ALLEVIATION OF SOIL PHYSICAL CONSTRAINTS IN DIRECT-SEEDING SYSTEMS IN URUGUAY

BY

DANIEL L. MARTINO

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfilment of the Requirements
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Department of Plant Science
University of Manitoba
Winnipeg, Manitoba

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ABSTRACT

One of the major constraints to adoption of zero tillage in Uruguay is soil compaction, which results from a combination of factors including a wet climate, fine textured soils with low water infiltration capacities, and traffic by machinery and cattle. These conditions would be particularly detrimental during the transition from tillage-based systems. The objectives of this thesis were: (1) to assess the extent of soil physical constraints for crop production with zero tillage in Uruguay; (2) to develop analytical methods for describing soil quality from the standpoint of physical structure; (3) to evaluate the effectiveness of soil loosening by the Paraplow in increasing the viability of direct-seeding systems; and (4) to study the interactions of crop sequences with subsoiling by Paraplow on soil properties and crop behaviour.

The evidence obtained supports the conclusion that soils impose certain restrictions for the development of crops with direct seeding, chiefly low infiltration capacity, low oxygen diffusion rates, and high soil strength. Subsoiling was effective in relieving these constraints over all the volume of the upper 0.45 m of soil, with a maximum effect at 0.2-0.3 m depth. Paraplowing induced yield increases of between 14 (wheat) and 102 % (corn), associated with improved crop emergence, a more thorough soil exploration by roots, superior weed control, higher tiller survival and reduced floret abortion. The effects of paraplowing on soil physical properties rapidly declined with time after subsoiling, but lasted for up to 25 months. Effects on crop productivity had similar residuality. The additional yield advantage of paraplowing before each crop, compared with one pass in two years was very small, considering the extra energy cost involved. Sunflower as the first crop in the cropping sequence resulted in reduced infiltration capacity of the soil in the subsequent cropping seasons, as compared with rotations that started with corn. This was reflected in a 4 % reduction in wheat and barley productivity, mainly due to lower kernel weight. Wheat tolerated adverse soil physical conditions better than barley.

A cone penetrometer was extensively used to assess soil physical quality. Penetration resistance (PR) measured at a certain soil depth was not independent of PR values in soil layers located up to 180 mm above. However, 77 % of this effect was restricted to a distance of 45 mm. Autocorrelation was highest where PR decreased with depth, and it was concluded that only in this case PR values should be corrected. The relationship between soil moisture and PR was described by an exponential model, and was affected by soil management practices, as well as by the soil depth considered. The empirical coefficient *b*, which described the rate of change of PR with moisture at low moisture contents, varied between -0.003 and -1.10 among the 14 situations analysed. The lower limit of available water, defined as the soil moisture content at which PR equals 2 MPa, was also shown to vary widely with tillage practices.

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1. INTRODUCTION

Two decades ago, a major concern was to produce enough food to feed the world in year 2000. As a result of achievements of science, education, government development policies and private companies, that goal seems to have been accomplished, at least temporarily, for most of the world. In spite of human population growth, the increase in production in recent times has made the availability of food per capita today 20% higher than in 1960 (World Resources Institute 1996). The hunger that exists in some parts of the world, particularly in sub-Saharan Africa, is due to unequal distribution resulting from poverty, and not to a lack of technology for producing the amount of food that is needed.

Past increase in food production is mainly attributable to higher land productivity. This increase in productivity has often been at the expense of natural resource depletion and environment damage. In consequence, a growing concern for achieving what is known as sustainable agricultural systems of production has been recently developed.

As part of this movement toward sustainable agriculture, and concurrent with the appearance of some triggering factors such as the discovery of the herbicide glyphosate (Baird *et al.* 1971) and certain agricultural engineering developments, zero-tillage -or direct-seeding- technologies are being adopted worldwide. A new revolution in the history of agriculture was started. In the development of these new systems, many concepts which were once thought to be fundamental principles have to be revised. Some of the practices applied for decades and even centuries, were based on the fact that soils were tilled.

