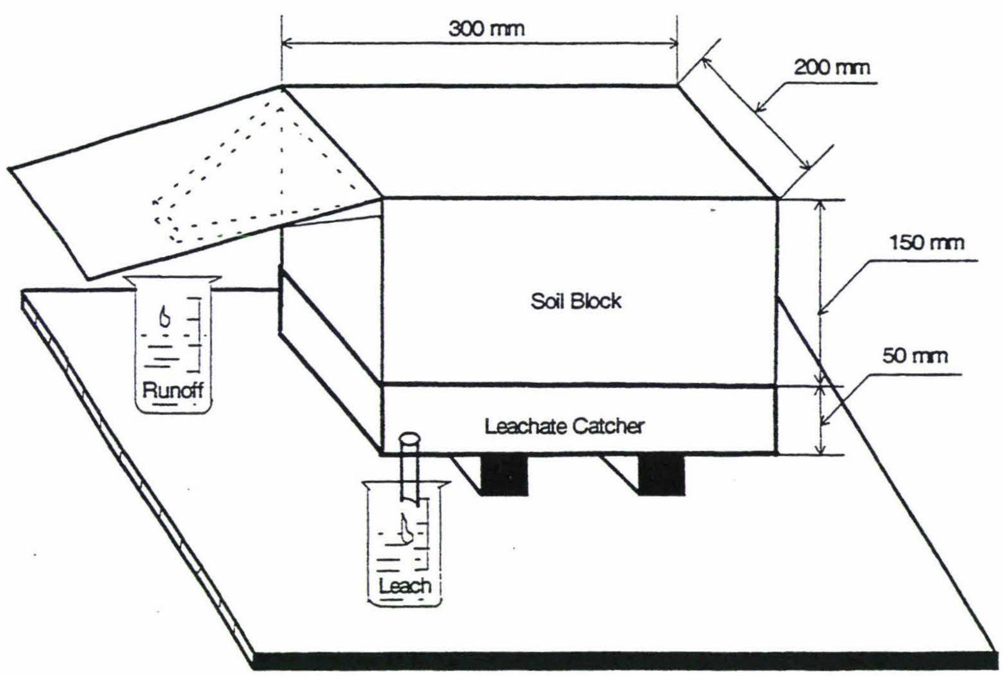


Figure 3.3 Schematic diagram of the apparatus specially designed for runoff and leachate measurements (Source: Guo, 1997)

3.3.4 Crop rotation establishment

3.3.4.1 Summer maize

Summer fodder maize was sown on the 8th of December 1998 at seed rate of 65 kg ha^{-1}. The sowing was done with Aitchinson seed drill model Seedmatic 1112, simultaneously with fertilizer application (Nitrophoska having 12% N, 10% P, 10% K, 1% S). The fertilizer application rate was 120 kg ha^{-1}. Two months later, on 12 February 1999, samples of maize plants were taken for the purpose of dry matter measurement. The maize was then grazed by a mob of sheep at maturity. The 1999 summer maize was sown in early December with the same NT and MP tillage treatments. Maize samples for dry matter measurement were taken on 16 February 2000.

3.3.4.2 Winter oats

The winter oats were sown at a seed rate of 120 kg ha^{-1} on 19 April 1999 with 200 kg ha^{-1} of Nitrophoska fertilizer with the Aitchison seed drill model Seedamatic 1112. On 10 June 1999 oats plant samples were taken from the NT and MP plots for dry matter measurement. The crop was then harvested by sheep grazing at maturity.

3.4 Rainfall Simulator

Erosion research using rainfall simulators has been conducted for more than 50 years (Shelton et al., 1985). Erosion deals with a complexity of interactions of variables such as rainfall, soil characteristics, topography and tillage. For these to be well understood, more controlled conditions than those under natural rainfall need to be attained. This is basically the main logic for the design and development of the most recent rainfall simulators.

Desirable characteristics of a rainfall simulator have been suggested by many studies (Moore, et al., 1983; Shelton et al., 1985; and Meyer, 1994), which can be summarized as follows:

(i) Similarity to natural rainfall in drop size distribution and fall velocity.

(ii) Most drops have an angle of impact of nearly vertical.

(iii) Capability to reproduce rainstorms with intensity, duration, uniformity and continuity which are of interest of any specific purpose.

(iv) Applicability to a research area sufficiently large to represent the treatments and conditions under investigation.

(v) Mobility from one research site to another.

Massey University's Institute of Natural Resource, has developed a laboratory rainfall simulator based on the design of USDA-ARS demonstration rainfall simulator developed by Dr. John Laflen at the Ohio State University (Hairsine, 1999). This portable rainfall simulator suits reasonably many purposes in the soil and hydrology research, especially studies related to soil erosion and soil and water quality. It consists of fan oscillating spray nozzles which produce rainfall rates, drop sizes and drop velocities similar to natural rainfall. Water is pumped from a reservoir to the nozzles and excess water is confined and drained back to the reservoir by a roof canopy and a hose. This tool can also simulate variable rainfall intensities by varying the time between sweeps.

As a laboratory equipment, it has been designed specifically for laboratory research, as shown in Figure 3.4. The experiments with this rainfall simulator were limited to evaluating two types of tillage and permanent pasture and their effects on soil and water runoff. The slope of 5% inclination in the field was also taken into account in the simulation process. With this rather limited design, however, it was expected that the test may produce results which reflected relevant differences.

The target rainfall parameter used in this research was intensity of ± 50 mm/hr. This is in accordance with Meyer (1994), who suggested that rainfall intensities between 0.2 and 2 mm/min are usually of greatest importance. Intensities below and above this range are not of major interest in the soil and hydrologic studies.

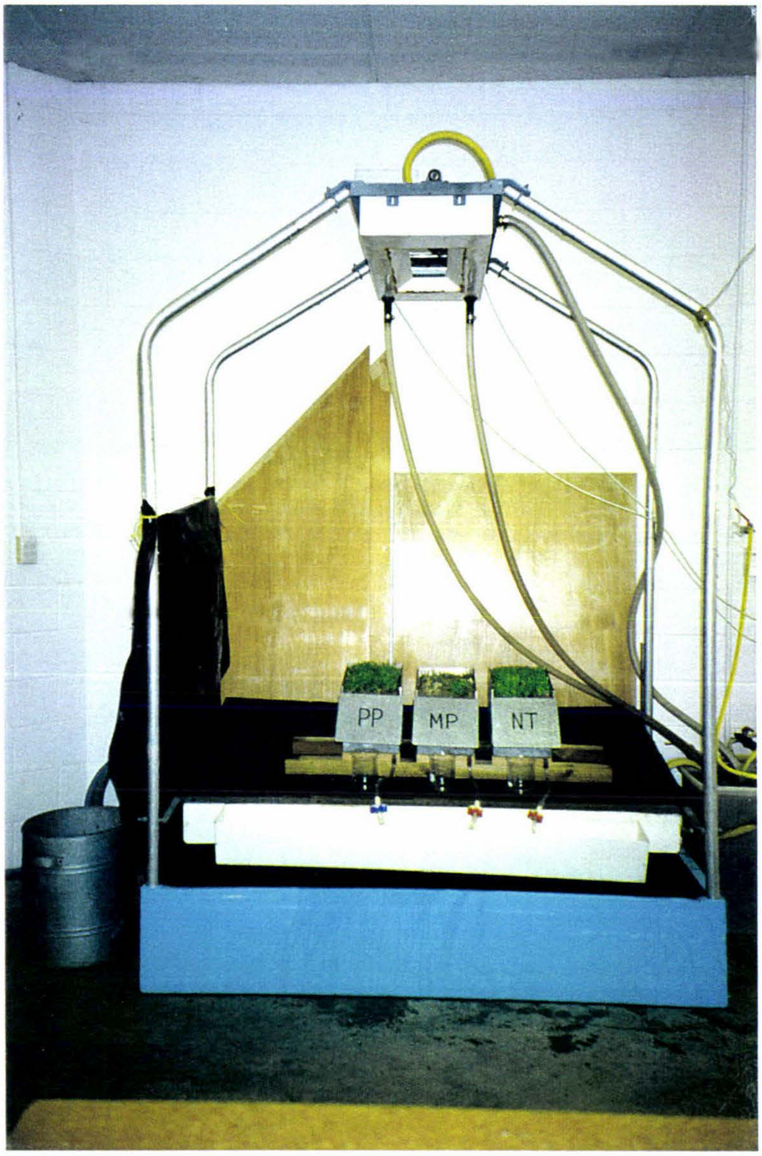


Figure 3.4 The rainfall simulator developed by Massey University's Institute of Natural Resources

3.5 Field Measurements

The key soil physical indicators measured in the field were: (a) soil penetration resistance. (b) water infiltration rate (c) soil bulk density (d) soil water content and (e) crop dry matter.

3.5.1 Penetration resistance

The presence or absence of annual moldboard ploughing largely influence the magnitude and persistence of machinery-induced soil compaction in the topsoil (Hakansson and Voorhees, 1998). Inclusively in this research is the aim to assess the soil compaction under two types of tillage and under permanent pasture. It is recognized however, the high degree of interactions between several soil factors, the dynamic environment, and variable and unpredictable climatic conditions contribute to soil compaction. Thus, apart from other parameters measured in this study, penetration resistance has been used as a parameter to help characterize the degree of soil compactness under different tillage practices.

A Bush® recording cone penetrometer (Mark 1 model 1979) with 12.2 mm cone diameter was used to measure soil penetration resistance in each plot to a depth of 400 mm (Figure 3.5.). Data are reported as the maximum force recorded as the cone passed through each 50-mm layer. The locations were chosen at random and the penetrometer was pushed into the soil by hand at a constant rate (Guo, 1997). Measurements of soil penetration resistance were done twice. The first was done on 27 April 1999, a week after the winter oats were sown.

This time was considered appropriate in order to examine the soil conditions shortly after cultivation. On the contrary, the second measurement was done six months later, on 22 October 1999, after all the plots were left undisturbed, and just one month prior to the next summer maize season. A natural consolidation of soil was presumed to have taken place during this period of time. Thus, appreciable differences on the results were expected upon these two different timings.

Figure 3.5 Soil penetration resistance measurement

3.5.2 Water infiltration rate

The infiltration rate was measured using double-cylinder infiltrometers. A smaller cylinder is placed concentrically inside another cylinder. Diameters were 210 mm for the inner and 420 mm for the outer cylinder. These were driven into a depth about 100 mm. Equal water levels were maintained in both cylinders, and the infiltration rate was measured in the inner cylinder only. Readings were taken at regular intervals by recording the fall of water level in the inner cylinder.

The reason behind this system of measurement was to let the outer, annular space between the two rings 'absorb' all the edge and divergence effects, so that the infiltration from the inner ring would be a true measure of the vertical infiltration rate of the soil. However, this logic is disputable, as the infiltration rate from the inner cylinder is also very much affected by lateral divergence (Bower, 1986).

Despite the above contradiction, the use of rather large cylinders in this experiment was expected to reduce the effects of the lateral divergence of the flow below the cylinders. The results, thus, were believed to be rather estimates than true measures. However, these could reasonably serve as realistic indicators of the effects of the differing types of soil treatments on soil water retention and infiltrability.

The first measurement was conducted on 22 December 1998 simulating early summer. The second measurement was carried out on 14 February 1999. This was to simulate late summer. The third measurement was done four months later, on 16 June 1999, reflecting winter period. The fourth measurement was taken on 5 October 1999 to simulate mid to late spring. These temporal observations were expected to result in some useful complementary inputs for the whole research.

3.5.3 Bulk density

Bulk density is a widely used value. For a given soil, it varies with the structural condition of the soil. For this reason, it is often used as a measure of soil structure (Blake and Hartge, 1986). Four samples were taken from each plot at different depths: 0-50, 50-100, 100-150, and 150-200 mm. The samples were weighed, oven-dried at

105°C overnight, and reweighed. Bulk density was calculated as the ratio of the oven-dry mass of soil to the bulk volume of the sample.

There was only a single measurement done during this study. It was accomplished on 27th of April 1999, the same time as the first measurement of soil penetration resistance. It was presumed that drastic changes in the bulk density may have not occurred, thus, a second measurement was found not necessary. Instead, the results of this experiment were to be compared to those obtained during the previous study by Guo (1997), carried out in the same plots on March 1996, exactly after three years.

3.5.4 Soil water content

As far as the objectives of this research are concerned, the analysis of water content is primarily viewed as a guide to determine the extent of the capacity of the soil to absorb and store water as affected by different tillage practices and permanent pasture. Furthermore, the importance of moisture content data as a supplement to the analysis of other soil parameters within the context of this research is also recognised.

Soil samples at appropriate depths from each plot were collected at different times, corresponding to the sampling for bulk density, aggregation stability, and prior to the infiltration rate measurement. The samples were weighed, oven-dried at 105° C overnight, and reweighed. Both volumetric and gravimetric water content were determined from the change of volume / mass after oven-drying.

3.5.5 Crop dry matter

Crop dry matters were measured by taking crop plant samples at maturity prior to grazing. Oats samples were taken on 12 February 1999. Maize samples were collected during two cropping seasons i.e. summer 1998 and summer 1999. Plants were cut at the bottom end close to soil surface, at random from each plot, oven-dried and dry matter weighed.

3.6 Laboratory Measurements

3.6.1 Aggregation stability

The water-stability of soil aggregates is an important physical characteristic of cultivated soils primarily due to the recognition of the empiricism involved in relating aggregate size measurements to field phenomena. It measures the extent to which the small soil crumbs produced by cultivation are likely to remain intact and separate from one another through subsequent rain and mechanical disturbance. Wet-sieving analysis to determine aggregate water stability were carried out on 2.0 - 4.0 mm aggregates using the method of Gradwell (1972). This is basically a modification of Yoder's method described by Kemper and Rosenau (1986).

The main apparatus used in this method is the wet sieving tank. It is approximately 35 cm wide x 45 cm long x 30 cm deep (Figure 3.6a). Six stacks of 13 cm sieves are carried in a frame which is moved up and down a distance of 3 cm, thirty times a minute. Each sieve stack comprises of three sieves stacked from top to bottom with apertures of 2.0, 1.0, and 0.5 mm respectively (Dando, 1999).

Samples were air-dried soon after sampling. The larger clods were broken down by hand and the whole sample placed into shallow trays and air-dried. Once air-dry, the samples were mechanically sieved to extract aggregates between 2-4 mm in diameter (Figure 3.6b). Samples of 2-4 mm were analysed soon after air-drying. Basically, the aggregates were placed on the top sieves which were then moved up and down under water and the proportion of crumbs remaining on the sieves after a period of time being a measure of stability.

Kemper and Rosenau (1986) have suggested that differences between aggregate stabilities are generally more detectable if they are subjected to greater disruptive forces involved in direct immersion of dry aggregates at atmospheric pressure, or prolonged sieving. Therefore, in this experiment two sieving durations were used. The first, using 60 minutes duration, was carried out on 7th of September 1999, and the second, with 30 minutes sieving duration, was conducted on 11th of October 1999.

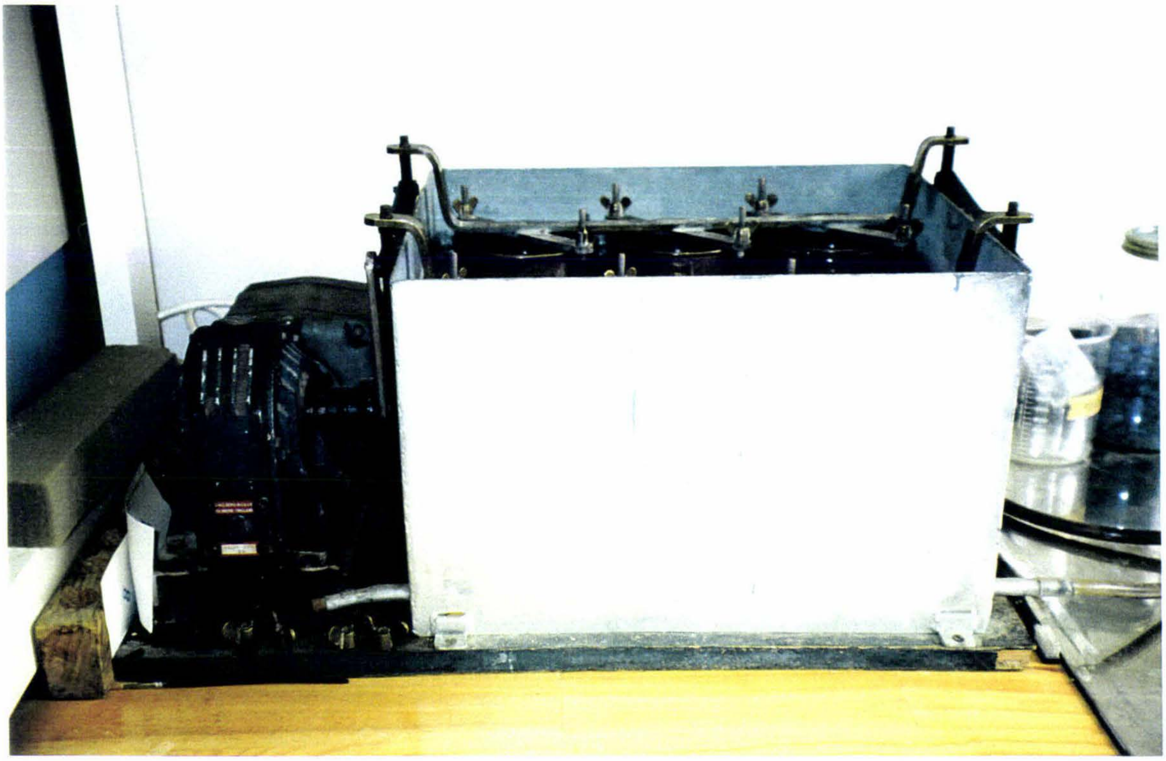


Figure 3.6a Wet-sieving tank

Figure 3.6b Sieving for the extraction of 2 - 4 mm soil aggregates

3.6.2 Runoff, sediment and leachate

As has been described in Section 3.4, a laboratory rainfall simulator was used to measure surface water runoff, sediment and leachate. Rainfall intensity was pulsed, within an average application rate of 50 mm/hr for one hour, simulating a rainstorm (Guo, 1997). The experiments were carried out twice starting on 24 August 1999, with the first being a pilot experiment.

The volume of water runoff was collected at every ten minutes interval. The total volumes of surface runoff were determined by adding all runoff samples thus collected. The volume of water-sediment mix for each sample was obtained from the surface water runoff. A part of the water-sediment mix was used to determine the amounts of soil sediment in surface water runoff. The dry mass of sediment was determined after evaporating the water off in an oven at 105^{o}C for 24 hours. The sediment concentration in surface water runoff was determined by multiplying the mean mass of sediment by the mean volume of surface water runoff from each ten minutes interval.

The water leachate was collected by using a catching tray placed immediately below the soil cores (Figure 3.4.). The volume of leachate sample was collected at ten minutes intervals. The sum of six collections over one hour was equivalent to the total volume of water leachate.

3.6.3 Soil pH, total C and N analysis

Soil pH, total C and N were taken at once. Soil pH was determined by using a pH electrode metre. Soil organic carbon content was measured using a Laboratory Equipment Corporation (Leco) high-frequency induction furnace (Blakemore et al., 1987). The measurements were done on subsamples taken from air-dried soil collected from each plot. Samples were collected from two depths, 0-50 and 50-100 mm, from each plot after the winter oats were grazed, and from the adjacent pasture plots on September 1999. Soil from each plot was bulked before subsampling. Organic-N content of the 0-50 and 50-100 mm samples were determined by the Kjedahl method.

3.7 Statistical Analysis

The analysis of all data obtained during this study was carried out using the statistical package of SAS (Statistical Analysis System). Analysis of variance (ANOVA) was among other computations completed with SAS programme (SAS Institute Inc., 1989) for the purpose of this analysis.