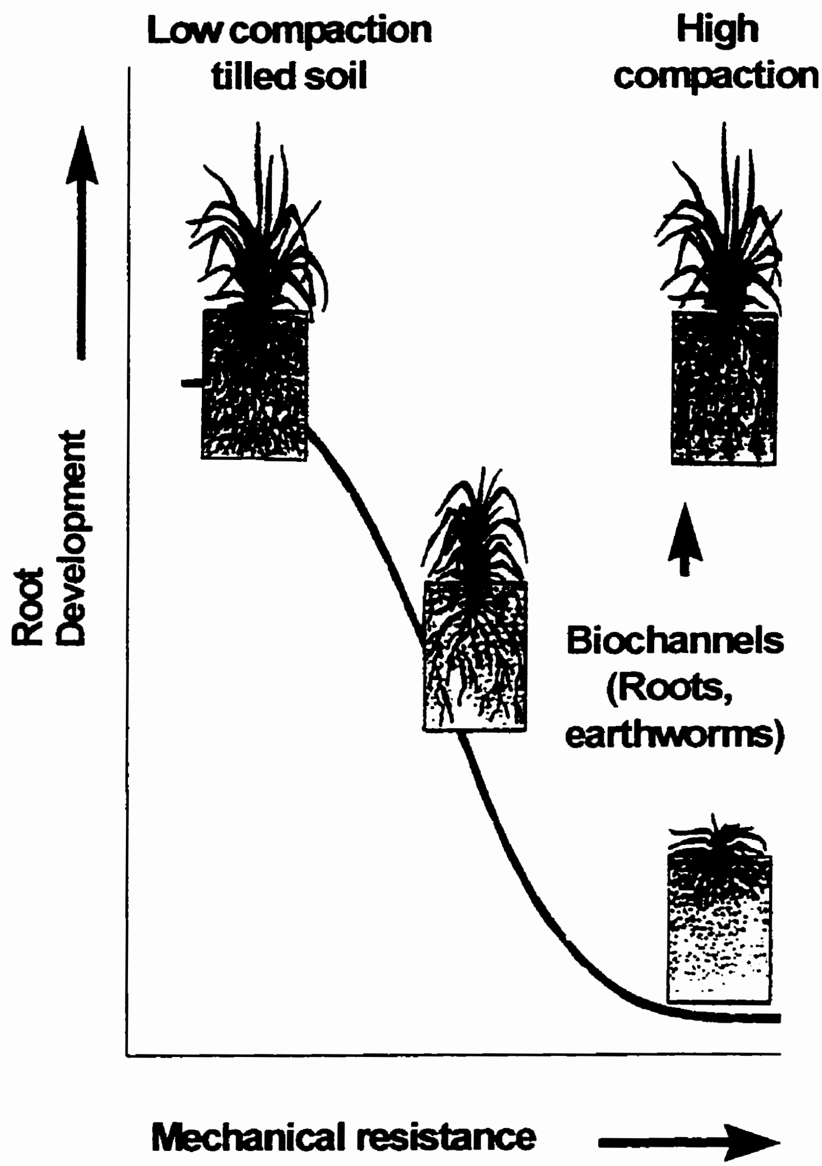
A huge challenge that agricultural research has been tackling for some time, is to provide the necessary knowledge to optimize the new systems in as short a time as possible.

Yet there is optimism that this challenge can be met. Agricultural sciences have today infinitely more abundant and sophisticated tools than when the tillage-based systems were developed. The widespread availability of powerful computers, communication devices, data loggers, and the development of sophisticated laboratory equipment make it possible to do things today that were unthinkable only 20 years ago.

Zero tillage has been increasingly used in Uruguay, where crops have been produced as part of mixed crop-livestock systems for more than three decades. One of the major constraints to adoption of zero tillage in Uruguay is soil compaction, which results from a combination of factors including a wet climate, a dominance of medium to fine textured soils with low water infiltration capacities, and compaction by machinery traffic and grazing cattle.