Chapter 4

Results and Discussion

4.1 Introduction

As a contributing part towards a major study on long-term tillage trial, this research has studied several soil physical properties in an attempt to provide an assessment of soil structure suitability for crop production management. The results were quite visible despite its relatively simple methodology as described in chapter 3. Changes in the selected soil physical properties five years after the trial was established were as anticipated. These changes are important tools to characterize and distinguish differences developing in the soil physical conditions due to soil management or tillage comparisons.

Soil compaction was characterized by assessing soil penetration resistance, bulk density and soil water content. Empirical relationships among these properties were determined by using simple statistical regression analyses. For large set of data, especially those from laboratory based experiments, regression equations to relate soil strength, bulk density and soil water content earlier developed by Busscher et al. (1987) are recommended. Water infiltration experiments were conducted four times over one year period, in an attempt to account for any seasonal variability. Macropore continuity was, presumably, one of the main soil structure parameters induced by mechanical treatments employed during this study. The pore system in the untilled plots is often more continuous because the old earthworm and root channels, are maintained. Previous studies in this trial have indicated a significantly higher earthworm population under the PP and NT treatments compared to the MP treatment (Guo, 1997; Aslam, 1998). Field experiment was also carried out to compare dry matter yields obtained from the NT with that from MP.

Soil aggregate stability was another core parameter of this study assessed through a laboratory analysis. Also, under laboratory conditions and simulated rainfall, water runoff and leachate were collected and statistically analysed. Laboratory work was also employed to measure selected chemical nutrients from the 0-10 and 10-20 cm soil layers.

4.2 Field Measurements

4.2.1 Penetration resistance

The first measurement was taken a week after the winter oats were sown on 19 April 1999. The results indicate the soil resistance was about twice as much in the two top layers (0-5 cm and 5-10 cm) in the PP and NT plots compared to MP (Table 4.1). A significant difference was found at all layers down to 40 cm soil profile depth under the MP treatment, showing consistently lower soil resistance to penetration as compared to the PP and NT treatments. Although the results demonstrate that there was difference in the soil resistance between the NT and the PP plots for the top 0-10 cm, an unexpected significant difference was observed at the 10-15 cm layer. An apparent increasing trend in penetration resistance was observed with increasing in soil depth especially for the PP and MP treatments.

Table 4.1 Effects of tillage practices and cropping regime on soil penetration resistance (MPa) (measured on 27th April 1999 during early winter oats growing season)

Soil depth (cm)	Treatments*			$LSD_{0.05}$
	PP	MP	NT	
0-5	1.168 a	0.608 b	1.255 a	0.268
5-10	2.465 a	1.060 b	2.640 a	0.325
10-15	2.740 b	1.755 c	3.030 a	0.290
15-20	3.098 a	2.240 b	2.958 a	0.353
20-25	3.345 a	2.253 c	2.858 b	0.387
25-30	3.460 a	2.695 b	2.828 ab	0.707
30-35	3.733 a	3.063 b	2.930 b	0.640
35-40	3.765 a	3.385 ab	2.993 b	0.552

Values followed by the same letter in each row are not significantly different (P<0.05)
**)PP=Permanent pasture; MP=Moldboard plough; NT=No-tillage*

A second soil penetration measurement was undertaken in the same plots six months later. By this time all the plots were left undisturbed under crop and soil had recompacted. Results were demonstrably different to the first measurement (Table 4.2).

The MP plots showed significantly greater resistance compared to the other two treatments in the 0-20 cm soil depth. Below this depth with exception of the 35-40 cm layer, contrastingly, the MP plots showed soil resistance which was similar to the NT and PP treatments. The NT and PP plots showed generally similar resistance characteristics.

Overall, a clear and consistent pattern of soil penetration resistance can be observed at the top 20 cm soil. Below this depth differences in soil strength virtually disappear. Thus a differentiation of the soil profile into two major layers i.e. 0-20 cm (the ploughing depth) and >20 cm become obvious. Presuming the top 20 cm soil layer, the plough layer, is the most affected part of the soil profile by any cropping and tillage regimes, therefore the measurement of the other variables for this research down to this specific depth only may be justified.

Table 4.2 Effects of tillage practices and cropping regime on soil penetration resistance (MPa) (measured on 22nd October 1999 after winter oats harvest and spring fallow)

Soil depth (cm)	Treatments*			$LSD_{0.05}$
	PP	MP	NT	
0-5	1.645 b	2.863 a	1.730 b	0.481
5-10	2.588 b	4.423 a	2.850 b	0.604
10-15	3.275 b	4.618 a	3.830 b	0.748
15-20	3.630 b	4.425 a	4.308 ab	0.794
20-25	3.925 a	3.995 a	4.395 a	n.s.
25-30	4.180 a	3.663 a	4.410 a	n.s.
30-35	4.413 a	3.598 a	4.215 a	n.s.
35-40	4.638 a	3.473 b	4.008 ab	0.680

Values followed by the same letter in each row are not significantly different (P<0.05)
**) PP=Permanent pasture; MP=Moldboard plough; NT=No-tillage*

An obvious indication shown by the first penetration resistance measurement was that the recently cultivated soil in the MP plots was, not unexpectedly, significantly less compacted than the soils under the other two treatments. The results in Table 4.1 indicate that the MP resulted in lower values not only at the tilth layer or rooting zone as it is assumed to be at the 0-20 cm soil depth, but it appeared to happen further down to 40 cm depth. Especially down to the 20 cm depth, the results were undoubtedly logical because the soils were tilled about 2 weeks prior to the sowing of the winter oats. By the time the measurement was taken, the soils under the MP treatment appeared to be still soft and loose and thus offer less resistance to the downward force of the penetrometer. Interestingly, the soil layer below 20 cm also showed low resistance under the MP than the PP and NT treatments. There could be a number of reasons such as previous crop rooting effects, or differences in soil moisture at this depth, which were not measured in this study.

These results concur with those previously reported by Horne et al. (1992). In a similar trial on a silt loam, in an early summer maize-growing season, these authors found full tillage to result in substantially lower penetration resistance than minimum and zero tillages at 5-25 cm soil profile. Hughes et al. (1992) also reported a correlation between the high soil resistance under no-tillage and lower seed emergence and plant yield within their study.

At the Massey University experimental site, in poorly drained silt loam, Aslam (1997) and Guo (1997) also found similar results. Both studies concluded that at the end of the crop season the continuous ploughing resulted in a significantly higher soil strength at the 0-5 cm upper soil layer and remarkably lower values for the underlying layers comparing to the no-tillage and permanent pasture soils. In regard to plant root development, contrastingly, Aslam (1997) found oats roots to be denser and longer in the no-tillage plots than in the conventionally tilled plots. On the other hand, Hughes et al. (1992) concluded that the summer maize seedlings found difficulties in penetrating the untilled soils which may have resulted in lower maize yield in untilled soil as compared to that from the ploughed soil.

The results in Tables 4.1 and 4.2 also indicate similarities between NT and PP soils. The PP as a control treatment was statistically similar to the NT. The pasture plots showed a degree of compaction mainly affected by natural amelioration and sheep trampling effect during grazing as part of the trial. In the NT plots, the tractor and drill equipment pressure may have contributed to the state of soil compactness.

Figure 4.1 shows regression analyses between soil depth and the soil penetration resistance under the PP, MP and NT treatments measured during early winter oats growing season 1999. The regression analyses showed that the increase in soil penetration resistance was linearly correlated with the increase in soil depth especially under the PP ($R^2 = 0.835$) and MP ($R^2 = 0.970$) treatments. This may be attributed to the fact that below the cultivated soil horizon, the soil structure was different. This could probably be related to a condition where soil water status, total porosity and the air-filled porosity were low, but on the other hand, the mechanical impedance and bulk density were high. As stated by Hakansson and Voorhees (1998), it is rare to find a loose subsoil, however, numerous studies could be found in regard to subsoil compaction, inter alia, those reported by Logsdon et al. (1992) and Hakansson and Reeder (1994).

After the oats were grazed by sheep and left fallow during spring, soils in the MP plots appeared to have been consolidated to an extent where compaction was greater than the soils under the other two treatments. Wetting and drying effects during the transitional period of winter to spring may have enhanced the compaction process. It appeared to affect not only the soil penetration resistance in the MP plots but also in the PP and NT plots as well, if the two measurement events were to be compared. Taking the upper 0-5 cm soil layer as an example, an apparent increase in penetration resistance was noticed from approximately 1.2 to 1.6, 0.6 to 2.9, and 1.3 to 1.7 MPa for the PP, MP, and NT respectively, after a period of six months. A general increasing trend in soil resistance was also observed for the lower layers under all the treatments after this period of time. Another observation from the second set of measurements in the MP plots was the decrease in soil resistance observed at the depths below 20 cm. This may confirm the characterization of another differing soil horizon just below the cultivated layer as mentioned before. Regression analysis results also demonstrate no clear trend between soil depth and soil penetration resistance under MP whereas a linear correlation was found under PP and NT plots (Figure 4.2). Below this 20 cm depth, the statistical analysis showed only insignificant differences among all the treatments. Detailed raw data and statistical analysis results are presented in Appendix 1.1.

Contrasting with the current results, the study by Horne et al. (1992) in a period after maize harvest, found consistently lower resistance to penetration in the 3-20 cm depth on full tillage and minimum tillage plots compared to no-tillage and pasture plots. The negligible effect of seasonal variation from summer to autumn in soil water content appeared to be confirmed. On another silt loam study by Hussain et al. (1998), two events of cone index measurements i.e. during planting and 25 days after planting were reported. No-tillage (NT) resulted in a significantly higher resistance at the upper 0-8 cm soil layer compared to both the chisel plough (CP) and moldboard plough (MP) at both events. Below this layer down to 68 cm depth, the differences were insignificant among all the three treatments.

In conclusion, the significantly greater compaction was observed in the MP plots at the end of the crop season (second measurement) down to 20 cm soil profile, whereas other researchers found the greater resistance to be occurring only at the upper layer of 0-5 cm (Guo, 1997) and 0-3 cm (Horne et al., 1992). This could be due to the continuously tilled soil having low surface aggregate stability and becoming prone to recompaction within short period after tillage.

By contrast, Hussain et al (1998) found that NT produced consistently and significantly greater resistance at the top 0-8 cm soil profile. It's probable, therefore, that soil with similar texture (silt loam) can behave differently to various tillage treatments and cropping patterns. Especially within the context of this discussion, it may be possible that factors such as clay content, soil moisture regime, and other soil structural indices may have contributed to the differences mentioned above.

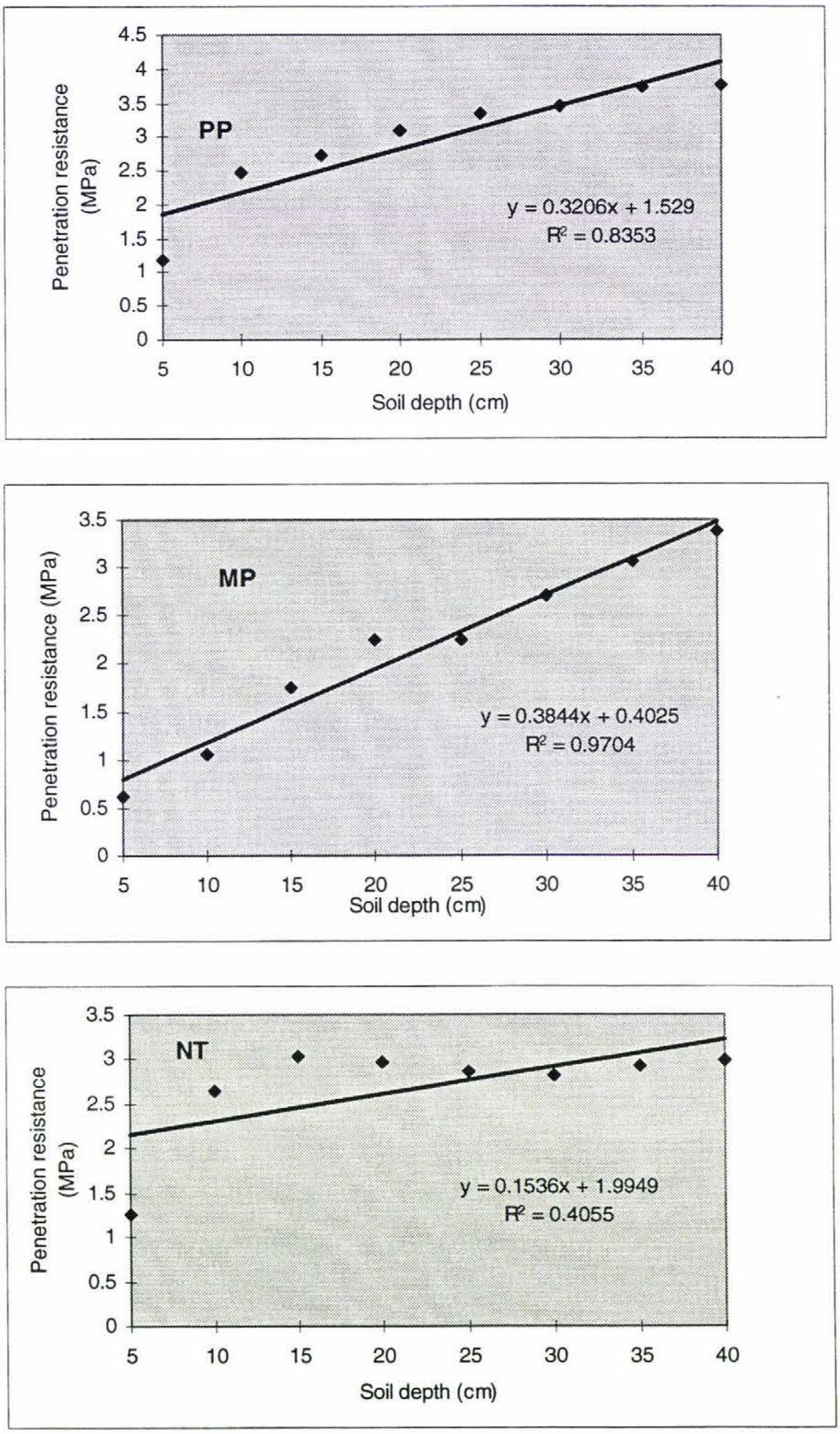


Figure 4.1 Regression analysis between soil depth (cm) and soil penetration resistance (MPa) under the PP (permanent pasture), MP (moldboard plough) and NT (no-tillage) treatments measured during early winter oats growing season 1999

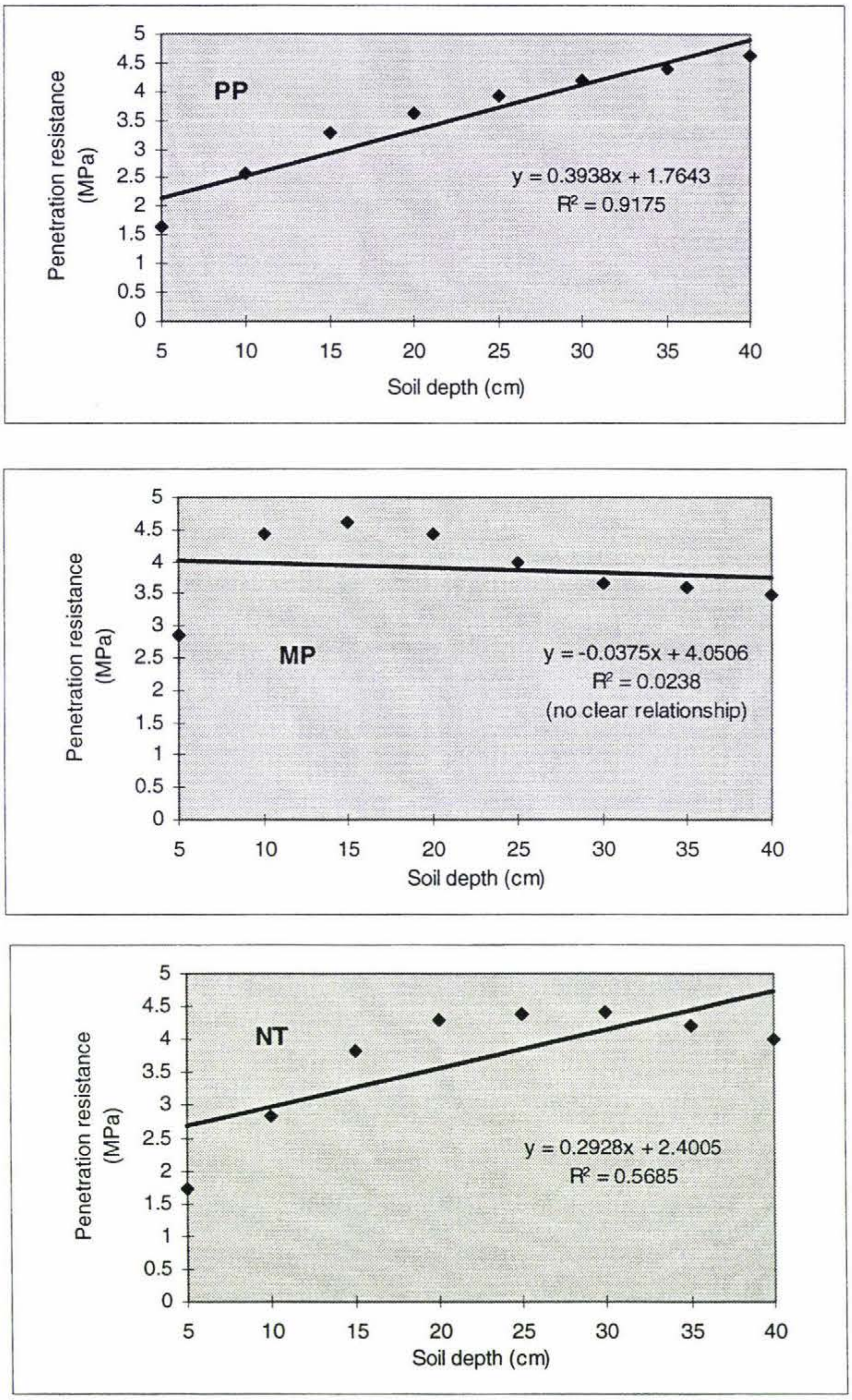


Figure 4.2 Regression analysis between soil depth (cm) and soil penetration resistance (MPa) under the PP (permanent pasture), MP (moldboard plough) and NT (no-tillage) treatments measured after winter oats grazing and spring fallow 1999

4.2.2 Water infiltration rate

The soil water infiltration rates were measured four times during these experiments. As shown in Table 4.3, an average of four events of infiltration rate measurements showed significant differences during the course of one year period. The average infiltration rate was in the order of MP<NT=PP.

The first measurement was taken in the early summer of December 1998. This resulted in almost similar values of infiltration rate for all the treatments at P = 0.05. The measurements were taken two weeks after sowing the maize crop in the NT and MP plots. Two months later, and one week prior to grazing of fodder maize, the second measurement was accomplished, simulating mid-summer dry conditions. At this time, the results showed the order of PP>NT>MP with the rates differing markedly among all the treatments.

Table 4.3 The effects of tillage practices and cropping regime on soil water infiltration rate (mm/min)

Date of measurement	Treatments*			$LSD_{0.05}$
	PP	MP	NT	
22/12/98	0.80 a	0.75 a	1.20 a	n.s.
14/02/99	1.70 a	0.75 c	1.20 b	0.33
16/06/99	0.98 a	0.35 b	1.05 a	0.49
05/10/99	1.39 a	0.97 a	1.20 a	n.s.
Average	1.22 a	0.70 b	1.16 a	0.449

Values followed by the same letter in each row are not significantly different (P<0.05)
**) PP=Permanent pasture; MP=Moldboard plough; NT=No-tillage*

The third measurement was conducted in the winter of 1999, a week prior to sheep-grazing the oats from the MP and NT plots. The NT plots showed the highest infiltration rate, and equally with the PP, these two treatments were significantly higher than the MP. Interestingly at this time of the year, the MP treatment resulted in the lowest value of infiltration rate among all treatments.

The final measurement carried out in mid spring 1999 showed similar characteristics as the first one. Prior to this measurement, the NT and MP were left uncropped in winter following the grazing of winter oats. No significant differences in infiltration rates were found among the treatments in this measurement.

The average of four events of measurements during the year clearly indicates that the soil infiltrability was most negatively affected under the MP treatment. The effects of the NT treatment were similar to the PP in all measurements. Despite relatively high degree of compactness encountered in the NT plots as previously discussed, it appeared that the macropore continuity, especially at the top 20 cm soil profile, has been improved for these plots. This may be one of the reasons for such a higher infiltration rate to occur. Many studies have suggested the earthworm channels to be one of the factors contributing to the macropore continuity improvement. Previous reports on earthworm population at this experimental site confirmed NT to produce more earthworms than the MP. On July 1996, Guo et al. (1999a) found 313, 254, 159 earthworms (numbers m^{-2}) for the PP, NT, and MP respectively. In June the following year, Aslam (1998) found 429, 363, 110 earthworms (number m^{-2}) for the same order of treatments. Taking the last measurement (Aslam, 1998) as the point of reference, it can be concluded that after 2 years of conversion from pasture land, the MP reduced the earthworm population to 74% whereas the reduction under the NT was only 15%.

The purpose of measuring water infiltration four times during a year was essentially to assess any temporal variability effects. Rates under the no-tillage were consistently similar during the year whereas slight variability was encountered in the PP and MP plots. The highest rate under the PP was found at the second measurement (February 1999). Putting aside the first and fourth measurement, as there was no significant difference observed among treatments, the second and third events confirmed the results of the experiments conducted by Guo (1997) two years after the experiment had started (refer to Table 2.5). Guo's first infiltration rate measurement results were in the order of PP>NT>MP appeared to be confirmed by the second event of the present study. Also, within the same season in a year, the results from the third measurement of the current study were similar to the results of Guo's second experiment accomplished in August

1996. The only difference between these two studies was in the magnitude of the infiltration rates under all the treatments. It is clear from the current results that there was significantly higher soil infiltrability after five years of starting the initial experiment, compared to that reported by Guo (1997) for the same plots. One possible reason could be the different methods for measurement used in the two studies. Guo used a small rectangular steel infiltrometer while the latter study employed a quite large double ring infiltrometer.

Detailed raw data and statistical analyses of infiltration rate measurements are shown in Appendix 1.2.

Literature concerning tillage and soil hydraulic properties are widely available. Water movement and macroporosity experiment under a rainfall simulator was the subject of study of Chan and Mead (1989). Their study clearly demonstrated that conventional tillage reduced macropore density as well as their continuity. Thus, under conventional tillage, infiltration was greatly hampered leading to significantly higher run-off. Contrastingly, the same soil cropped using direct drill techniques had a similar macroporosity to the pasture soil, which was significantly higher than conventional tillage. In another study on 25 years of continuous corn cultivation under different tillage practices, Lal and Vandoren (1990) also concluded that both the cumulative infiltration and infiltration rates were somewhat higher for no-tillage (NT) than moldboard plough (MP) and chisel plough (CP) treatments. Similarly Benjamin (1993) suggested the NT system to have 30 to 180% greater saturated hydraulic conductivity than either the CP or MP systems. The NT systems with a corn-corn rotation showed a greater slope of the log unsaturated hydraulic conductivity; log volumetric water content relationship on two of the soils indicating greater water movement through a few relatively large pores for this system than for either the CP or MP.

However, during the first minutes of measurement the infiltration could be high under cultivated soils. Lal et al (1989) for instance, pointed out that the initial infiltration was significantly greater in the continuous plough-till than no-till treatments. This was apparently caused by high total porosity in the freshly ploughed plots. However, their study also found later on that the structural collapse of cultivated soils resulted in a lower equilibrium infiltration rate than the untilled soils. Ball et al. (1994) reported reverse results to the above studies. Their study found the infiltration rate to be more on ploughed + drilled than direct drilled plots ($P<0.001$) and pore continuity to be higher under the MP than NT as well ($P<0.01$).

4.2.3 Bulk density

The bulk density was measured at four depths from each of the experimental plots. The results indicated a trend toward high bulk density at all depths in the NT plots as compared with the MP plots (Table 4.4). However, significant differences only appeared at the 0-5 cm and 10-15 cm depths between the NT and MP plots. For these respective depths there was significant difference ($P<0.05$) found between the NT and PP plots. Viewing the soil profile as a whole, by taking the average impact at four depths under all the treatments, the analysis showed no differences in bulk density among the treatments. The detailed raw data and statistical analyses are presented in Appendix 1.3.

Table 4.4 The effects of tillage practices and cropping regime on soil bulk density (g cm^{-3}) (measured on 27th April 1999 during early winter oats growing season)

Soil depth (cm)	Treatments*			$LSD_{0.05}$
	PP	MP	NT	
0-5	1.21 ab	1.12 b	1.31 a	0.113
5-10	1.31 a	1.31a	1.36 a	n.s.
10-15	1.37 ab	1.31 b	1.42 a	0.078
15-20	1.40 a	1.44 a	1.47 a	n.s.
Average	1.32 a	1.29 a	1.39 a	n.s.

Values followed by the same letter in each row are not significantly different ($P<0.05$)
**)PP=Permanent pasture; MP=Moldboard plough; NT=No-tillage*

The results cited above partly confirm previous studies (Guo, 1997; Hussain et al. (1998). Measuring bulk density each year on two occasions, 25 days after planting and at midseason, during an 8-year study Hussain et al. (1998) found a similar 8-year average of bulk density between tilled and untilled plots. Guo (1997), comparing permanent pasture (PP), moldboard plough (MP) and no-tillage (NT) treatments, in his first experiment also found no significant differences among all the treatments. However, as mentioned by Blake and Hartge (1986), bulk density is not invariant for a given soil because it changes according to structural condition of the soil. It was not unexpected therefore that for the midseason Hussain et al. (1998) found significantly higher bulk density in the NT plots than CT and MP plots, whereas Guo (1997), on the other hand, in his second experiment, found the MP to result in higher bulk density. Inconsistent effects of different tillage practices on soil bulk density were also reported by a different study (Benjamin, 1993).

Relatively high bulk density found in the NT plots was an indication of higher soil density and lower total porosity under this treatment than the other two treatments. This evidence partly demonstrates the soil surface to be comparatively compacted in the NT compared to the MP as this was also indicated by the rather high penetration resistance under the NT for this time of the season as discussed previously. A good correlation between soil bulk density and soil penetration was found under all the treatments as shown in Figure 4.3. The impact of compaction caused by machinery wheel traffic remains on the surface as partly confirmed by significantly higher bulk density at the top 0-5 cm soil under no-tillage treatment compared to the other two treatments. Although the NT has relatively high bulk density, consequently a lower total porosity, it also has higher water content as compared with the MP as described in the next section. This means that water-filled porosity under the NT was higher as indicated by the experimental results of Hussain et al. (1998) earlier. Both at 25 days after planting and at the midseason, despite the higher total porosity found in MP plots, their results showed the NT to constantly have higher water-filled porosity.

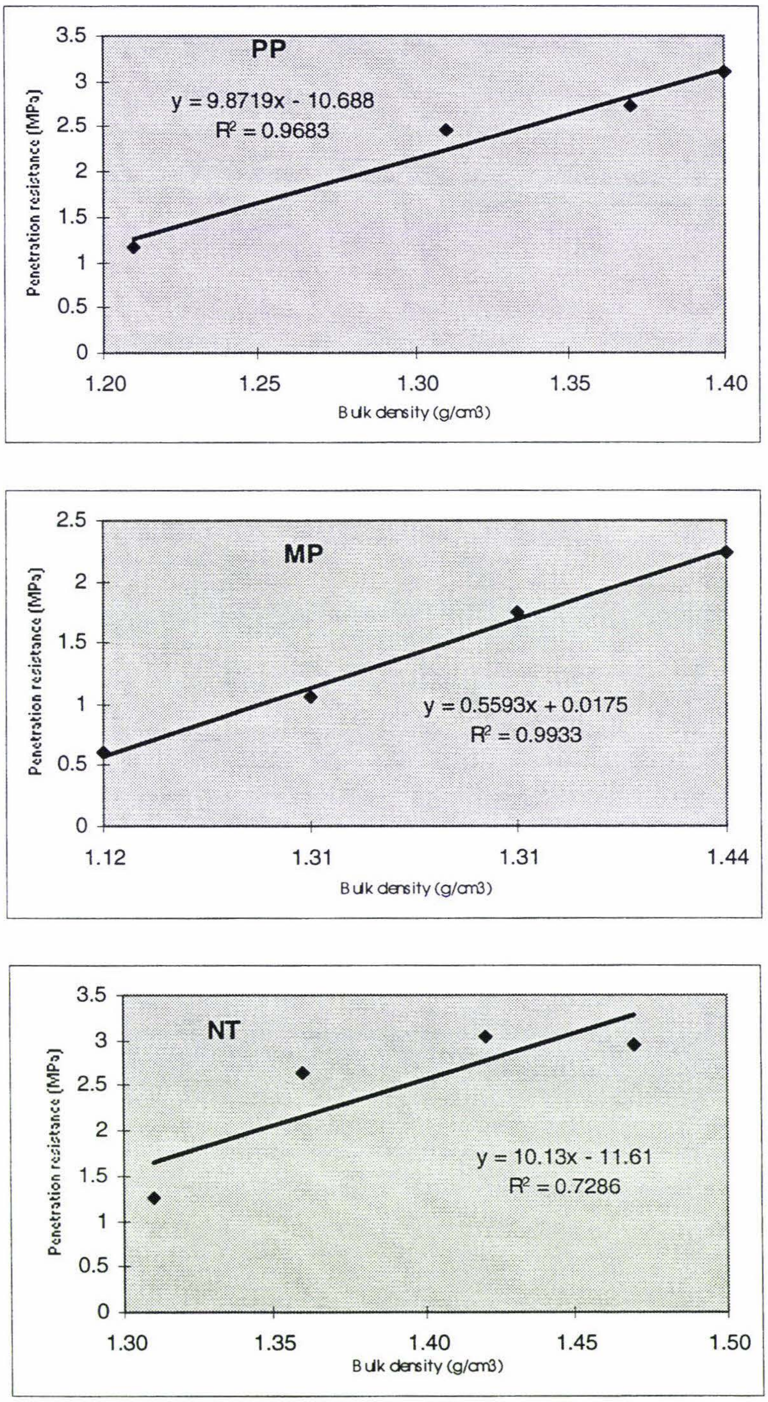


Figure 4.3 Regression analysis between soil bulk density (g/cm^3) and soil penetration resistance (MPa) on the top 20 cm soil layer under PP, MP and NT management measured during early winter oats growing season 1999

Even though soil bulk density was greater for no-till systems compared with tilled systems in the experimental fields of Sauer et al. (1990), Horne et al. (1992), Karlen et al. (1994) and Hussain et al. (1998), water retention and infiltration for the no-till soils were as great or greater than for the tilled soils. This was attributed both to a more stable soil structure in the no-till system and to an increase in the number of continuous earthworm channels connected to the soil surface. This also seemed to be the case in the current study as the results of aggregation stability experiments discussed later in section 4.3.1.

4.2.4 Water content

Soil cores used for bulk density measurement were also used for determining water content. Table 4.5. shows the effects of the soil tillage practices on soil water content while the detailed raw data and statistical analyses are presented in Appendix 1.4.

Table 4.5 Effects of tillage practices and cropping regime on soil water content (%) (measured on 27th April 1999 during early winter oats growing season)

Soil depth (cm)	Treatments*			$LSD_{0.05}$
	PP	MP	NT	
0-5	16.98 a	17.40 a	18.89 a	n.s.
5-10	17.22 b	19.19 ab	22.26 a	4.149
10-15	17.43 b	20.63 ab	23.04 a	3.542
15-20	16.36 b	19.17ab	22.05 a	4.112
Average	16.99 b	19.10 b	21.56 a	2.129

Values followed by the same letter in each row are not significantly different (P<0.05)
**) PP=Permanent pasture; MP=Moldboard plough; NT=No-tillage*

There was no significant difference among all the treatments in the top 5 cm soil depth. Overall, the NT plots appear to have the highest water content values at all depths compared to the other two treatments. Contrastingly, the lowest values were found under the PP treatment. The statistical analysis showed the NT to be higher (P<0.05) as compared with the PP treatment at depths below 5 cm, while it was similar (P<0.05) with the MP treatment. Taking the cumulative value from four depths it confirmed the water content to be significantly higher under the NT compared to the MP and PP.

The results clearly indicate that significantly higher water retention occurred on the NT plots than the PP and MP especially for the soil layers of 5-10, 10-15 and 15–20 cm. The cumulative water content data (0-20 cm), also indicates this difference. This evidence could be closely associated with a higher water-filled porosity under the NT than PP and MP as already mentioned before. Previous work using the same plots by Guo (1997), also concluded the NT to maintain high soil moisture.

The difference between the two studies lays on the experimental fact that PP plots during Guo's study contained significantly more soil water than NT whereas the current study shows the opposite. There should be an increase in water retention under PP treatment related to its higher organic C content (refer to Table 4.12) but it was unlikely to occur. It was possible that more water was lost through evapotranspiration in the pasture plots while in the NT plots the loss was inhibited by the high amount of residue left on the surface. This allowed higher conservation of soil moisture in the root zone.

Regression analysis between the soil water content and soil penetration resistance indicated no correlation under PP treatment while a moderate and good correlation was found for the MP ($R^2 = 0.4449$) and NT ($R^2 = 0.7348$) respectively. Low water retention found in the PP plots was presumably the affecting factor for such a poor correlation. Instead, the high level of aggregates formation found in pasture soils, as will be described later, was probably the key contributing factor to the high penetration resistance in the PP soils. The details of the regression analyses are shown in Figure 4.4.

Soil moisture under various tillage treatments has been the subject of numerous studies. Karlen et al. (1994) reported more pore space with moldboard and chisel ploughing than with no-till; however, more water filled and residual pores were found in the no-till. They suggested that 12 years of continuous no-tillage developed a structure with small pores and an increase in plant available water as a result of this change in pore size distribution.

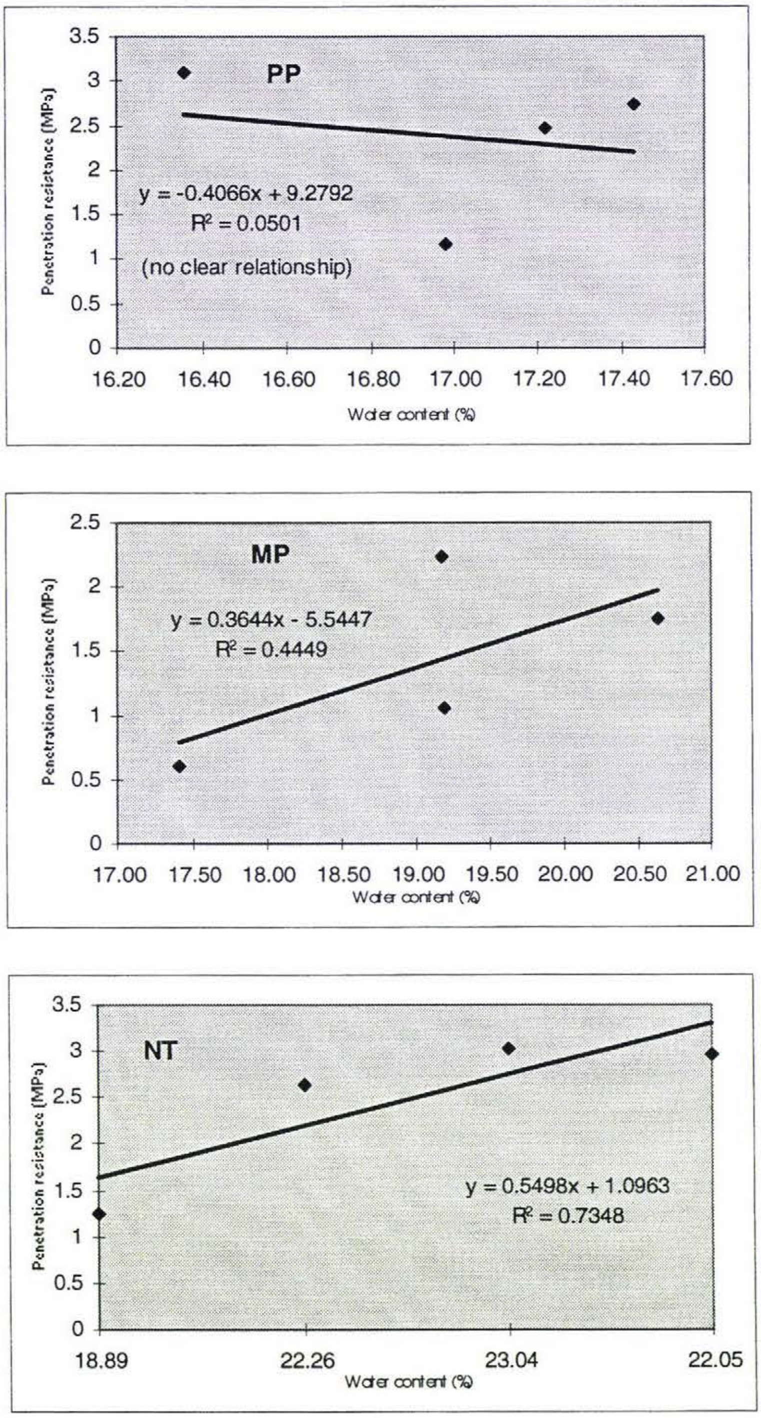


Figure 4.4 Regression analysis between soil water content (%) and soil penetration resistance (MPa) on the top 20 cm soil layer under PP, MP and NT management measured during early winter oats growing season 1999

Hussain et al (1998), in a study on moderately well drained silt loam, found no significant differences in water-adjusted cone index and soil water content at 25 days after planting (DAP) under NT, CP, and MP. However, at planting in the following year, they found higher soil water contents with the NT treatment compared with CT and MP systems in the 0-15 cm soil layer. This was attributed to the presence of higher amount of soil residue on the soil surface, which improved infiltration, decreased runoff, and restricted evaporation. Soil water contents were lower at midseason than at 25 DAP in 1996 for all tillage treatments as a result of extraction of soil water by the soybean crop.

4.2.5 Crop dry matter

Three cropping seasons i.e. two summer maize cropping seasons and one winter oats cropping were established during the course of this study. The results are given in Table 4.6 and the detailed raw data and the statistical analysis is shown in Appendix 1.5.

Table 4.6 Effects of soil tillage systems on crop dry matter (grams)

Crop/date	Treatment *		$LSD_{0.05}$
	MP	NT	
Maize 12/02/99 **	83.58 b	349.58 a	78.88
Oats 11/06/99 ***	126.70 a	119.58 a	n.s.
Maize 16/02/00	246.18 a	271.45 a	n.s.

Values followed by the same letter in each row are not significantly different (P<0.05)
**) MP=Moldboard plough; NT=No-tillage*
***) Maize data previously reported by Hou (1999), was measured per plant basis and not on area basis, because unusually dry climatic conditions reduced plant establishment that season (data based on 10 plant DM)*
****) Oats samples were taken using quadrat method*

The NT treatment appeared to result in higher maize dry matter than the MP, however a significant difference was only found in the 1999 season. On the other hand, the oats resulted in similar dry matter yield between the two tillage systems.

The soil physical conditions created by the NT treatment under the design of this trial have suited the optimum requirements for plant growth and production. The dry matter yield of winter oats for instance confirmed similar results for the same plots reported by Guo (1997). In a similar long term summer maize-winter oats rotation, Hughes et al.

(1992) found no significant differences in oats dry matter between continuous zero tillage treatment and the minimum and fully tilled treatments.

Interestingly, the 1999 maize dry matter reported by Hou (1999) was significantly higher in the NT plots than MP plots. The reason for this marked difference were reported to be the dry summer month than usual. Because the no-tillage promotes high soil moisture conservation, this probably led to healthier plants in the NT as compared with the conventionally cultivated soil. Hughes et al. (1992) by contrast, found a 10-year average of maize dry matter to be significantly lower under zero tillage than fully tilled treatment. In a similar trial, Ekeberg and Riley (1997) reported a generally good performance of cereals and potatoes with shallow or minimum tillage. And this was attributed to the favourable soil physical conditions, which have been established, and to the successful control of weeds.