Crops growing in undisturbed soil are often subjected to poor seed-soil contact, frequent waterlogging, high mechanical impedance for root growth, nutrient deficiency, and frequent moisture stress (Blevins and Frye 1993, Ehlers *et al.* 1987). These conditions would be particularly detrimental during the transition from tillage-based systems, until the long-term accumulation of soil organic matter, and the action of growing and decaying roots, soil fauna and natural forces under zero tillage can cause soil structure to develop. Figure 1.1 represents a conceptual model of these processes. The left side of the curve shows a situation where soil structure is adequate, and plant growth is not limited by soil physical factors. As mechanical resistance increases due to factors such as soil compaction and degradation, plant growth will be impaired. Such may well be the case where a zero-tillage system was just started in a poorly structured soil. After a number of years, soil structure can be built by natural agents, leading to the situation represented in the upper right corner in Fig. 1.1. Here, roots would

Figure 1.1. A model of the effect of soil compaction on root development, and the long-term improvement of the soil structure in undisturbed soils.



grow through a system of biochannels which are predominantly vertical, and would explore the soil sufficiently to sustain plants that are as healthy and productive as those growing in tilled soil.

The process represented by the arrow on the right side of Fig. 1.1 can take a very long time and thus prevent the viability of zero-tillage in excessively compacted soils. It is necessary to develop ways of accelerating this process.

Soil loosening by mechanical means while preserving the residue cover is one way of reducing excess soil compaction in the short term, without impairing the long-term action of soil structure building. Exploiting the ability of certain species to produce extended root systems in compacted soils is another approach to avoid productivity losses in the short term, and to accelerate soil structure building by biological tillage (Dexter 1991).

In light of the above, this thesis had the following major objectives: 1) To assess the extent of soil physical constraints for crop production with zero tillage in mixed systems in Uruguay. 2) To adapt and develop analytical methods for describing soil quality from the standpoint of physical structure. 3) To evaluate the effectiveness of soil mechanical loosening by a specialized subsoiler, the Paraplow, in increasing the viability of direct-seeding systems in fine-textured soils subjected to frequent traffic in wet conditions. 4) To study the interactions of crop sequences with subsoiling by Paraplow on soil properties and crop behaviour.

2. LITERATURE REVIEW

2.1. INTRODUCTION

Soils are the reservoir of nutrients, water, energy and oxygen for plants, and provide the physical support for roots. The physical structure of soil regulates the storage capacity and the intensity and direction of flow of different compounds and energy, and varies widely in response to genetic and environmental factors.

Measurement of soil structure is complicated by the complexity of the soil system, and the multiplicity of its functions. The basic mineralogical composition and particle size distribution, as well as the way these particles are bonded together to build aggregates, are major factors in determining the various soil physical properties. These factors can be easily quantified according to well-established standard methods (Klute 1986) to provide some description of the system. However, the strong interaction of these factors with climate, biological activity and agricultural practices, produce a profusion of possible structures even for the same basic mineralogical composition and particle size distribution.

The highly dynamic nature of soil structure poses an additional difficulty for its measurement. One single event, such as a rainfall event or a tillage operation, can drastically modify the soil structure in a short-time period. Consequently, soil structure can only be defined by means of parameters that measure only partial processes or properties, with reference to a certain time frame. This review deals with the physical process of root growth, and therefore is mainly focussed on to those aspects of the soil structure that affect this biological process.

2.2. SOIL FUNDAMENTAL PROPERTIES DEFINING THE PHYSICAL ENVIRONMENT OF ROOTS

Letey (1985) analysed the relationship between soil physical properties and crop production. He stated that, even though a large number of variables, including bulk density, pore size distribution, and aggregate stability have a definite influence on root development, plant growth is directly governed by only four fundamental physical factors: mechanical impedance, and water, oxygen and energy availability. The measurable properties associated with these factors are, respectively, penetration resistance (PR) to metal probes, soil water potential, oxygen diffusion rate, and temperature.

The determination of the optimum levels of these variables is complicated by the fact that they are closely interrelated and that they vary in both time and space. As stated by Letey (1985), of the four factors, soil moisture is the most dominant. An analysis of each of these variables and their influence on plants follows.

2.2.1. Penetration Resistance

Plant roots growing in porous media have to overcome mechanical resistance. This is achieved either by penetrating pre-existent pores and channels big enough to accommodate the roots (Wiersum 1957), or by deforming the structure of the medium. Roots deform the soil mainly by shearing failure and compression (Barley and Greacen 1967). Because of this, the soil properties that ultimately control mechanical impedance to roots are shearing strength, which is in turn a function of cohesiveness and angle of internal friction, and compressibility.

Soil penetration resistance depends mainly on soil type (i.e. soil texture), bulk density and soil moisture content (Taylor and Gardner 1963, Camp and Lund 1968, Taylor and Ratliff

1969, Ayers and Perumpral 1982, Henderson *et al.* 1988). These effects are discussed in the following sections.

2.2.1.1. *Cone Penetrometers*

Cone probes of static penetration are the standard instruments for measuring soil mechanical impedance to root growth and for detecting compacted soil layers. Available penetrometers are capable of recording resistance values at depth increments as small as 0.01 m, to a maximum depth of 1 m.

As a penetrometer is pushed down into the soil, several processes occur, including cutting of soil, shearing failure with compression, involving metal-to-soil and soil-to-soil friction. The volume of the cone is accommodated by compressing the surrounding soil. The volume of soil subjected to deformation can be spherical, with radii up to ten times the probe radius, for blunt (included semi angle of 30°) probes (Farrell and Greacen 1966), or cylindrical for sharp (included semi angle of 5°) probes (Greacen *et al.* 1968). Because more pressure is required to form a compacted sphere than a cylinder, point resistance tends to be higher for blunt than for sharp probes (Bengough and Mullins 1991). The fundamental property one would like to determine is the point resistance. However, measured penetration resistance is the sum of point resistance, and a frictional component, the latter being higher for sharp probes due to a larger contact area between cone and soil.

Blunt cones compact the soil in the path of the probe, creating a body of soil that moves ahead of the probe, thus artificially increasing the frictional resistance offered by the soil at the depths below. To minimise both soil-metal and soil-soil frictional interferences, cones of medium included semi angles are widely used. Koolen and Vaandrager (1984) and

Voorhees *et al.* (1975) have found that lowest cone resistances occur at semi angles between 15° and 20°.

The speed at which the cone probe is introduced into the soil is another factor affecting the measured resistance, since soil compression is a time-dependent process. Slowly moving probes would allow the soil particles being stressed to rearrange and transmit the pressure to particles located further away. Thus, one expects a more representative measurement with slow than with fast penetration. Also, the probe causes tensile failure, which relieves stress at the tip, and is also time-dependent. Waldron and Constantin (1970) and Voorhees *et al.* (1975) demonstrated this effect of speed for slowly moving (less than 1 mm/min), fine probes. Bradford *et al.* (1971) concluded that the time-dependence effect was negligible when fine probes were driven into the soil at speeds higher than 1 mm/min. Freitag (1968) demonstrated that increasing penetration speed increased cone resistance in fine-grained soils.

The resistance sensed by a cone probe penetrating into a soil is the sum of the pressure at the tip of the cone and a frictional component, which includes soil-metal friction and adhesion. Tip pressure is a function of soil shearing strength -determined by cohesion and angle of internal friction- and compressibility (Farrell and Greacen 1966). Soil-metal friction can be of high magnitude (Armbruster *et al.* 1990) and is often not reported as a separate component of penetration resistance.

2.2.1.2. *Effect of Soil Moisture on Penetration Resistance*

Soil moisture affects all five factors mentioned above (cohesion, angle of internal friction, compressibility, soil-metal friction and adhesion). Cohesion is at its minimum in saturated soil due to the presence of free water in soil pores. As soil moisture decreases, negative water potentials develop, and water held by soil particles acts as a bonding agent, thus increasing cohesion. The contribution of matric potential to soil cohesion is directly proportional to the absolute value of matric potential multiplied by a factor depending on the degree of saturation, as was demonstrated by Williams and Shaykewich (1970). This proportionality factor increases sigmoidally from 0 to 1 as soil moisture increases from dry to saturated. This implies that soil cohesion reaches a maximum at certain intermediate soil moisture content, at which the degree of soil saturation is still kept at a relatively high level. Decreasing soil moisture content beyond this maximum value would decrease soil cohesion.

Camp and Gill (1969) reported a linear decrease in cohesion and also in angle of internal friction as soil moisture content was increased from 0 to 30 % by weight. The decrease in both parameters was the more pronounced the finer was the soil texture. They attributed these changes in cohesion and angle of internal friction to increase in soil density due to shrinkage and to some other unknown factor. This latter factor could well have been the contribution of soil matric potential, as stated by Williams and Shaykewich (1970).