Studies previously cited (Chapter 2, section 2.2.3.2) have reported that conservation tillage have performed well in terms of DM yields on heavy soils (Conacher and Conacher, 1986) and on light free-draining soils (Janson, 1984) and even out-yielded conventional tillage practices (Dickson and Ritchie, 1996; Barber et al., 1996). Conversely, less crop yields (Acharya and Sharma, 1994) and variable results (Lindwall et al., 1994) were reported under no-tillage treatment as compared with conventional tillage systems. In essence, as far as crop yields are concerned, it is difficult to establish any clear and major advantage of no-tillage. However, in general, given favourable conditions are met, such as adequate soil water, sufficient rainfall and good drainage, reasonable soil feritility and good weed control, crop yields under conservation tillage can be equal to or higher than under conventional tillage systems.

4.3 Laboratory Measurements

4.3.1 Aggregation stability

Wet-sieving method was used to assess the stability of soil aggregates from the experimental plots. The method appeared to successfully characterize the differences resulting from different soil tillage treatments. The sieving duration employed was 30 minutes as this was part of the standard procedure for aggregation stability experiments at the Landcare Research, New Zealand. The stability of the aggregates, ranging from <5 to >2 mm, was determined for two major layers of the soil profile, 0-10 and 10-20 cm soil layers from each plot.

Table 4.7 The effects of tillage practices on soil water-stable aggregates of the 0-10 cm soil layer using 30 minutes wet-sieving (%)

MWD** (mm)	Treatments*			$LSD_{0.05}$
	PP	MP	NT	
>2	54.7 a	4.8 b	37.4 a	13.39
1-2	14.3 b	8.6 b	22.5 a	6.41
0.5-1	6.1 b	12.7 a	10.8 a	2.65
<0.5	24.8 b	73.8 a	29.2 b	7.52

Values followed by the same letter in each row are not significantly different (P<0.05)
**) PP=Permanent pasture; MP=Moldboard plough; NT=No-tillage*
***) MWD = mean weight diameter*

For the upper layer of 0-10 cm the results demonstrated that the PP plots appeared to have the highest macroaggregate stability (MWD > 2 mm = 54.7%). However, the statistical analysis ($P \leq 0.05$) showed the PP to be insignificantly different compared with the NT (MWD > 2 mm = 37.4 %). According to the analysis, macroaggregates for both the PP and NT were markedly higher than the MP (MWD > 2 mm = 4.8 %).

On percentage basis, the total aggregates remaining on sieve for the PP, MP, and NT were 75.2, 26.2, and 70.8 % respectively (Figure 4.5). This percentage is a sum of the aggregates remaining at the three sieves employed in the experiment. The data and details of the statistical analyses presented in the table are of equal importance. However, for the convenience of comparison among treatments, aggregates with diameters above 2 mm (macroaggregates) and below 5mm (microaggregates) are indeed the most indicative values of the extent the aggregates were able to resist the disruptive and erosive force of water.

As for the subsoil, the 10-20 cm soil layer in this context, greater portion of aggregates above 2 mm was retained on the sieves under the PP treatment (Table 4.8). For this range of aggregates, the PP differed significantly with MP and NT. The effects on the smaller aggregates (1-2 mm, and 0.5-1mm) were rather mixed. However, the MP produced consistently the lowest values at all ranges of aggregates.

Summing up all the retained aggregates for the PP, MP, and NT treatments, the percentages were 54.8, 24.2, and 44.6 respectively. Relating these respective values to the original sample of aggregates it is easy to extrapolate that the microaggregates (<5 mm) were screened out and eroded during the sieving treatment. Overall, the results suggest that the effects exerted by the treatments on the subsoil were of similar pattern although differences were not as well defined as the surface soil (Figure 4.6).

Table 4.8 The effects of tillage practices on soil water-stable aggregates of the 10-20 cm soil layer using 30 minutes wet-sieving (%)

MWD** (mm)	Treatments*			$LSD_{0.05}$
	PP	MP	NT	
>2	21.3 a	3.5 b	10.7 b	7.66
1-2	20.8 a	8.8 b	17.5 a	3.93
0.5-1	12.6 b	11.9 b	16.4 a	3.21
<0.5	45.2 b	75.8 a	55.4 b	10.38

Values followed by the same letter in each row are not significantly different (P<0.05)
**) PP=Permanent pasture; MP=Moldboard plough; NT=No-tillage*
***) MWD = mean weight diameter*

In separate experiments the 60 minute wet-sieving was also used. For the topsoil (0-10 cm), the results show similar pattern as for the 30-minute wet-sieving previously described (Table 4.9). The MP soils were consistently and significantly less stable compared to the PP and NT soils which were similar amongst themselves. Between the PP and NT, no significant differences were found at all range of the aggregates measured. The total percentage of the aggregates remaining on the sieves after 60 minutes sieving were 58.8%, 21.2%, and 53.5% for the PP, MP, and NT respectively (Figure 4.7).

Table 4.9 The effects of tillage practices on soil water-stable aggregates of the 0-10 cm soil layer using 60 minutes wet-sieving (%)

MWD** (mm)	Treatments*			$LSD_{0.05}$
	PP	MP	NT	
>2	21.3 a	3.7 b	16.1 a	6.98
1-2	25.1 a	7.3 b	23.5 a	6.01
0.5-1	12.4 a	10.2 b	13.9 a	3.12
<0.5	41.2 b	78.8 a	46.5 b	11.56

Values followed by the same letter in each row are not significantly different (P<0.05)
**) PP=Permanent pasture; MP=Moldboard plough; NT=No-tillage*
***) MWD = mean weight diameter*

Table 4.10 The effects of tillage practices on soil water-stable aggregates of the 10-20 cm soil layer using 60 minutes wet-sieving (%)

MWD** (mm)	Treatments*			$LSD_{0.05}$
	PP	MP	NT	
>2	11.5 a	3.5 b	11.7 a	6.10
1-2	16.9 a	7.6 b	17.4 a	2.83
0.5-1	12.7 a	10.9 b	14.3 a	3.19
<0.5	58.8 b	78.0 a	46.5 b	9.27

Values followed by the same letter in each row are not significantly different (P<0.05)
**) PP=Permanent pasture; MP=Moldboard plough; NT=No-tillage*
***) MWD = mean weight diameter*

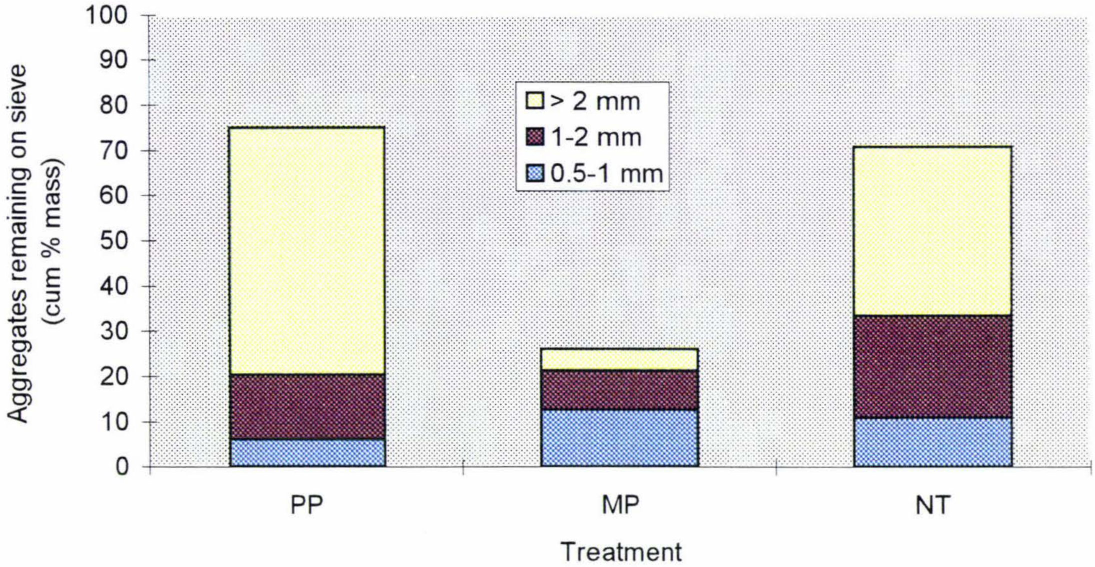


Figure 4.5 Water-stable aggregates remaining on sieve for the top 0-10 cm soil layer under 30 minutes wet-sieving duration as affected by tillage and pasture management

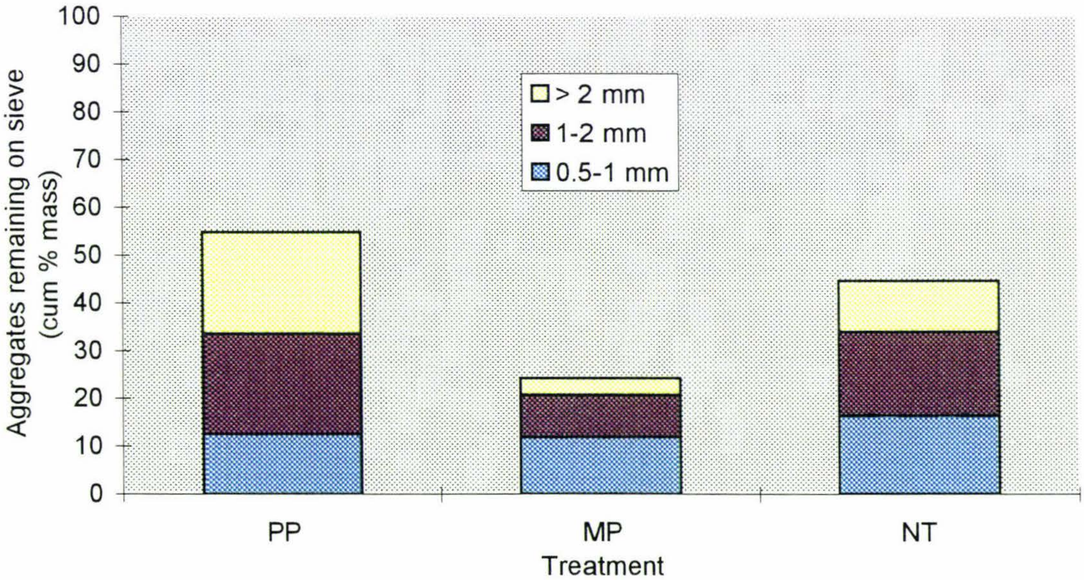


Figure 4.6 Water-stable aggregates remaining on sieve for the 10-20 cm soil layer under 30 minutes wet-sieving duration as affected by tillage and pasture management

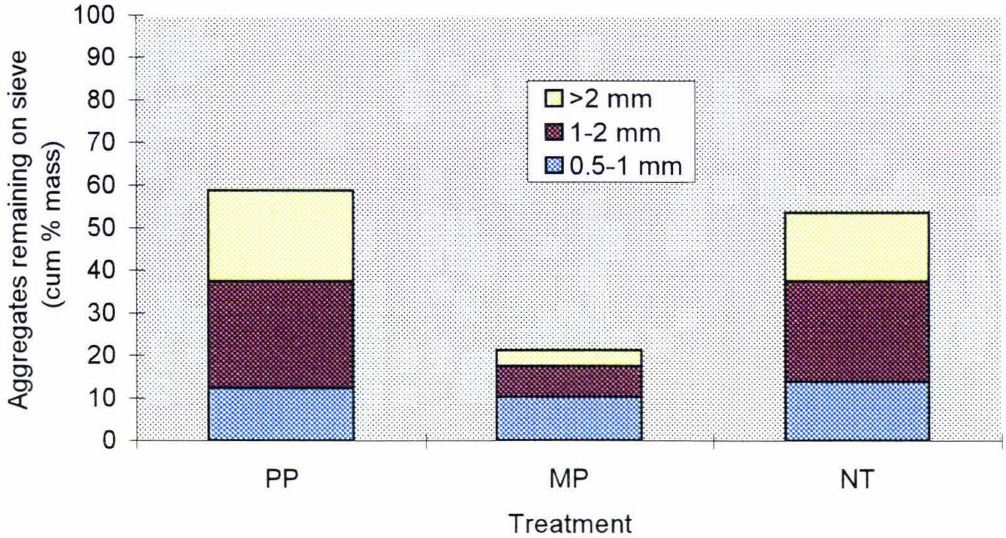


Figure 4.7 Water-stable aggregates remaining on sieve for the top 0-10 cm soil layer under 60 minutes wet-sieving duration as affected by tillage and pasture management

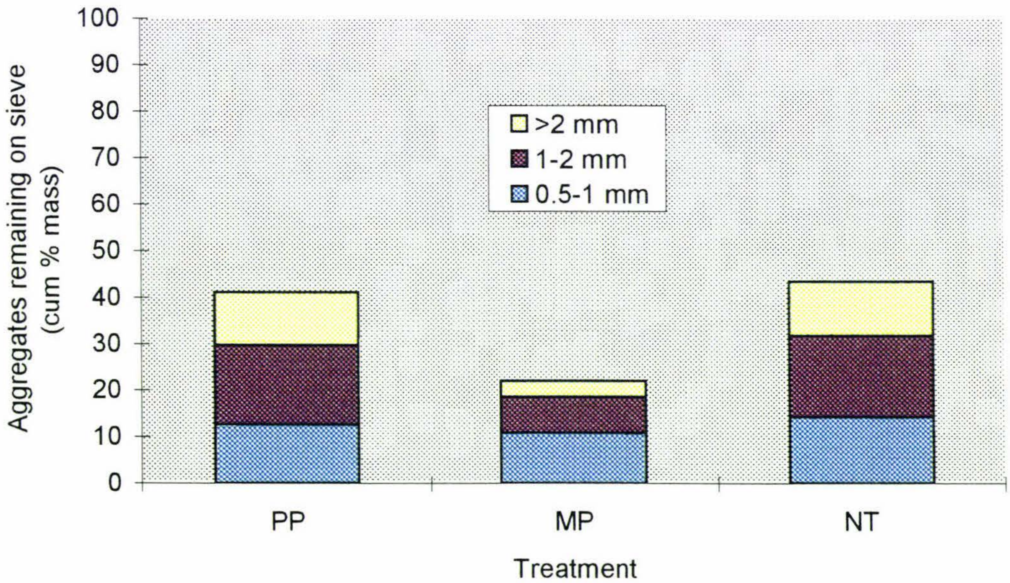


Figure 4.8 Water-stable aggregates remaining on sieve for the 10-20 cm soil layer under 60 minutes wet-sieving duration as affected by tillage and pasture management

Similar pattern as the topsoil also occurred for the subsoil (Table 4.10 and Figure 4.8). It is assumed from the results that this layer has been to a lesser extent affected by the soil mechanical treatments as well. The resistance against the force of water was reflected by the amount of aggregates remaining on the sieve for the PP, MP, and NT, which were 41.2, 22, and 53.5 % respectively. Interestingly, at this layer, the NT appeared to be rather more stable although not significantly compared to the PP. Also it appeared that the 60 minutes sieving duration drastically reduced the stability of the topsoil down to an extent similar to the subsoil, specifically with regard to MP and NT soils (Figure 4.8).

Previously there were no experiments conducted on aggregate stability measurement for the Massey tillage trial plots to be considered as point of reference for this study. Therefore, pasture plots in this discussion served as control treatment for the tillage system comparisons. Another comparable results could be those obtained from the 60-minute sieving duration. However, this method was employed to explore simulated effects of long-term rainfall as shown in section 4.3.2. Therefore, further discussion is focused on the results of the 30-minute wet-sieving experiment essentially with respect to the topsoil, and also to compare these results with the findings of other similar studies. In addition to that, previous works using soils in Manawatu region, New Zealand reported by Horne et al. (1992) and Sparling et al. (1992) could reasonably serve as reference point.

As has been stated earlier, this study found the topsoil aggregates remaining on sieves for PP, MP and NT were 75.2, 26.2, and 70.8 % respectively. Comparing with the results reported by Horne et al. (1992), there are similarities in aggregate stabilities between the two studies especially under pasture treatment and also in the order in which it was affected by the soil tillage treatments. They found 'the retained all sieves index' was 80%, 46% and 58% for permanent pasture, fully tilled, and zero tilled treatments respectively. Although only using a short 10 minutes sieving duration, their results suggested that zero-tillage soil had decreased aggregate stability relative to the soil under permanent pasture. Contrastingly, only a small difference in aggregate stability was observed between the fully tilled and zero-tillage soils. In another

Manawatu silt loam study, Sparling et al. (1992) also reported that after 14 years of continuous cultivation following pasture conversion, over 85% of the aggregates (0-20 cm depth) were less than 0.5 mm, compared with 20-49% under pasture. In a more recent study, Haynes (1999) also found aggregation stability to be higher under long-term permanent pasture and zero tilled annual grass than long-term arable cropping and conventionally cultivated annual grass.

Using the same sieving time duration (30 minutes), Beare et al. (1994) also reported surface samples to be significantly influenced by tillage practices. Macroaggregates above 2000 μm in diameter made up the largest percentage of the whole soil, and these aggregates were nearly 1.5 times greater ($P<0.05$) in no-tillage than in conventional tillage. The smaller aggregates made up a greater proportion of the surface soil under conventional tillage than no-tillage. No significant differences in the distribution of water-stable aggregates from deeper soils (5-15 cm) of both the NT and CT were noticed. These findings partly concur with those resulted from the present study.

The aggregation stability values resulted from this study are believed to be associated with the soil organic matter induced by the tillage and pasture treatments. As shown in Table 4.13 for the top 0-10 cm soil layer, organic C under the MP treatment was significantly lower compared to the NT and PP treatments. And this could be the reason for the lower stability of soil aggregates under MP especially those aggregates of above 2 mm and 1-2 mm of diameter as previously suggested in Table 4.7. For macroaggregates (> 2 mm) the percentage was of 11 and 8 times higher in the PP and NT as compared with the MP respectively. As for the 10-20 cm soil layer similar order was observed. PP has consistently and significantly higher aggregates of 1-2 mm and > 2 mm MWD than the MP. As for the >2mm MWD aggregates for NT and MP the differences were insignificant. This is not unexpected given the similarities in organic C and organic N for both treatments for this respective layer as indicated in Table 4.14.

While Horne et al. (1992) found only small differences in organic carbon content between treatments in the 0-20 cm soil depth, Watts and Dexter (1997) using a simulated tillage found an increase in water stable aggregates with increase in soil organic carbon. Findings of the latter study appeared to confirm earlier data reported by

Sparling et al. (1992). Their results suggested a strong relationship between the proportion of water-stable macroaggregates and microbial C, much stronger than that between macroaggregate stability and organic C.

4.3.2 Runoff and leachate

A pilot experiment showed a number of errors and inadequacies which were related to inadequate handling procedures during soil cores extraction from the field and during laboratory experimentation set up. The results of the formal experiment, as given in the Tables 4.11 and 4.12, show wide variability in data. Given the small quantities of either water runoff or leachate, and for simplification in calculations and comparison, volumetric unit (ml) was used instead of the level/height unit (mm) of water commonly used in literature.

4.3.2.1. Water runoff

The statistical analysis of data show insignificant differences in water runoff under all the treatments with exception for the 40 minutes rainfall data. Given large LSD's obtained from the analysis, it is obviously an indicator of huge variability among the replications under each treatment. The inadvertent measurement errors which occurred during the experiment might have somewhat influenced the results. These results, however, largely confirm the findings of previous studies described in chapter 2 (section 2.3.4). The detailed data and statistical analyses of water runoff are given in the Appendix 2.2.1.

The trend of increase in runoff over time during rainfall appears to be confirmed by the regression analysis as shown in Figure 4.10. Apart from a moderate correlation between water runoff and rainfall duration found under NT treatment (R^2 = 0.3784), a good relationship was found under PP (R^2 = 0.629) and MP (R^2 = 0.969).