The increase in bulk density with soil drying would increase cohesion (Camp and Gill 1969) due to higher number of contacts between particles per unit volume of soil, and this would mask the decrease in soil cohesion expected at the lowest moisture contents. Ayers and Bowen (1987) reported an increase in both cohesion and angle of internal friction in a loamy sand, with a soil moisture increase from 3 to 10%. The increase in cohesion was greater at high soil densities.

Compressibility is also closely related to soil water content (Larson *et al.* 1980). As soil moisture increases, the maximum bulk density achieved by a compaction force increases, up to a maximum occurring at some water content below saturation. Above this point, pore water pressure starts to rise, acting against compressive forces, thus reducing compressibility. Henderson *et al.* (1988) found that for several sandy soils, maximum compressibility occurred between 60 and 90 % of pore saturation. They also speculated that compressibility was higher in soils containing a wide range of particle sizes because fine particles could be accommodated within large pores between coarser soil particles. The change in compressibility with soil moisture is obviously related to soil strength parameters discussed above. In fact, soil compressibility integrates the effects of cohesion and angle of internal friction. Both pioneer works in the subject (Farrell and Greacen 1966, and Greacen *et al.* 1968) assumed that compressibility was the main soil property involved in determining penetration resistance.

The effects of soil moisture on adhesion and skin friction are not specifically reported in the literature. It can be speculated that these two variables behave in a similar manner as cohesion and internal friction, respectively, with maxima at some very low water content, and minima at saturation.

As a result of the modifications of the five factors mentioned above, the overall effect of soil moisture on penetration resistance would be as follows: if soil shrinkage and expansion are not involved, the strength parameters and compressibility would be the main determinant of resistance, and the relationship would show a maximum in penetration resistance (PR) at intermediate moisture levels (Ayers and Perumpral 1982). On the other hand, if friction is involved, the decrease in soil strength at low moisture would be compensated for by increasing soil-to-soil and soil-to-metal friction. The resulting function would show an exponential increase in penetration resistance with decreases in soil moisture.

The relationship between PR and moisture is a function of water retention properties, which in turn is related to soil structure (Gupta *et al.* 1989). Consequently, determination of this relationship would be an important tool for describing soil structure.

2.2.1.3. *Effect of Bulk Density and Soil Type on Penetration Resistance*

The effect of soil drying on penetration resistance described above is more marked at higher soil bulk densities (Taylor and Ratliff 1969, Ayers and Perumpral 1982). An increase in soil density implies a more tight packing of soil particles, which causes the angle of internal friction to increase. Also, as bulk density increases, soil compressibility decreases, thus making the soil harder to penetrate by roots or metal probes.

The particle size distribution of a soil is an important factor determining the penetration resistance. Because of their high cohesiveness, clay soils develop extremely high levels of penetration resistance upon drying. Working with artificial soils with bulk density of 2 Mg m^{-3}, Ayers and Perumpral (1982) determined that the maximum penetration resistance in a soil with 100 % clay was 12 MPa, at a moisture content of around 10 % by weight. Meanwhile, a soil composed by only sand particles, had a maximum penetration resistance of only 0.05 MPa, at 6 % moisture. In reality, clay soils usually have much lower bulk density and higher soil moisture, and therefore, penetration resistance values are usually much lower than those reported by Ayers and Perumpral (1982). On the other hand, sandy soils may develop very high penetration resistance due to high friction, and values found normally are higher than those expected from their cohesiveness (Henderson *et al.* 1988).

Mielke *et al.* (1994) estimated for a wide range of real soils that at a given soil moisture content, the penetration resistance increased with clay proportion. The increase in soil strength with drying was not so directly related to clay content, and was higher for a silty clay loam than for a clay.

2.2.2. Soil Moisture

The availability of soil moisture is one of the major factors governing crop development. In addition, soil moisture content markedly affects oxygen diffusion rate, soil temperature, and mechanical resistance to root growth.

Water occupies the pore space of the soil, and is retained in the soil matrix by various forces. To uptake water, a plant must overcome these forces, which are very low when the soil moisture content is near saturation, and increase as the soil gets drier. The relationship between soil moisture content, expressed as the percent of volume space occupied by water, and the soil water potential, expressed as the energy required to bring soil water to free water state, is a fundamental property of soil known as the water retention characteristic curve (Hamblin 1985, Hanks 1992). The shape of this curve is a function of soil structure (Gupta *et al.* 1989, Nimmo 1997, Shaykewich 1970) among other factors.

Only a fraction of the water present in a soil may be used by plants. According to the classical concept, available moisture is that retained between two notable points of the water characteristic retention curve: field capacity and permanent wilting point. Field capacity is the water retained after a saturated soil is drained until water discharge virtually stops (Veihmeyer and Hendrickson 1949), and generally corresponds to matric potentials between -10 and -50 kPa. Wilting point is the minimum soil moisture at which plants can grow, corresponding to a potential near -1.5 MPa (Hillel 1980).

These limits are affected by a number of factors, and in general, available soil moisture is less than the difference between field capacity and wilting point. The concept of field capacity as the ideal water content may be invalidated if, as occurs in poorly structured soils, the oxygen diffusion to roots is impaired. On the other hand, the lower limit of available water is coincident with the wilting point only when roots can keep growing against the increasing mechanical resistance that develops when soil gets dry. The distance from which roots can extract water from soil is reduced to a few millimetres in dry soil, due to the decrease in hydraulic conductivity that occurs at low moisture content (Gardner 1960). Because of this, water extraction at low water potentials depends on the presence of high root densities.

These limitations to the classical concept led Letey (1985) to define the non-limiting water range (NLWR) as the water retained between an upper limit determined by either field capacity or the point at which oxygen becomes limiting, whichever is lower; and a lower limit, defined by either the wilting point or the moisture content at which mechanical impedance becomes limiting, whichever is higher. da Silva *et al.* (1994) perfected this concept by introducing the least-limiting water range (LLWR) concept, and provided the first characterizations of this indicator in two soils. They proposed to use LLWR as an indicator of soil structural quality, and in a later work (da Silva and Kay 1996) attempted to relate LLWR with crop yield.

2.2.3 Soil Temperature

The soil surface intercepts energy in the form of solar radiation (short wave) and atmospheric radiation (long wave), and emits long-wave radiation at a rate governed by soil temperature. The balance of these processes, known as net radiation (Davies and Idso 1979), is positive in the daytime, and negative at night. The net radiation energy is stored as heat in the soil, used by biological processes, dissipated as heat by convection, or dissipated as latent heat by water evaporation from soil (Rosenberg *et al.* 1983). When soil moisture content is high, evaporation is the process consuming the most energy, whereas in dry conditions, most of the net radiation energy is used to warm up the soil and air (Ross *et al.* 1985), and then lost as night radiation to the atmosphere. As a consequence, soil temperature is lower and less variable in wet than in dry soil (Hanks 1992).

The proportion of net radiation that is used for heat storage in soil depends on soil structure and moisture content. Due to the high specific heat of water, wet soils are capable of absorbing large amounts of energy with relatively small changes in soil temperature (Hillel 1980), and since heat flow within the soil is driven by temperature gradients, heat movement to deep soil layers is limited.

The effect of soil structure on temperature is evident mainly in relatively dry soils. Specific heat is about five times lower for soil minerals than water, and therefore, temperature gradients are easily created in dry soils. If the number of contact points between soil particles is large, as is the case in compacted or light-textured soils, thermal diffusivity is also large.

Optimal soil temperatures for root development are somewhat lower than those for shoot growth. Depending on the plant species, they vary between 20 and 25 °C (Bowen 1991).

2.2.4. Oxygen Diffusion Rate

Plant roots and microorganisms in the rhizosphere use oxygen as the main final acceptor of electrons in the respiratory process. Oxygen molecules diffuse from the atmosphere into the soil through the porous space, which is occupied by air and water. Oxygen has low water solubility (0.039 $g.L^{-1}$ at standard temperature and pressure). Also, the diffusivity of oxygen is four orders of magnitude higher in air than in water. Consequently, the supply of oxygen to roots depends on the existence of a continuous system of air-filled pores. Therefore, soil moisture content, pore-size distribution and landscape positions are soil properties directly affecting the aeration status of roots.