Table 4.11 The effects of tillage practices and permanent pasture on water runoff under a rainfall simulator

Time (minutes)	Runoff (ml)			LSD $_{0.05}$
	PP*	MP	NT	
10	6.15 a	14.13 a	9.15 a	n.s.
20	5.23 a	26.35 a	14.73 a	n.s.
30	10.25 a	33.80 a	18.80 a	n.s.
40	12.00 b	66.50 a	13.55 b	44.60
50	11.78 a	77.00 a	14.05 a	n.s.
60	10.50 a	92.13 a	19.15 a	n.s.

Values followed by the same letter in each row are not significantly different (P<0.05)
Soil corer size: 300 mm long x 200 mm wide x 150 mm
**) PP=Permanent pasture; MP=Moldboard plough; NT=No-tillage*

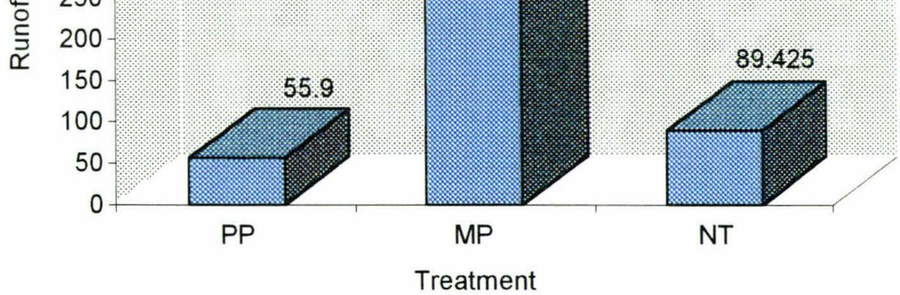


Figure 4.9 The effects of tillage practices and permanent pasture on total water runoff during one hour simulated rainfall

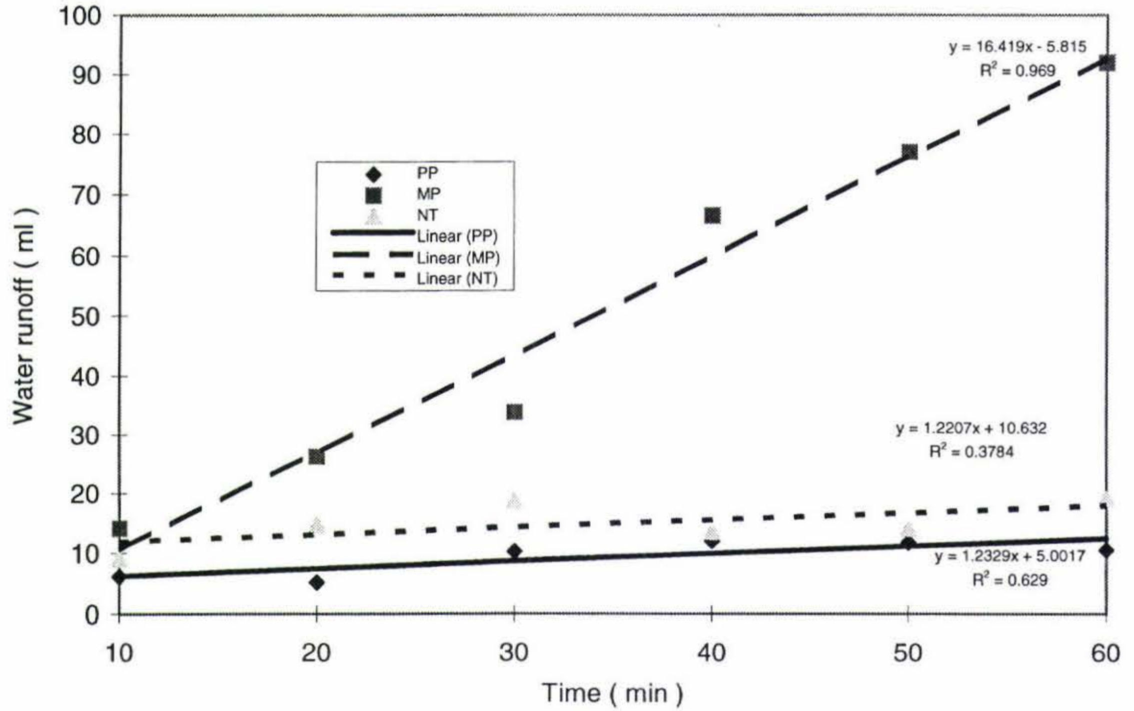


Figure 4.10 Regression analysis between water runoff and tillage practices and pasture management over 60 minutes of rainfall duration

As expected, the highest total runoff water obtained after one-hour rainfall was under the MP treatment (Figure 4.9). Earlier studies at the same tillage trial by Guo et al. (1999b) using rainfall simulator, and Hou (1999) using field measurement, indicated MP treatment to have caused more surface water runoff than the other two treatments. By contrast, less water runoff was found in NT plots, which indicated that more water infiltrated through the soil profile, as was clearly indicated by highest occurrence in leachate. Choudhary et al. (1997) compared moldboard plough, chisel plough, and no-tillage treatments, reported soil erosion and runoff to be markedly affected by these treatments in the order of NT<CP<MP. Soil splash was reported to be 2.5-fold higher under the MP treatment than the other two treatments. The present study generally reflected these findings.

Data regarding soil sediment in water runoff are not available from the current study due to very little amount of runoff collected for some intervals of time under all the treatments. However, early sediment data from the same plots have demonstrated the MP to cause soil losses as much as 100 times higher than those from NT and PP (refer to the first experiment of Guo, 1997). Early, in a sprinkler infiltration study, Karlen et al. (1994) reported that sediment concentrations ($P \leq 0.02$) and estimated soil loss ($P \leq 0.07$) from the long-term no-till treatment were significantly lower than those from the moldboard plough treatment. The amount of surface cover presumably contributed to less soil loss from the untilled plots. Their study also suggested the surface cover to have increased the water stability aggregates, a predominant factor assumed to affect water entry and resistance to soil degradation.

Soil losses through surface water runoff also imply losses of nutrients. The previous study using the same soils have indicated losses of nutrients to be markedly affected by tillage practices and pasture management. Guo et al. (1999b) reported losses of N, P, and K were significantly different in the order of MP>NT>PP. These results, especially comparing the NT and MP plots, are in line with those reported by Lal (1997), who suggested that despite surface application of fertilizers, runoff from untilled watershed had lower concentrations of plant nutrients than that from plough-tilled watershed. Lal's study also concluded that well-maintained pastures effectively reduced runoff and nutrient concentrations in runoff water.

4.3.2.1. Leachate

The leachate experiment results given in the Table 4.12 show a reverse trend from those of runoff water data. The results generally indicate similar effects of tillage practices as those from previous studies. The lowest total volume of leachate collected during one hour-simulated rainfall was found under MP, and by contrast, the NT produced the highest amount of leachate (Figure 4.11). The increase of water leachate collected over time is shown in the regression analysis data as given in Figure 4.12, with exception of MP. A linear relationship existed between water leachate and rainfall duration both under the PP (R^2 = 0.3038) and MP (R^2 = 0.8847). The detailed data and statistical analyses of water leachate are given in the Appendix 2.2.2.

Guo (1997), using the same plots three years earlier, found significantly higher amounts of water leachate under the NT and PP than the MP. Similarly, Choudhary et al. (1997) also reported water leachate to be markedly affected by moldboard plough (MP), chisel plough (CP) and no-tillage (NT) treatments which were in the order of NT>CP>MP. In a lysimeter study, Lal (1997) suggested that soil structure deteriorated very rapidly in cropped lysimeters, owing to reduction in soil organic contents and decrease in earthworm activity. Lal also found out that cropped lysimeters exhibited hard-setting characteristics and had drastically low infiltration rate, low internal drainage, and consequently low leaching losses.

Early findings from both Guo et al. (1999b) and Lal (1997) suggested that higher nutrient losses were found in water leachate than water runoff. Guo suggested that the tillage and pasture treatments had markedly affected the nutrient 'losses' through leaching.

Table 4.12 The effects of tillage practices and permanent pasture on the amount of leachate under a rainfall simulator

Time (minutes)	Leachate (ml)			$LSD_{0.05}$
	PP*	MP	NT	
10	181.75 b	250.00 a	253.75 a	59.79
20	296.25 a	296.25 a	367.50 a	n.s.
30	290.00 a	267.50 a	387.50 a	n.s.
40	271.25 b	245.00 b	418.5 a	131.02
50	275.00 b	270.00 b	443.75 a	151.87
60	286.25 b	263.75 b	472.50 a	172.02

Values followed by the same letter in each row are not significantly different (P<0.05)
Soil corer size: 300 mm long x 200 mm wide x 150 mm
**) PP=Permanent pasture; MP=Moldboard plough; NT=No-tillage*

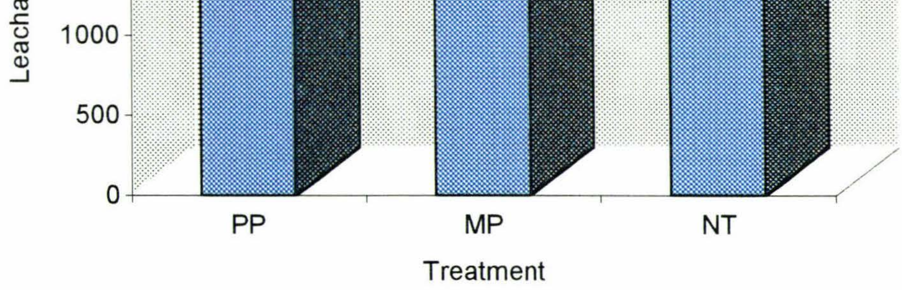


Figure 4.11 The effects of tillage practices and permanent pasture on total amount of leachate during one hour simulated rainfall

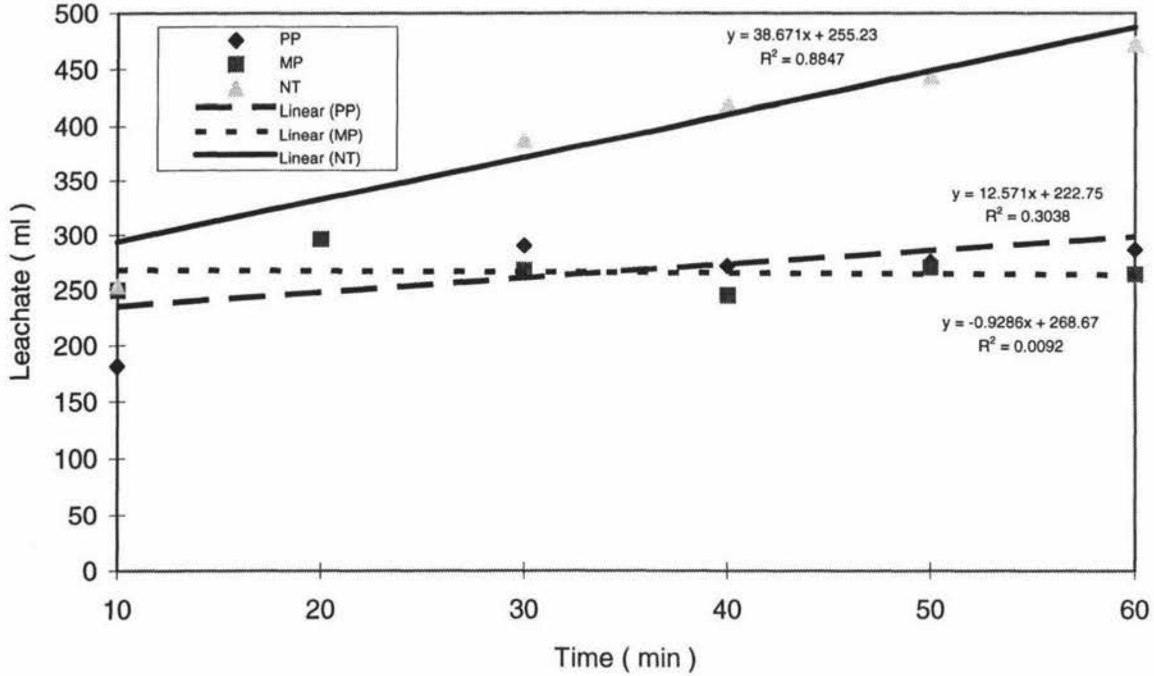


Figure 4.12 Regression analysis between water leachate and tillage practices and pasture management over 60 minutes of rainfall duration

The order in which the nutrient losses (N, P, K) through leaching were affected was PP>NT>MP. Comparing the NT and MP treatments, Guo's data showed 'losses' of N, P, and K through leaching under NT were about 4 up to 6 times higher than those from MP treatment. A major concern apart from the 'losses' of such vital crop nutrients, is the higher potential contamination of groundwater by such nutrients and other chemicals derived from applied pesticides. Because conservation tillage practices, and specifically direct-drilling, relies mainly on herbicides use for weed control, the risk of groundwater contamination may be higher under these practices than conventional tillage practices. However, there is no evidence yet of this phenomenon happening as most herbicides decompose in the soil. A brief review of literature regarding interaction of pesticides with tillage practices has been described in the previous chapter. However, information regarding this issue is widely available in literature elsewhere.

4.3.3 Soil pH, Total C and N

Table 4.13 indicates the analysis of selected chemical indicators in the topsoil affected by three different soil treatments. Soil pH was significantly lower (acidic) in NT soils compared to the other two treatments ($P<0.05$). For comparison of cultivation effects on total C and N/ha basis, total C and N values were recalculated using the respective bulk density data. Organic C was found in the order of PP=NT>MP with a significantly higher level under the PP and NT compared to the MP. The MP also shows significantly lower organic N content compared to the PP and NT.

Table 4.13 Selected soil chemical indicators on the topsoil (0-10 cm) as affected by different soil tillage practices

Indicators	Treatments*			$LSD_{0.05}$
	PP	MP	NT	
Soil pH (H_2O)	5.31 a	5.30 a	5.10 b	0.170
Total C (%)	2.75 a	2.17 c	2.43 b	0.221
(t/ha)	34.61 a	26.33 b	32.44 a	3.344
Total N (%)	0.24 a	0.21 b	0.22 ab	0.027
(t/ha)	3.06 a	2.49 b	2.96 a	0.345

Values followed by the same letter in each row are not significantly different (P<0.05)
**) PP=Permanent pasture; MP=Moldboard plough; NT=No-tillage*

As for the subsoil (10-20 cm), similar evidence with the topsoil was observed in regard with soil pH. For this layer, interestingly the organic C and organic N contents were rather similar under all the treatments as no significant differences were found (Table 4.14).

Table 4.14 Selected soil chemical indicators on the subsoil (10-20 cm) as affected by different soil tillage practices

Indicators	Treatments*			$LSD_{0.05}$
	PP	MP	NT	
Soil pH (H_2O)	5.32 a	5.26 a	5.10 b	0.136
Total C (%)	1.84 a	1.93 a	1.80 a	n.s.
(t/ha)	25.41 a	26.51 a	25.99 a	n.s.
Total N (%)	0.17 a	0.19 a	0.17 a	n.s.
(t/ha)	2.35 a	2.54 a	2.49 a	n.s.

Values followed by the same letter in each row are not significantly different (P<0.05)
**) PP=Permanent pasture; MP=Moldboard plough; NT=No-tillage*

4.3.3.1 Soil pH

Soil pH at depths, 0-10 cm and 10-20 cm, showed a significantly lower level under the NT treatment compared to the other two treatments. This suggested that the adoption of NT over a long-term appeared to decrease soil pH following conversion from pasture to cropping. This result is also in line with that reported by Choudhary et al. (1997) which indicated that cropping using direct-drilling methods over many years may cause soil surface to become more acidic. This may be due to the accumulation of surface applied fertilizers stratifying the soil surface. At the 10-20 cm soil depth, the reason for such a low pH could be due to movement of organic acids from decomposing residues.

An insignificant effect of tillage treatments on soil pH has been reported for the first year (Guo, 1997) and after three years (Aslam, 1998) of cropping for the tillage trial.

However, a significant change in soil pH has occurred after 5 years of continuous cultivation following conversion from pasture. This may be an early indication that this level of pH under NT could prevail longer term or it may be a start of decline in soil pH. This data concurs with earlier data by Dalal et al. (1991), who studied tillage effects over 20 years and found that soil pH was substantially lower under zero-tillage (ZT) than conventional tillage (CT) treatment in the 0-25 and 25-50 mm layers by 0.23 and 0.33 units respectively. This pH level was further depressed by residue retention and fertilizer N application. They also found soil pH to be significantly and negatively correlated with both organic C ($r = -0.66$, $P<0.001$) and total N ($r = -0.71$, $P<0.001$).

4.3.3.2 Total C

The changes in total organic C are more evident in the 0-10 cm soil depth. Both the MP and NT have resulted in a marked decline in total C level compared to PP. Total C losses from native soils and long-term pasture following cropping were also reported by similar studies (Sparling, 1992; Aslam et al., 1999, Haynes, 2000). At the 10-20 cm soil layer, the total C level is lower than that of the upper layer and distributed quite equally in all plots as only insignificant differences were noticed among the treatments. Overall, at 0-20 cm soil layer, a total C of 60.02, 52.84 and 58.43 t/ha were estimated for PP, MP and NT respectively. Thus, the decline of total organic C after 5 years of continuous double-cropping was almost 12% in the MP plots and 2.65% in the NT plots.

Comparing pasture to continuous maize cropping at four different soils in the Manawatu region, New Zealand, Sparling et al. (1992) found a significant decline in both organic C and microbial C. In a Manawatu silt loam for example, their results indicated a decline of 61% of organic C and 68% of microbial C after 14 years of continuous cultivation following conversion from pasture land. Aslam et al. (1999), similarly, reported a decline of microbial C concentration by 29% within two years of converting permanent pasture to continuous double-cropping. In a recent publication, Haynes (2000) reported the effects of long-term pasture and arable cropping on soil labile organic matter. His study found out that with increasing period under pasture, soil organic content increased and the amounts of labile organic matter extracted also increased.

The total C results for the upper 0-10 cm soil layer indicate a significantly higher amount of total C (18.8%) in the NT plots than the MP plots. The high retention of crop residue and less soil disturbance on the NT plots may have resulted in such higher level of C. Previous results from the same plots also suggest a higher total C level (19%) in the NT soils compared to the MP soils (Aslam, 1998). Beare et al. (1994) and Campbell et al. (1996) have also reported similar results. The former study, comparing NT and CT reported that the whole-soil organic C was 18% higher in the NT (30.7 mg C ha^{-1}) than CT (26.1 mg C ha^{-1}). In the latter study, it was found that cropping frequency did not affect soil organic C, but soil C content was greater under NT than under mechanically tilled continuous wheat (cont. W) and fallow-wheat (F-W) rotations. The effects were apparent in the 0-15 cm soil depth. According to Sparling et al. (1992), the marked organic C content decline in the cultivated soils is caused mainly by the reduced organic matter inputs and the decomposition of existing organic matter enhanced by tillage.

4.3.3.3 Total N

Increased use of N-fertilizers in crop production has been accompanied by increased amounts of N compounds in the general soil water environment. The results (Table 4.13) for the upper 0-10 cm clearly indicate total N level to be significantly higher in the PP and NT plots compared to the MP plots. This can be partly attributed to the differential fertilizer N applications received in the past. At 10-20 cm soil depth, the total N was lower than the topsoil N level, and similar to C, it was equally distributed in all plots.

The above results are in line with the study of Biederbeck et al. (1997) who found a significantly higher potentially mineralizable N under zero-tillage compared to conventional tillage system. Their study also suggested that tillage depressed microbial populations and the ability of the soil to mineralize C and N in the 0-5 cm soil layer. A recent report by Aslam et al. (1999) also demonstrated a significantly higher ($P < 0.05$) microbial biomass N under the PP and NT treatments than MP treatment. A close correlation between microbial biomass N and anaerobic mineralizable N was indicated by Dalal et al. (1991), who also suggested that the former provide a labile source of N in soil. The labile fractions, as stated by Haynes (1999), are important components of organic matter quality, which influence crop productivity. Mineralizable N for instance, can contribute greatly to crop N requirements but also to leaching losses of nitrate to groundwater.

For pasture in particular, the study of Haynes (1999) demonstrated the positive effect that a short-term (5 years) pasture can have on soil organic matter quantity and quality and its attendant benefits on N fertilizer and soil structure. Their results also indicated that the particulate organic matter (POM) comprised a higher percentage of total aggregate N in surface soils of the NT than CT soils. Previous study by Campbell et al. (1996) also reported total N to be higher under NT than under tilled systems in continuous wheat and wheat-fallow rotations.

Low N level found in the MP plots is probably due to accelerated decomposition of organic matter induced by tillage, with concomitant release of N in excess of the needs of microbial biomass, which also decreases as the available C decreases. Early data from the same plots reported by Guo (1997) also suggest that N losses through surface runoff was twice as higher in the MP plots as in the NT and PP plots. One year later, Aslam (1998) reported a decline in microbial biomass N of 53% in the same MP soils at 0-5 cm soil layer. There could be other reasons for the decline of N level in the MP plots such as deep leaching or denitrification which warrant further examinations.

4.4 Summary

Experimental results have demonstrated that 5 years of continuous conventional tillage with moldboard plough (MP) and no-tillage (NT) have significantly affected some physical characteristics of the soils.

Penetration resistance was significantly lower in the MP plots, at the early oats growing season and within two weeks after land preparation, compared to the NT and PP plots. However, the trend reversed within six months, following grazing and spring fallow. Generally, there was a linear correlation between soil penetration resistance and soil depth.

Water infiltration rate measurement results over one year period indicated an average value significantly higher under the NT and PP treatments than MP treatment. Bulk density measured at the time of early oats planting season indicated a remarkably higher level at the top 0-5 cm soil layer in the NT compared to the MP plots. A substantially higher level (11%) of water content was found in the NT plots compared to that from the MP plot. The NT treatment produced comparable winter oats and summer maize dry matter yield with those under the MP treatment.

Regression analysis results, not unexpectedly, indicated a strong relationship between soil bulk density and soil penetration resistance. This relationship was indicated by R^2 values of 0.968, 0.993, and 0.729 for the PP, MP, and NT treatments respectively. Similar analyses indicated a strong relationship between soil water content and soil penetration resistance, except for PP treatment (R^2 = 0.050). The respective R^2 values found for the MP and NT were 0.445 and 0.735.

The NT soils were substantially more stable than the MP soils but similar to the PP soils. The macroaggregates (> 2 mm diameter) made up the largest proportion of the soil for PP (54.7 %) and NT (37.4%), whereas for MP the macroaggregates were 4.8%. The results also indicated that 73.8% of soil in the top 10 cm of MP plots had less than 0.5 mm water-stable aggregates.

Runoff and leachate experiments produced wide variability in results due to a number of factors. However the results clearly suggested that the MP treatment had caused more surface runoff than the other two treatments. By contrast, water runoff was lower in the NT plots, which was also reflected by the occurrence of more water leaching under this treatment compared to the MP treatment.

The NT soils were also slightly more acidic (lower pH) both at 0-10 and 10-20 cm soil layers. Both the MP and NT had resulted in a relative decline in total C level compared to the PP at the 0-10 cm soil layer. The decline of total C content in the 0-20 cm soil layer after 5 years of continuous double-cropping was almost 12% in the MP plots and 2.65% in the NT plots. Total N at the 0-10 cm soil layer was lower under the MP treatment compared to the other two treatments.

Chapter 5
Conclusions

5.1 General

Literature for this study has revealed that scientific advances and technological innovations in agriculture had contributed quite successfully in meeting a growing demand for food production. Adversely, the global food production system has at the same time overdrawn and degraded the natural resources upon which agriculture mostly depends.

Practical and empirical evidence also indicated that the most severe form of agricultural degradation is that caused by erosion and non-point source pollution. Judicious land use and choice of appropriate crop management would help reverse these degradative trends.

Numerous studies suggested soil tillage to play an important role in agricultural sustainability. It influences crop yields through its effects on soil properties that regulate nutrient and water supply, competition with pests, and co-restrictive biophysical and socio-economic constraints. Appropriate tillage methods differ among soils, crops, and climatic regions, and the choice depends on a range of interacting factors.

The literature also suggested a prevalence of soil degradation in many agricultural production and agroecology systems. To avert further degradation, the soil productivity balance must be shifted from degrading processes to conserving processes. Conservation tillage is one of the soil conserving practices increasingly recognized worldwide despite its empirical benefits still largely undergoing continuous research. In fragile eco-regions and marginal lands of the tropics where agricultural sustainability is in urgent need to be attained, conservation tillage could provide promising benefits. However, it is also recognized that there is no single tillage system that can be widely used for the diverse soil and climatic conditions.

5.2 Experimental Findings

Results from both the field and laboratory experiments generally suggested that 5 years of continuous no-tillage have improved soil structure relative to conventional tillage. Such improvement was shown by changes in selected soil properties observed through experimental assessment. The empirical results indicated that NT soils were markedly more stable, and although rather compacted, such soils were able to retain and transmit more water throughout the soil profile.

5.2.1 Field studies

Experimental results have demonstrated that 5 years of continuous conventional tillage with moldboard plough (MP) and no-tillage (NT) have significantly affected some physical characteristics of the soils at the longer term tillage trial at Massey University.

1. Soil penetration resistance was significantly lower in the MP plots, at the early oats growing season and within two weeks after land preparation, compared to the NT and PP plots. The level of soil resistance was almost twice as much at the 0-10 cm soil depth in the NT and PP soils compared to the MP soils. This was not unexpected because of recent tillage operations in the MP field. However, the trend reversed within six months, following grazing and spring fallow. As the cultivated field recompacted, surface soil became harder than the NT and pasture soil. Generally, there was a linear correlation between soil penetration resistance and soil depth.

2. Water infiltration rate measurement results over one year period indicated an average value significantly higher under the NT and PP treatments than MP treatment. These results suggest that macropore continuity, water-filled porosity and other hydraulic properties were improved under NT.

3. Bulk density measured at the time of early oats planting season indicated a remarkably higher level at the top 0-5 cm soil layer in the NT compared to the MP plots. Although the difference among the average values of four layers were insignificant under all the treatments, the results suggested that the NT plots were

more compacted at that time of planting season and had lower total porosity than the MP soil.

4. Regression analysis results, not unexpectedly, indicated a strong relationship between soil bulk density and soil penetration resistance. The significance of this relationship was indicated by R^2 values of 0.968, 0.993, and 0.729 for the PP, MP, and NT treatments respectively.

5. Experimental results indicated a substantially higher level (11%) of water content in the NT plots compared to that from the MP plots. These results of water content measurement, carried out during early oats growing season, suggested that although the NT soils were more resistant to penetration, and had lower total porosity as indicated by higher level of bulk density, they infiltrated and retained more water.

6. Regression analyses indicated a strong relationship between soil water content and soil penetration resistance, except for PP treatment (R^2 = 0.050). The linear correlation found for the MP and NT was indicated by R^2 values of 0.445 and 0.735 respectively.

7. Although the soil undergoes less disturbance under the NT treatment, it produced comparable winter oats and summer maize dry matter yield with those under the MP treatment.

5.2.2 Laboratory analyses

1. The NT soils were substantially more stable than the MP soils but similar to the PP soils. For the surface soil (0-10 cm soil depth) the water-stable aggregates remaining on sieve for the PP, MP, and NT were 75.2, 26.2 and 70.8% respectively. The macroaggregates (> 2 mm diameter) made up the largest proportion of the soil for PP (54.7%) and NT (37.4%), whereas for MP the macroaggregates were 4.8%. The results also indicated that 73.8% of MP soil in the top 10 cm had less than 0.5 mm water-stable aggregates. By contrast, PP and NT had water-stable aggregates less than 0.5 mm at 24.8 and 29.2% respectively. Prolonged sieving (60 minutes) also confirmed the above results. These suggested that the sediment detachment in the MP

soils by water was much easier compared to the NT and PP management. Thus the MP soils were the most vulnerable to erosion.

2. Runoff and leachate experiments produced wide variability in results due to a number of factors. However the results clearly suggested that the MP treatment had caused more surface runoff than the other two treatments. By contrast, water runoff was lower in the NT plots, which was also reflected by the occurrence of more water leaching under this treatment compared to the MP treatment. These results suggested the potential losses of surface soil and plant nutrients through sediment and water runoff and potential threat of surface water contamination by agrochemical under MP practice. On the other, the NT could also pose potential risk for groundwater contamination through leaching of chemicals derived from surface applied pesticides. Notwithstanding, there is no evidence to suggest such risk of groundwater contamination from these experiments.

3. The NT soils were also slightly more acidic (lower pH) both at 0-10 and 10-20 cm soil layers suggesting that this was possibly due to the accumulation and stratification of the applied fertilizers at the soil surface and the movement of organic acids from decomposing residues.

4. Both the MP and NT had resulted in a relative decline in total C level compared to the PP at the 0-10 cm soil layer. The decline of total C content after 5 years of continuous double-cropping in the 0-20 cm soil layer was about 12% in the MP plots and 2.65% in the NT plots.

5. Total N at the 0-10 cm soil layer was significantly lower under the MP treatment compared to the other two treatments. This low N level is probably due to accelerated decomposition of organic matter induced by tillage, with concomitant release of N in excess of the needs of microbial biomass, which also decreases as the available C decreases. Total N was distributed quite evenly under all the treatments at the 10-20 cm soil depth.

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APPENDICES

APPENDIX 1

Field Experiments

1.1 Detailed data and statistical analysis of soil penetration resistance results

1.1.1 First Experiment (27/4/99)

Table 1.1.1 Results of the first soil penetration resistance measurement

OBS	Trt*)	PR1 (MPa) at 0-5 cm	PR1 (MPa) at 5-10 cm	PR1 MPa) at 10-15 cm	PR1 (MPa) at 15-20 cm	PR1 (MPa) at 20-25 cm	PR1 (MPa) at 25-30 cm	PR1 (MPa) at 30-35 cm	PR1 (MPa) at 35-40 cm
1	PP	0.88	2.23	2.69	2.95	3.26	3.43	3.46	3.51
2	PP	1.42	2.38	2.63	2.78	2.92	3.13	3.49	3.62
3	PP	1.32	2.33	2.59	3.22	3.47	3.39	3.81	3.69
4	PP	1.05	2.92	3.05	3.44	3.73	3.89	4.17	4.24
5	MP	0.51	0.99	1.69	2.31	2.22	2.26	2.39	2.78
6	MP	0.66	1.01	1.84	2.06	2.05	2.01	2.81	3.27
7	MP	0.66	1.00	1.65	2.28	2.34	3.47	3.78	3.87
8	MP	0.60	1.24	1.84	2.31	2.40	3.04	3.27	3.62
9	NT	1.24	2.48	2.83	2.88	2.79	2.70	3.05	3.20
10	NT	1.08	2.65	2.88	2.70	2.66	2.75	2.91	3.01
11	NT	1.40	2.68	3.14	3.05	2.88	2.79	2.79	2.79
12	NT	1.30	2.75	3.27	3.20	3.10	3.07	2.97	2.97

*) PP=permanent pasture, MP=moldboard plough, NT=no-tillage

ANALYSIS: COMPARISON OF TREATMENTS

General Linear Models Procedure

Dependent Variable: P105 Soil penetration resistance (MPa) at 0-5 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.98735000	0.49367500	17.60	0.0008
Error	9	0.25245000	0.02805000		
Corrected Total	11	1.23980000			
	R-Square	C.V.	Root MSE		P105 Mean
	0.796378	16.58231	0.16748134		1.01000000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.98735000	0.49367500	17.60	0.0008

ANALYSIS: COMPARISON OF TREATMENTS

General Linear Models Procedure

Dependent Variable: P110 Soil penetration resistance (MPa) at 5-10 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	6.00140000	3.00070000	72.89	0.0001
Error	9	0.37050000	0.04116667		
Corrected Total	11	6.37190000			
	R-Square	C.V.	Root MSE		P110 Mean
	0.941854	9.873270	0.20289570		2.05500000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	6.00140000	3.00070000	72.89	0.0001

ANALYSIS: COMPARISON OF TREATMENTS

General Linear Models Procedure

Dependent Variable: P115 Soil penetration resistance (MPa) at 10-15 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	3.57326667	1.78663333	54.49	0.0001
Error	9	0.29510000	0.03278889		
Corrected Total	11	3.86836667			
	R-Square	C.V.	Root MSE		P115 Mean
	0.923715	7.219018	0.18107702		2.50833333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	3.57326667	1.78663333	54.49	0.0001

ANALYSIS: COMPARISON OF TREATMENTS

General Linear Models Procedure

Dependent Variable: P120 Soil penetration resistance (MPa) at 15-20 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1.69295000	0.84647500	17.38	0.0008
Error	9	0.43835000	0.04870556		
Corrected Total	11	2.13130000			
	R-Square	C.V.	Root MSE		P120 Mean
	0.794327	7.981676	0.22069335		2.76500000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	1.69295000	0.84647500	17.38	0.0008

ANALYSIS: COMPARISON OF TREATMENTS

General Linear Models Procedure

Dependent Variable: P125 Soil penetration resistance (MPa) at 20-25 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	2.39631667	1.19815833	20.50	0.0004
Error	9	0.52605000	0.05845000		
Corrected Total	11	2.92236667			
	R-Square	C.V.	Root MSE		P125 Mean
	0.819992	8.578274	0.24176435		2.81833333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	2.39631667	1.19815833	20.50	0.0004

ANALYSIS: COMPARISON OF TREATMENTS

General Linear Models Procedure

Dependent Variable: P130 Soil penetration resistance (MPa) at 25-30 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1.33711667	0.66855833	3.42	0.0786
Error	9	1.76017500	0.19557500		
Corrected Total	11	3.09729167			
	R-Square	C.V.	Root MSE		P130 Mean
	0.431705	14.77001	0.44223862		2.99416667
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	1.33711667	0.66855833	3.42	0.0786

ANALYSIS: COMPARISON OF TREATMENTS

General Linear Models Procedure

Dependent Variable: P135 Soil penetration resistance (MPa) at 30-35 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1.48061667	0.74030833	4.63	0.0415
Error	9	1.44035000	0.16003889		
Corrected Total	11	2.92096667			
	R-Square	C.V.	Root MSE		P135 Mean
	0.506893	12.34083	0.40004861		3.24166667
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	1.48061667	0.74030833	4.63	0.0415

ANALYSIS: COMPARISON OF TREATMENTS

General Linear Models Procedure

Dependent Variable: P140 Soil penetration resistance (MPa) at 35-40 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1.19361667	0.59680833	5.01	0.0345
Error	9	1.07187500	0.11909722		
Corrected Total	11	2.26549167			
	R-Square	C.V.	Root MSE		P140 Mean
	0.526869	10.20768	0.34510465		3.38083333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	1.19361667	0.59680833	5.01	0.0345

1.1.2 Second Experiment (22/10/99)

Table 1.1.2 Results of the second soil penetration resistance measurement

OBS	Trt*)	PR2 (MPa) at 0-5 cm	PR2 (MPa) at 5-10 cm	PR2 (MPa) at 10-15 cm	PR2 (MPa) at 15-20 cm	PR2 (MPa) at 20-25 cm	PR2 (MPa) at 25-30 cm	PR2 (MPa) at 30-35 cm	PR2 (MPa) at 35-40 cm
1	PP	1.44	2.08	2.50	2.89	3.10	3.31	3.59	3.78
2	PP	1.46	2.66	3.43	3.75	4.13	4.37	4.55	4.62
3	PP	1.69	2.78	3.55	3.86	4.05	4.31	4.48	4.95
4	PP	1.99	2.83	3.62	4.02	4.42	4.73	5.03	5.20
5	MP	2.57	5.04	5.10	5.05	4.72	3.94	3.68	3.57
6	MP	3.24	4.47	4.80	4.68	4.25	3.84	3.61	3.23
7	MP	3.17	4.30	4.55	4.24	3.89	3.93	4.10	3.82
8	MP	2.47	3.88	4.02	3.73	3.12	2.94	3.00	3.27
9	NT	1.43	2.47	3.34	4.02	4.02	4.11	3.76	3.58
10	NT	1.73	2.94	4.15	4.46	4.45	4.46	4.21	4.10
11	NT	1.93	3.13	4.20	4.80	5.03	5.04	4.87	4.15
12	NT	1.83	2.86	3.63	3.95	4.08	4.03	4.02	4.20

*) PP=permanent pasture, MP=moldborad plough, NT=no-tillage

ANALYSIS: COMPARISON OF TREATMENTS

General Linear Models Procedure

Dependent Variable: P205 Soil penetration resistance (MPa) at 0-5 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	3.69611667	1.84805833	20.43	0.0005
Error	9	0.81397500	0.09044167		
Corrected Total	11	4.51009167			
	R-Square	C.V.	Root MSE		P205 Mean
	0.819521	14.46422	0.30073521		2.07916667
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	3.69611667	1.84805833	20.43	0.0005

ANALYSIS: COMPARISON OF TREATMENTS

General Linear Models Procedure

Dependent Variable: P210 Soil penetration resistance (MPa) at 5-10 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	7.87851667	3.93925833	27.64	0.0001
Error	9	1.28255000	0.14250556		
Corrected Total	11	9.16106667			
	R-Square	C.V.	Root MSE		P210 Mean
	0.860000	11.48577	0.37749908		3.28666667
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	7.87851667	3.93925833	27.64	0.0001

ANALYSIS: COMPARISON OF TREATMENTS

General Linear Models Procedure

Dependent Variable: P215 Soil penetration resistance (MPa) at 10-15 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	3.64065000	1.82032500	8.33	0.0090
Error	9	1.96637500	0.21848611		
Corrected Total	11	5.60702500			
	R-Square	C.V.	Root MSE		P215 Mean
	0.649302	11.96225	0.46742498		3.90750000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	3.64065000	1.82032500	8.33	0.0090

ANALYSIS: COMPARISON OF TREATMENTS

General Linear Models Procedure

Dependent Variable: P220 Soil penetration resistance (MPa) at 15-20 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1.47311667	0.73655833	2.99	0.1009
Error	9	2.21617500	0.24624167		
Corrected Total	11	3.68929167			
	R-Square	C.V.	Root MSE		P220 Mean
	0.399295	12.04192	0.49622743		4.12083333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	1.47311667	0.73655833	2.99	0.1009

ANALYSIS: COMPARISON OF TREATMENTS

General Linear Models Procedure

Dependent Variable: P225 Soil penetration resistance (MPa) at 20-25 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.51440000	0.25720000	0.77	0.4902
Error	9	2.99670000	0.33296667		
Corrected Total	11	3.51110000			
	R-Square	C.V.	Root MSE		P225 Mean
	0.146507	14.05682	0.57703264		4.10500000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.51440000	0.25720000	0.77	0.4902

ANALYSIS: COMPARISON OF TREATMENTS

General Linear Models Procedure

Dependent Variable: P230 Soil penetration resistance (MPa) at 25-30 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1.17261667	0.58630833	2.16	0.1719
Error	9	2.44827500	0.27203056		
Corrected Total	11	3.62089167			
	R-Square	C.V.	Root MSE		P230 Mean
	0.323847	12.77043	0.52156549		4.08416667
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	1.17261667	0.58630833	2.16	0.1719

ANALYSIS: COMPARISON OF TREATMENTS

General Linear Models Procedure

Dependent Variable: P235 Soil penetration resistance (MPa) at 30-35 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1.44605000	0.72302500	2.74	0.1174
Error	9	2.37185000	0.26353889		
Corrected Total	11	3.81790000			
	R-Square	C.V.	Root MSE		P235 Mean
	0.378755	12.59780	0.51336039		4.07500000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	1.44605000	0.72302500	2.74	0.1174

ANALYSIS: COMPARISON OF TREATMENTS

General Linear Models Procedure

Dependent Variable: P240 Soil penetration resistance (MPa) at 35-40 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	2.72046667	1.36023333	7.52	0.0120
Error	9	1.62842500	0.18093611		
Corrected Total	11	4.34889167			
	R-Square	C.V.	Root MSE		P240 Mean
	0.625554	10.53103	0.42536586		4.03916667
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	2.72046667	1.36023333	7.52	0.0120

1.2 Detailed data and statistical analysis of water infiltration rate measurement results

Table 1.2 Results of the water infiltration rate experiments

OBS	Treatment	Infilt. rate (mm/min)on 22/12/98	Infilt. rate (mm/min)on 14/02/99	Infilt. rate (mm/min)on 16/06/99	Infilt. rate (mm/min)on 05/10/99	Infilt. rate (mm/min) Average
1	Permanent pasture	0.6	1.8	1.1	2.1	0.80
2	Permanent pasture	1.2	1.8	0.6	1.8	1.70
3	Permanent pasture	0.6	1.6	1.1	0.9	0.98
4	Permanent pasture	0.8	1.6	1.1	0.8	1.39
5	Moldboard plough	1.4	0.8	0.5	1.0	0.75
6	Moldboard plough	0.4	1.0	0.3	0.8	0.75
7	Moldboard plough	0.6	0.8	0.3	0.9	0.35
8	Moldboard plough	0.6	0.4	0.3	1.2	0.97
9	No-tillage	0.8	1.0	1.3	1.9	1.20
10	No-tillage	1.8	1.4	1.4	1.1	1.20
11	No-tillage	1.2	1.0	1.1	1.0	1.05
12	No-tillage	1.0	1.4	0.4	0.8	1.20

ANALYSIS: COMPARISON OF INFILTRATION RATES
General Linear Models Procedure

Dependent Variable: INF1 Infiltration rate (mm/min) on 22/12/98

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.48666667	0.24333333	1.58	0.2590
Error	9	1.39000000	0.15444444		
Corrected Total	11	1.87666667			

R-Square	C.V.	Root MSE	INF1 Mean
0.259325	42.87209	0.39299420	0.91666667

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.48666667	0.24333333	1.58	0.2590

ANALYSIS: COMPARISON OF INFILTRATION RATES
General Linear Models Procedure

Dependent Variable: INF2 Infiltration rate (mm/min) on 14/02/99

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1.80666667	0.90333333	20.85	0.0004
Error	9	0.39000000	0.04333333		
Corrected Total	11	2.19666667			

R-Square	C.V.	Root MSE	INF2 Mean
0.822458	17.10958	0.20816660	1.21666667

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	1.80666667	0.90333333	20.85	0.0004

ANALYSIS: COMPARISON OF INFILTRATION RATES
General Linear Models Procedure

Dependent Variable: INF3 Infiltration rate (mm/min) on 16/06/99

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1.18166667	0.59083333	6.43	0.0185
Error	9	0.82750000	0.09194444		
Corrected Total	11	2.00916667			
	R-Square	C.V.	Root MSE		INF3 Mean
	0.588138	38.30191	0.30322342		0.79166667
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	1.18166667	0.59083333	6.43	0.0185

ANALYSIS: COMPARISON OF INFILTRATION RATES
General Linear Models Procedure

Dependent Variable: INF4 Infiltration rate (mm/min) on 05/10/99

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.36166667	0.18083333	0.79	0.4810
Error	9	2.04750000	0.22750000		
Corrected Total	11	2.40916667			
	R-Square	C.V.	Root MSE		INF4 Mean
	0.150121	40.02542	0.47696960		1.19166667
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.36166667	0.18083333	0.79	0.4810

ANALYSIS: COMPARISON OF INFILTRATION RATES
General Linear Models Procedure

Dependent Variable: INF5 Infiltration rate (mm/min) Average

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.63331667	0.31665833	4.01	0.0568
Error	9	0.71045000	0.07893889		
Corrected Total	11	1.34376667			
	R-Square	C.V.	Root MSE		INF5 Mean
	0.471300	27.32194	0.28096065		1.02833333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.63331667	0.31665833	4.01	0.0568

1.3 Detailed data and statistical analysis of bulk density measurement results

Table 1.3 Results of soil bulk density measurement

OBS	Treatment	BD (g/cm3) at 0-5 cm	BD (g/cm3) at 5-10 cm	BD (g/cm3) at 10-15 cm	BD (g/cm3) at 15-20 cm	BD (g/cm3) average
1	Permanent pasture	1.14	1.33	1.40	1.43	1.21
2	Permanent pasture	1.28	1.33	1.31	1.46	1.31
3	Permanent pasture	1.20	1.28	1.37	1.36	1.37
4	Permanent pasture	1.22	1.30	1.38	1.35	1.40
5	Moldboard plough	1.04	1.34	1.21	1.21	1.12
6	Moldboard plough	1.05	1.37	1.35	1.50	1.31
7	Moldboard plough	1.19	1.23	1.30	1.46	1.31
8	Moldboard plough	1.18	1.31	1.37	1.58	1.44
9	No-tillage	1.22	1.35	1.40	1.47	1.31
10	No-tillage	1.34	1.28	1.43	1.43	1.36
11	No-tillage	1.30	1.31	1.40	1.32	1.42
12	No-tillage	1.39	1.48	1.45	1.65	1.47

ANALYSIS: COMPARISON OF TREATMENTS
General Linear Models Procedure

Dependent Variable: BD05 Bulk density (g/cm^3) at 0-5 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.07805000	0.03902500	7.77	0.0109
Error	9	0.04517500	0.00501944		
Corrected Total	11	0.12322500			
	R-Square	C.V.	Root MSE		BD05 Mean
	0.633394	5.843137	0.07084804		1.21250000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.07805000	0.03902500	7.77	0.0109

ANALYSIS: COMPARISON OF TREATMENTS
General Linear Models Procedure

Dependent Variable: BD10 Bulk density (g/cm^3) at 5-10 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.00511667	0.00255833	0.64	0.5497
Error	9	0.03597500	0.00399722		
Corrected Total	11	0.04109167			
	R-Square	C.V.	Root MSE		BD10 Mean
	0.124518	4.768593	0.06322359		1.32583333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.00511667	0.00255833	0.64	0.5497

ANALYSIS: COMPARISON OF TREATMENTS
General Linear Models Procedure

Dependent Variable: BD15 Bulk density (g/cm^3) at 10-15 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.02531667	0.01265833	5.28	0.0304
Error	9	0.02157500	0.00239722		
Corrected Total	11	0.04689167			
	R-Square	C.V.	Root MSE		BD15 Mean
	0.539897	3.589110	0.04896144		1.36416667
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.02531667	0.01265833	5.28	0.0304

ANALYSIS: COMPARISON OF TREATMENTS
General Linear Models Procedure

Dependent Variable: BD20 Bulk density (g/cm^3) at 15-20 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.00915000	0.00457500	0.29	0.7544
Error	9	0.14155000	0.01572778		
Corrected Total	11	0.15070000			
	R-Square	C.V.	Root MSE		BD20 Mean
	0.060717	8.739403	0.12541044		1.43500000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.00915000	0.00457500	0.29	0.7544

ANALYSIS: COMPARISON OF TREATMENTS
General Linear Models Procedure

Dependent Variable: BDAVR Bulk density (g/cm^3) average of four depths

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.01911667	0.00955833	0.98	0.4120
Error	9	0.08777500	0.00975278		
Corrected Total	11	0.10689167			
	R-Square	C.V.	Root MSE		BDAVR Mean
	0.178842	7.392850	0.09875615		1.33583333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.01911667	0.00955833	0.98	0.4120

1.4 Detailed data and statistical analysis of soil water content measurement results

Table 1.4 Results of soil water content measurement

OBS	Treatment	WC (%) at 0-5 cm	WC (%) at 5-10 cm	WC (%) at 10-15 cm	WC (%) at 15-20 cm	WC (%) average
1	Permanent pasture	16.87	15.58	16.63	15.23	16.98
2	Permanent pasture	17.66	16.45	16.74	15.46	17.22
3	Permanent pasture	20.42	23.00	22.20	20.29	17.43
4	Permanent pasture	12.97	13.84	14.14	14.44	16.36
5	Moldboard plough	18.14	20.07	20.57	19.01	17.40
6	Moldboard plough	16.95	19.78	20.00	18.49	19.19
7	Moldboard plough	16.49	17.54	21.26	19.41	20.63
8	Moldboard plough	18.03	19.38	20.71	19.75	19.17
9	No-tillage	20.47	22.07	22.24	20.78	18.89
10	No-tillage	16.25	20.83	21.77	21.69	22.26
11	No-tillage	19.46	24.67	25.53	27.01	23.04
12	No-tillage	19.38	21.45	22.63	18.73	22.05

ANALYSIS: COMPARISON OF TREATMENTS
General Linear Models Procedure

Dependent Variable: WC05 Water content (%) at 0-5 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	8.05235000	4.02617500	0.90	0.4413
Error	9	40.39427500	4.48825278		
Corrected Total	11	48.44662500			
	R-Square	C.V.	Root MSE		WC05 Mean
	0.166211	11.93045	2.11854969		17.75750000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	8.05235000	4.02617500	0.90	0.4413

ANALYSIS: COMPARISON OF TREATMENTS
General Linear Models Procedure

Dependent Variable: WC10 Water content (%) at 5-10 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	51.54125000	25.77062500	3.83	0.0626
Error	9	60.54145000	6.72682778		
Corrected Total	11	112.08270000			
	R-Square	C.V.	Root MSE		WC10 Mean
	0.459850	13.26317	2.59361288		19.55500000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	51.54125000	25.77062500	3.83	0.0626

ANALYSIS: COMPARISON OF TREATMENTS
General Linear Models Procedure

Dependent Variable: WC15 Water content (%) at 10-15 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	63.48311667	31.74155833	6.48	0.0181
Error	9	44.11785000	4.90198333		
Corrected Total	11	107.60096667			
	R-Square	C.V.	Root MSE		WC15 Mean
	0.589986	10.87002	2.21404231		20.36833333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	63.48311667	31.74155833	6.48	0.0181

ANALYSIS: COMPARISON OF TREATMENTS
General Linear Models Procedure

Dependent Variable: WC20 Water content (%) at 15-20 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	64.92701667	32.46350833	4.91	0.0361
Error	9	59.46647500	6.60738611		
Corrected Total	11	124.39349167			
	R-Square	C.V.	Root MSE		WC20 Mean
	0.521949	13.39433	2.57048363		19.19083333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	64.92701667	32.46350833	4.91	0.0361

ANALYSIS: COMPARISON OF TREATMENTS
General Linear Models Procedure

Dependent Variable: WCAVR Water content (%) average

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	41.72041667	20.86020833	11.78	0.0031
Error	9	15.93655000	1.77072778		
Corrected Total	11	57.65696667			
	R-Square	C.V.	Root MSE		WCAVR Mean
	0.723597	6.924050	1.33068696		19.21833333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	41.72041667	20.86020833	11.78	0.0031

1.5 Detailed data and statistical analysis of dry matter yield from MP and NT crops

Table 1.5 Results of soil water content measurement

OBS	Treatment	Oats dry matter (grm) on 11/06/99	Maize dry matter (grm) on 16/02/00
1	Moldboard plough	91.1	223.2
2	Moldboard plough	171.8	225.0
3	Moldboard plough	119.6	271.0
4	Moldboard plough	124.3	265.5
5	No-tillage	105.5	312.3
6	No-tillage	126.1	286.0
7	No-tillage	139.5	267.1
8	No-tillage	107.2	220.4

ANALYSIS: COMPARISON OF DRY MATTER YIELD
General Linear Models Procedure

Dependent Variable: DM1 Oats dry matter (grm) on 11/06/99

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	101.53125000	101.53125000	0.15	0.7148
Error	6	4148.36750000	691.39458333		
Corrected Total	7	4249.89875000			
	R-Square	C.V.	Root MSE		DM1 Mean
	0.023890	21.35368	26.29438311		123.13750000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	1	101.53125000	101.53125000	0.15	0.7148

ANALYSIS: COMPARISON OF DRY MATTER YIELD
General Linear Models Procedure

Dependent Variable: DM2 Maize dry matter (grm) on 16/02/00

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	1277.65125000	1277.65125000	1.18	0.3182
Error	6	6471.41750000	1078.56958333		
Corrected Total	7	7749.06875000			
	R-Square	C.V.	Root MSE		DM2 Mean
	0.164878	12.68933	32.84158314		258.81250000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	1	1277.65125000	1277.65125000	1.18	0.3182

APPENDIX 2

Laboratory Experiments

2.1 Detailed data and statistical analysis of aggregation stability experiment results (60-minute sieving duration)

Table 2.1 Results of the aggregation stability experiment (60-minute sieving duration)

OBS	Trtnt*)	AG1 (%) of >2 mm	AG1 (%) of 1-2 mm	AG1 (%) of 0.5-1 mm	AG1 (%) of <0.5 mm	AG2 (%) of >2 mm	AG2 (%) of 1-2 mm	AG2 (%) of 0.5-1 mm	AG2 (%) of <0.5 mm
1	PP	19.2	25.3	14.6	40.9	17.2	16.7	10.1	56.0
2	PP	29.5	25.1	12.7	32.7	11.9	16.3	12.9	58.9
3	PP	16.0	24.2	12.9	46.9	8.2	16.2	12.4	63.2
4	PP	20.5	26.0	9.3	44.2	8.8	18.6	15.3	57.3
5	MP	5.4	7.3	13.3	74.0	8.5	9.9	13.1	68.5
6	MP	4.3	7.4	8.8	79.5	2.6	8.4	11.3	77.7
7	MP	3.1	8.9	10.1	77.9	2.2	5.9	11.4	80.5
8	MP	1.9	5.5	8.7	83.9	0.8	6.1	7.8	85.3
9	NT	20.1	19.3	12.5	48.1	16.0	19.1	13.5	51.4
10	NT	16.1	26.4	15.7	41.8	8.1	17.5	14.8	59.6
11	NT	9.6	17.4	13.2	59.8	13.9	18.6	16.3	51.2
12	NT	18.6	31.0	14.1	36.3	8.7	14.4	12.7	64.2

*) PP=permanent pasture, MP=moldboard plough, NT=no-tillage

ANALYSIS: COMPARISON OF TREATMENTS (60 min) at 0-10 cm soil depth
General Linear Models Procedure

Dependent Variable: AG12 Water-stable aggregates (%) of >2 mm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	656.08166667	328.04083333	17.19	0.0008
Error	9	171.72750000	19.08083333		
Corrected Total	11	827.80916667			
	R-Square	C.V.	Root MSE		AG12 Mean
	0.792552	31.90380	4.36816132		13.69166667
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	656.08166667	328.04083333	17.19	0.0008

ANALYSIS: COMPARISON OF TREATMENTS (60 min) at 0-10 cm soil depth
General Linear Models Procedure

Dependent Variable: AG11 Water-stable aggregates (%) of 1-2 mm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	781.62500000	390.81250000	27.70	0.0001
Error	9	126.96500000	14.10722222		
Corrected Total	11	908.59000000			
	R-Square	C.V.	Root MSE		AG11 Mean
	0.860262	20.13919	3.75595823		18.65000000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	781.62500000	390.81250000	27.70	0.0001

ANALYSIS: COMPARISON OF TREATMENTS (60 min) at 0-10 cm soil depth

General Linear Models Procedure

Dependent Variable: AG105 Water-stable aggregates (%) of 0.5-1 mm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	26.92666667	13.46333333	3.53	0.0739
Error	9	34.34250000	3.81583333		
Corrected Total	11	61.26916667			
	R-Square	C.V.	Root MSE		AG105 Mean
	0.439482	16.06648	1.95341581		12.1583333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	26.92666667	13.46333333	3.53	0.0739

ANALYSIS: COMPARISON OF TREATMENTS (60 min) at 0-10 cm soil depth

General Linear Models Procedure

Dependent Variable: AG100 Water-stable aggregates (%) of <0.5 mm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	3321.04500000	1660.52250000	31.81	0.0001
Error	9	469.75500000	52.19500000		
Corrected Total	11	3790.80000000			
	R-Square	C.V.	Root MSE		AG100 Mean
	0.876080	13.01732	7.22461072		55.50000000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	3321.04500000	1660.52250000	31.81	0.0001

ANALYSIS: COMPARISON OF TREATMENTS (60 min) at 10-20 cm soil depth

General Linear Models Procedure

Dependent Variable: AG22 Water-stable aggregates (%) of >2 mm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	173.92666667	86.96333333	5.98	0.0223
Error	9	130.90250000	14.54472222		
Corrected Total	11	304.82916667			
	R-Square	C.V.	Root MSE		AG22 Mean
	0.570571	42.81109	3.81375435		8.90833333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	173.92666667	86.96333333	5.98	0.0223

ANALYSIS: COMPARISON OF TREATMENTS (60 min) at 10-20 cm soil depth

General Linear Models Procedure

Dependent Variable: AG21 Water-stable aggregates (%) of 1-2 mm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	246.16500000	123.08250000	39.31	0.0001
Error	9	28.17750000	3.13083333		
Corrected Total	11	274.34250000			
	R-Square	C.V.	Root MSE		AG21 Mean
	0.897291	12.66130	1.76941610		13.97500000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	246.16500000	123.08250000	39.31	0.0001

ANALYSIS: COMPARISON OF TREATMENTS (60 min) at 10-20 cm soil depth

General Linear Models Procedure

Dependent Variable: AG205 Water-stable aggregates (%) of 0.5-1 mm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	23.47166667	11.73583333	2.94	0.1042
Error	9	35.95500000	3.99500000		
Corrected Total	11	59.42666667			
	R-Square	C.V.	Root MSE		AG205 Mean
	0.394969	15.82124	1.99874961		12.63333333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	23.47166667	11.73583333	2.94	0.1042

ANALYSIS: COMPARISON OF TREATMENTS (60 min) at 10-20 cm soil depth

General Linear Models Procedure

Dependent Variable: AG200 Water-stable aggregates (%) of <0.5 mm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1106.32666667	553.16333333	16.47	0.0010
Error	9	302.29000000	33.58777778		
Corrected Total	11	1408.61666667			
	R-Square	C.V.	Root MSE		AG200 Mean
	0.785399	8.987588	5.79549634		64.48333333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	1106.32666667	553.16333333	16.47	0.0010

2.2 Detailed data and statistical analysis of aggregation stability experiment results (30-minute sieving duration)

Table 2.2 Results of the aggregation stability experiment (30-minute sieving duration)

OBS	Trtnt*)	AG1 (%) of >2 mm	AG1 (%) of 1-2 mm	AG1 (%) of 0.5-1 mm	AG1 (%) of <0.5 mm	AG2 (%) of >2 mm	AG2 (%) of 1-2 mm	AG2 (%) of 0.5-1 mm	AG2 (%) of <0.5 mm
1	PP	56.5	12.9	7.0	23.6	27.7	21.0	16.1	35.2
2	PP	72.7	6.1	3.2	18.0	25.8	19.4	9.3	45.5
3	PP	41.9	22.0	6.4	29.7	14.9	22.7	11.7	50.7
4	PP	47.7	16.3	7.9	28.1	17.0	20.3	13.2	49.5
5	MP	5.1	9.0	14.9	71.0	2.6	7.6	12.1	77.7
6	MP	6.0	9.8	13.0	71.2	1.6	9.2	12.2	77.0
7	MP	4.7	9.1	12.0	74.2	8.7	11.6	12.0	67.7
8	MP	3.5	6.6	11.0	78.9	1.1	6.7	11.5	80.7
9	NT	43.1	22.9	11.0	23.0	16.6	22.5	15.4	45.5
10	NT	39.7	20.8	10.8	28.7	8.1	15.0	17.2	59.7
11	NT	36.3	24.2	9.4	30.1	10.1	16.3	14.2	59.4
12	NT	30.4	22.2	12.2	35.2	8.1	16.1	18.7	57.1

*) PP=permanent pasture, MP=moldboard plough, NT=no-tillage

ANALYSIS: COMPARISON OF TREATMENTS (30 min) at the 0-10 cm soil depth
General Linear Models Procedure

Dependent Variable: AG212 Water-stable aggregates (%) of >2 mm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	5129.56500000	2564.78250000	36.56	0.0001
Error	9	631.29500000	70.14388889		
Corrected Total	11	5760.86000000			
	R-Square	C.V.	Root MSE		AG212 Mean
	0.890417	25.92940	8.37519486		32.30000000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	5129.56500000	2564.78250000	36.56	0.0001

ANALYSIS: COMPARISON OF TREATMENTS (30 min) at the 0-10 cm soil depth
General Linear Models Procedure

Dependent Variable: AG211 Water-stable aggregates (%) of 1-2 mm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	390.58666667	195.29333333	12.18	0.0028
Error	9	144.36250000	16.04027778		
Corrected Total	11	534.94916667			
	R-Square	C.V.	Root MSE		AG211 Mean
	0.730138	26.42132	4.00503156		15.15833333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	390.58666667	195.29333333	12.18	0.0028

ANALYSIS: COMPARISON OF TREATMENTS (30 min) at the 0-10 cm soil depth
General Linear Models Procedure

Dependent Variable: AG2105 Water-stable aggregates (%) of 0.5-1 mm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	92.53500000	46.26750000	16.79	0.0009
Error	9	24.80500000	2.75611111		
Corrected Total	11	117.34000000			
	R-Square	C.V.	Root MSE		AG2105 Mean
	0.788606	16.76923	1.66015394		9.90000000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	92.53500000	46.26750000	16.79	0.0009

ANALYSIS: COMPARISON OF TREATMENTS (30 min) at the 0-10 cm soil depth
General Linear Models Procedure

Dependent Variable: AG2100 Water-stable aggregates (%) of <0.5 mm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	5873.12166667	2936.56083333	132.92	0.0001
Error	9	198.82750000	22.09194444		
Corrected Total	11	6071.94916667			
	R-Square	C.V.	Root MSE		AG2100 Mean
	0.967255	11.02257	4.70020685		42.64166667
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	5873.12166667	2936.56083333	132.92	0.0001

ANALYSIS: COMPARISON OF TREATMENTS (30 min) at the 10-20 cm soil depth
General Linear Models Procedure

Dependent Variable: AG222 Water-stable aggregates (%) of >2 mm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	644.95166667	322.47583333	14.05	0.0017
Error	9	206.55750000	22.95083333		
Corrected Total	11	851.50916667			
	R-Square	C.V.	Root MSE		AG222 Mean
	0.757422	40.39946	4.79070280		11.85833333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	644.95166667	322.47583333	14.05	0.0017

ANALYSIS: COMPARISON OF TREATMENTS (30 min) at the 10-20 cm soil depth
General Linear Models Procedure

Dependent Variable: AG221 Water-stable aggregates (%) of 1-2 mm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	310.51500000	155.25750000	25.71	0.0002
Err	9	54.34500000	6.03833333		
Corrected Total	11	364.86000000			
	R-Square	C.V.	Root MSE		AG221 Mean
	0.851052	15.65161	2.45730204		15.70000000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	310.51500000	155.25750000	25.71	0.0002

ANALYSIS: COMPARISON OF TREATMENTS (30 min) at the 10-20 cm soil depth
General Linear Models Procedure

Dependent Variable: AG2205 Water-stable aggregates (%) of 0.5-1 mm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	45.88166667	22.94083333	5.68	0.0254
Err	9	36.36500000	4.04055556		
Corrected Total	11	82.24666667			
	R-Square	C.V.	Root MSE		AG2205 Mean
	0.557854	14.74411	2.01011332		13.63333333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	45.88166667	22.94083333	5.68	0.0254

ANALYSIS: COMPARISON OF TREATMENTS (30 min) at the 10-20 cm soil depth
General Linear Models Procedure

Dependent Variable: AG2200 Water-stable aggregates (%) of <0.5 mm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1935.28666667	967.64333333	22.99	0.0003
Error	9	378.88250000	42.09805556		
Corrected Total	11	2314.16916667			
	R-Square	C.V.	Root MSE		AG2200 Mean
	0.836277	11.03296	6.48830144		58.80833333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	1935.28666667	967.64333333	22.99	0.0003

2.3 Detailed data and statistical analysis of water runoff and leachate experiment results

2.3.1 Runoff

Table 2.3.1 Results of water runoff experiment under a simulated rainfall

OBS	Trt*)	Runoff (ml) at 10 minutes rainfall	Runoff (ml) at 20 minutes rainfall	Runoff (ml) at 30 minutes rainfall	Runoff (ml) at 40 minutes rainfall	Runoff (ml) at 50 minutes rainfall	Runoff (ml) at 60 minutes rainfall
1	PP	2.2	4.8	14.0	15.0	8.0	8.0
2	PP	12.0	4.0	6.0	6.0	5.0	4.0
3	PP	7.4	6.6	9.0	14.0	16.5	11.0
4	PP	3.0	5.5	12.0	13.0	17.6	19.0
5	MP	7.5	18.0	34.0	36.0	7.0	6.0
6	MP	6.0	17.0	38.0	135.0	200.0	215.0
7	MP	25.0	41.0	25.0	48.0	38.0	65.0
8	MP	18.0	29.4	38.2	47.0	63.0	82.5
9	NT	1.4	1.4	1.2	1.4	2.2	3.6
10	NT	28.0	49.0	60.0	34.0	32.0	30.0
11	NT	4.0	3.7	4.5	8.4	9.5	26.0
12	NT	3.2	4.8	9.5	10.4	12.5	17.0

*) PP=permanent pasture, MP=moldboard plough, NT=no-tillage

ANALYSIS: EFFECTS OF TREATMENTS ON WATER RUNOFF
General Linear Models Procedure

Dependent Variable: R010 **Runoff (ml) at 10 minutes rainfall**

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	129.80166667	64.90083333	0.75	0.5010
Error	9	781.80750000	86.86750000		
Corrected Total	11	911.60916667			
	R-Square	C.V.	Root MSE		R010 Mean
	0.142387	95.02403	9.32027360		9.80833333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	129.80166667	64.90083333	0.75	0.5010

ANALYSIS: EFFECTS OF TREATMENTS ON WATER RUNOFF
General Linear Models Procedure

Dependent Variable: R020 **Runoff (ml) at 20 minutes rainfall**

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	895.54166667	447.77083333	2.06	0.1835
Error	9	1957.10500000	217.45611111		
Corrected Total	11	2852.64666667			
	R-Square	C.V.	Root MSE		R020 Mean
	0.313934	95.54898	14.74639316		15.43333333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	895.54166667	447.77083333	2.06	0.1835

ANALYSIS: EFFECTS OF TREATMENTS ON WATER RUNOFF
General Linear Models Procedure

Dependent Variable: R030 Runoff (ml) at 30 minutes rainfall

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1136.94000000	568.47000000	2.09	0.1798
Error	9	2449.41000000	272.15666667		
Corrected Total	11	3586.35000000			
	R-Square	C.V.	Root MSE		R030 Mean
	0.317019	78.74545	16.49717147		20.95000000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	1136.94000000	568.47000000	2.09	0.1798

ANALYSIS: EFFECTS OF TREATMENTS ON WATER RUNOFF
General Linear Models Procedure

Dependent Variable: R040 Runoff (ml) at 40 minutes rainfall

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	7701.80666667	3850.90333333	4.95	0.0354
Error	9	6997.27000000	777.47444444		
Corrected Total	11	14699.07666667			
	R-Square	C.V.	Root MSE		R040 Mean
	0.523965	90.87418	27.88322873		30.68333333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	7701.80666667	3850.90333333	4.95	0.0354

ANALYSIS: EFFECTS OF TREATMENTS ON WATER RUNOFF
General Linear Models Procedure

Dependent Variable: R050 Runoff (ml) at 50 minutes rainfall

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	10962.90500000	5481.45250000	2.21	0.1659
Error	9	22348.13750000	2483.12638889		
Corrected Total	11	33311.04250000			
	R-Square	C.V.	Root MSE		R050 Mean
	0.329107	145.3858	49.83097821		34.27500000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	10962.90500000	5481.45250000	2.21	0.1659

ANALYSIS: EFFECTS OF TREATMENTS ON WATER RUNOFF
General Linear Models Procedure

Dependent Variable: R060 Runoff (ml) at 60 minutes rainfall

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	16083.75166667	8041.87583333	3.03	0.0985
Error	9	23876.25750000	2652.91750000		
Corrected Total	11	39960.00916667			
	R-Square	C.V.	Root MSE		R060 Mean
	0.402496	126.8893	51.50648017		40.59166667
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	16083.75166667	8041.87583333	3.03	0.0985

2.3.2 Leachate

Table 2.3.2 Results of water leachate experiment under a simulated rainfall

OBS	Trt*)	Leachate (ml) at 10 minutes rainfall	Leachate (ml) at 20 minutes rainfall	Leachate (ml) at 30 minutes rainfall	Leachate (ml) at 40 minutes rainfall	Leachate (ml) at 50 minutes rainfall	Leachate (ml) at 60 minutes rainfall
1	PP	130	195	225	175	165	145
2	PP	190	295	330	345	360	370
3	PP	240	380	395	385	400	450
4	PP	167	315	210	180	175	180
5	MP	315	295	165	195	355	375
6	MP	230	335	320	255	175	160
7	MP	240	330	355	325	360	335
8	MP	215	225	230	205	190	185
9	NT	240	465	460	519	507	518
10	NT	260	325	350	395	425	485
11	NT	255	360	390	390	415	425
12	NT	260	320	350	370	428	462

*) PP=permanent pasture, MP=moldboard plough, NT=no-tillage

ANALYSIS: EFFECTS OF TREATMENTS ON WATER LEACHATE
General Linear Models Procedure

Dependent Variable: LC10 **Leachate (ml) at 10 minutes rainfall**

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	13141.50000000	6570.75000000	4.70	0.0400
Error	9	12575.50000000	1397.27777778		
Corrected Total	11	25717.00000000			
	R-Square	C.V.	Root MSE		LC10 Mean
	0.511004	16.35894	37.38017894		228.50000000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	13141.50000000	6570.75000000	4.70	0.0400

ANALYSIS: EFFECTS OF TREATMENTS ON WATER LEACHATE
General Linear Models Procedure

Dependent Variable: LC20 **Leachate (ml) at 20 minutes rainfall**

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	13537.50000000	6768.75000000	1.56	0.2613
Error	9	38962.50000000	4329.16666667		
Corrected Total	11	52500.00000000			
	R-Square	C.V.	Root MSE		LC20 Mean
	0.257857	20.56138	65.79640314		320.00000000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	13537.50000000	6768.75000000	1.56	0.2613

ANALYSIS: EFFECTS OF TREATMENTS ON WATER LEACHATE
General Linear Models Procedure

Dependent Variable: LC30 Leachate (ml) at 30 minutes rainfall

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	32550.00000000	16275.00000000	2.73	0.1184
Error	9	53650.00000000	5961.11111111		
Corrected Total	11	86200.00000000			

R-Square	C.V.	Root MSE	LC30 Mean
0.377610	24.51055	77.20823215	315.00000000

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	32550.00000000	16275.00000000	2.73	0.1184

ANALYSIS: EFFECTS OF TREATMENTS ON WATER LEACHATE
General Linear Models Procedure

Dependent Variable: LC40 Leachate (ml) at 40 minutes rainfall

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	69965.16666667	34982.58333333	5.21	0.0313
Error	9	60385.75000000	6709.52777778		
Corrected Total	11	130350.91666667			

R-Square	C.V.	Root MSE	LC40 Mean
0.536745	26.28886	81.91170721	311.58333333

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	69965.16666667	34982.58333333	5.21	0.0313

ANALYSIS: EFFECTS OF TREATMENTS ON WATER LEACHATE
General Linear Models Procedure

Dependent Variable: LC50 Leachate (ml) at 50 minutes rainfall

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	78254.16666667	39127.08333333	4.34	0.0479
Error	9	81126.75000000	9014.08333333		
Corrected Total	11	159380.91666667			

R-Square	C.V.	Root MSE	LC50 Mean
0.490988	28.80683	94.94252647	329.58333333

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	78254.16666667	39127.08333333	4.34	0.0479

ANALYSIS: EFFECTS OF TREATMENTS ON WATER LEACHATE
General Linear Models Procedure

Dependent Variable: LC60 Leachate (ml) at 60 minutes rainfall

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	105029.16666667	52514.58333333	4.54	0.0433
Error	9	104080.50000000	11564.50000000		
Corrected Total	11	209109.66666667			

R-Square	C.V.	Root MSE	LC60 Mean
0.502268	31.55160	107.53836525	340.83333333

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	105029.16666667	52514.58333333	4.54	0.0433

2.4 Detailed data and statistical analysis of selected soil chemical properties: total C, total N and soil pH (H_2O) under different soil treatments

Table 2.4 Total C, total N and soil pH(H_2O) at 0-10 and 10-20 cm soil depth under different soil treatments

OBS	Treatment	C (%) at 0-10 cm	C (%) at 10-20 cm	N (%) at 0-10 cm	N (%) at 10-20 cm	pH at 0-10 cm	pH at 10-20 cm
1	Moldboard plough	2.22	1.99	0.21	0.20	5.44	5.40
2	Moldboard plough	2.27	1.92	0.23	0.18	5.28	5.35
3	Moldboard plough	2.12	1.83	0.20	0.17	5.14	5.12
4	Moldboard plough	2.07	1.99	0.18	0.19	5.35	5.15
5	No-tillage	2.40	1.86	0.23	0.18	5.08	5.08
6	No-tillage	2.64	1.95	0.24	0.19	5.23	5.09
7	No-tillage	2.29	1.74	0.21	0.16	5.06	5.11
8	No-tillage	2.40	1.66	0.21	0.16	5.01	5.11
9	Permanent pasture	2.50	1.85	0.23	0.17	5.41	5.35
10	Permanent pasture	2.80	1.90	0.26	0.18	5.32	5.35
11	Permanent pasture	2.83	1.85	0.25	0.17	5.31	5.33
12	Permanent pasture	2.85	1.75	0.23	0.16	5.18	5.26

ANALYSIS: EFFECTS OF TREATMENTS ON SOIL TOTAL C
General Linear Models Procedure

Dependent Variable: C10 Total C (%) at 0-10 cm soil depth

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.66291667	0.33145833	17.37	0.0008
Error	9	0.17177500	0.01908611		
Corrected Total	11	0.83469167			
	R-Square	C.V.	Root MSE		C10 Mean
	0.794205	5.640796	0.13815249		2.44916667
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.66291667	0.33145833	17.37	0.0008

ANALYSIS: EFFECTS OF TREATMENTS ON SOIL TOTAL C
General Linear Models Procedure

Dependent Variable: C20 Total C (%) at 10-20 cm soil depth

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.03620000	0.01810000	2.08	0.1813
Error	9	0.07842500	0.00871389		
Corrected Total	11	0.11462500			
	R-Square	C.V.	Root MSE		C20 Mean
	0.315812	5.025476	0.09334821		1.85750000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.03620000	0.01810000	2.08	0.1813

ANALYSIS: EFFECTS OF TREATMENTS ON SOIL TOTAL N
General Linear Models Procedure

Dependent Variable: N10 Total N (%) at 0-10 cm soil depth

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.00281667	0.00140833	4.78	0.0384
Error	9	0.00265000	0.00029444		
Corrected Total	11	0.00546667			
	R-Square	C.V.	Root MSE		N10 Mean
	0.515244	7.683306	0.01715938		0.22333333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.00281667	0.00140833	4.78	0.0384

ANALYSIS: EFFECTS OF TREATMENTS ON SOIL TOTAL N
General Linear Models Procedure

Dependent Variable: N20 Total N (%) at 10-20 cm soil depth

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.00051667	0.00025833	1.69	0.2380
Error	9	0.00137500	0.00015278		
Corrected Total	11	0.00189167			
	R-Square	C.V.	Root MSE		N20 Mean
	0.273128	7.029572	0.01236033		0.17583333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.00051667	0.00025833	1.69	0.2380

ANALYSIS: EFFECTS OF TREATMENTS ON SOIL pH
General Linear Models Procedure

Dependent Variable: PH10 Soil pH at 0-10 cm soil depth

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.11621667	0.05810833	5.13	0.0325
Error	9	0.10187500	0.01131944		
Corrected Total	11	0.21809167			
	R-Square	C.V.	Root MSE		PH10 Mean
	0.532880	2.032661	0.10639288		5.23416667
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.11621667	0.05810833	5.13	0.0325

ANALYSIS: EFFECTS OF TREATMENTS ON SOIL pH
General Linear Models Procedure

Dependent Variable: PH20 Soil pH at 10-20 cm soil depth

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.10665000	0.05332500	7.33	0.0129
Error	9	0.06545000	0.00727222		
Corrected Total	11	0.17210000			
	R-Square	C.V.	Root MSE		PH20 Mean
	0.619698	1.632102	0.08527733		5.22500000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.10665000	0.05332500	7.33	0.0129

Table 2.5 Total C and total N (t/ha) at 0-10 and 10-20 cm soil depth under different soil treatments

OBS	Treatment	C (t/ha) at 0-10 cm	C (t/ha) at 10-20 cm	N (t/ha) at 0-10 cm	N (t/ha) at 10-20cm
1	Permanent pasture	30.88	26.18	2.84	2.41
2	Permanent pasture	36.54	26.32	3.39	2.49
3	Permanent pasture	35.09	25.25	3.10	2.32
4	Permanent pasture	35.91	23.89	2.90	2.18
5	Moldboard plough	26.42	24.08	2.50	2.42
6	Moldboard plough	27.47	27.36	2.78	2.57
7	Moldboard plough	25.65	25.25	2.42	2.35
8	Moldboard plough	25.77	29.35	2.24	2.80
9	No-tillage	30.84	26.69	2.96	2.58
10	No-tillage	34.58	27.89	3.14	2.72
11	No-tillage	29.88	23.66	2.74	2.18
12	No-tillage	34.44	25.73	3.01	2.48

ANALYSIS: EFFECTS OF TREATMENTS ON SOIL TOTAL C
General Linear Models Procedure

Dependent Variable: C10 Total C (t/ha) at 0-10 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	147.36995000	73.68497500	16.86	0.0009
Error	9	39.33487500	4.37054167		
Corrected Total	11	186.70482500			
	R-Square	C.V.	Root MSE		C10 Mean
	0.789321	6.717275	2.09058405		31.12250000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	147.36995000	73.68497500	16.86	0.0009

ANALYSIS: EFFECTS OF TREATMENTS ON SOIL TOTAL C
General Linear Models Procedure

Dependent Variable: C20 Total C (t/ha) at 10-20 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	2.42281667	1.21140833	0.37	0.7021
Error	9	29.63407500	3.29267500		
Corrected Total	11	32.05689167			
	R-Square	C.V.	Root MSE		C20 Mean
	0.075579	6.986965	1.81457295		25.97083333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	2.42281667	1.21140833	0.37	0.7021

ANALYSIS: EFFECTS OF TREATMENTS ON SOIL TOTAL N
General Linear Models Procedure

Dependent Variable: N10 Total N (t/ha) at 0-10 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.75305000	0.37652500	8.08	0.0098
Error	9	0.41925000	0.04658333		
Corrected Total	11	1.17230000			
	R-Square	C.V.	Root MSE		N10 Mean
	0.642370	7.613112	0.21583172		2.83500000
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.75305000	0.37652500	8.08	0.0098

ANALYSIS: EFFECTS OF TREATMENTS ON SOIL TOTAL N
General Linear Models Procedure

Dependent Variable: N20 Total N (t/ha) at 10-20 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.07446667	0.03723333	1.02	0.3994
Error	9	0.32910000	0.03656667		
Corrected Total	11	0.40356667			
	R-Square	C.V.	Root MSE		N20 Mean
	0.184521	7.778609	0.19122413		2.45833333
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.07446667	0.03723333	1.02	0.3994