It is commonly accepted that a soil with air-filled porosity lower than 10% would have limitations to the normal supply of oxygen to roots (Grable 1971). However, this is only an empirical figure, and can not be used in a wide range of situations. The measurement of the oxygen diffusion rate to a platinum micro electrode located in the soil (Lemon and Erickson 1952) would be a more reasonable indicator of the aeration status. Critical values for this parameter, below which root growth would be impaired, vary between 0.2 and 0.3 $\mu g\ O_2\ cm^{-2}\ min^{-1}$ (Stolzy and Letey 1964, Erickson 1982).

2.3. SOIL COMPACTION

The degree of soil packing or compactness determines suitability for crop growth, traffic bearing capacity, and susceptibility to erosion, among other factors. A very loose soil may provide adequate conditions for plant development, but can be susceptible to erosion and may not support machinery traffic. On the other extreme, soils with high degree of compactness may support traffic in a wide range of soil moisture contents, but impose important restrictions for plant growth.

Compaction is a widespread process of soil structure deterioration in agricultural systems, affecting crop production in all climates (Soane and van Ouwekerk 1994). In the past, the use of draft animals and steam tractors was a major cause of soil compaction. With the development of the internal combustion engine, the load on soils was reduced until the 1960's, when the trend towards increasingly heavier farm machinery started (Freitag 1979). At present, the use of heavy tractors with proportionally smaller tires impose an increasing load on agricultural lands.

Tillage loosens the soil, thus favouring water infiltration, aeration and root development. When soil is left unplowed, such as in no-tillage systems, natural consolidation tends to increase the soil bulk density, which adds to the effect of compacting agents like machinery and grazing animals.

2.3.1. Traffic-Induced Soil Compaction

Wheel traffic causes a densification of the soil underneath. The increase in bulk density of soil and the depth affected depend on factors such as soil texture, soil moisture content, contact pressure, axle load, speed of vehicle and number of passes (Arvidsson and Håkansson 1996, Raghavan et al. 1990).

Compared to the abundance of knowledge on soil compaction by agricultural machinery, there is very little information on the effects of trampling by grazing animals on soil properties. It can be estimated from hoof basal area and body weight data that grazing animals apply pressures on soil in the range from 150 (for a 300-kg steer) to 350 kPa (for an adult sheep), figures notoriously higher than those corresponding to farm tractors, which are in the order of 80 (high-flotation tires) to160 kPa (single radial tires) (Wood *et al.* 1991). In consequence, the degree and extent of soil densification would be expected to be higher when caused by animals than by tractors.

In this sense, Touchton *et al.* (1989) detected compaction produced by animals to a depth of 50 cm, while the effect of traffic during planting of summer crops following winter grazing reached only to 25 cm. Hill and Meza-Montalvo (1990) reported that wheel traffic on tram-lines during 14 years caused soil compaction underneath that extended to less than 30-cm depth. Wood *et al.* (1993) found that traffic by heavy grain carts, with a tyre pressure of 210 kPa, caused changes in soil physical properties to the 40-cm depth.

Soil damage due to compaction can be minimized by avoiding traffic on wet soil. In this sense, Proffitt *et al.* (1995) found that continuous grazing of a pasture with sheep increased soil bulk density of a clay loam by 7 %, and reduced water infiltration capacity to 58 % that of the non-grazed control. However, when sheep were retired every time the soil moisture content reached the plastic limit, soil deterioration was not nearly as serious as with continuous grazing.

The degree of compaction caused by tractors can also be controlled by the type of wheels used. Brown *et al.* (1992) reported that wheeled tractors, with ground pressures of 125 kPa, caused more compaction than track-type tractors, which had ground pressures of 40 kPa. Due to a more uniform stress distribution, metal tracks are usually less damaging to soil than rubber tracks (Marsili and Servadio 1996). The use of high-flotation tires (Wood *et al.* 1991) is another way of reducing compaction forces applied on soils.

2.3.2. Plant-Root-Induced Soil Compaction

Plant roots also cause soil compaction by radial enlarging. Dexter (1987) proposed a model for describing this process. His main assumptions were as follows: a) the volume of the root is accommodated by the loss of an equal volume of pore space from the surrounding soil; b) the soil adjacent to the root is compressed to a minimum possible porosity, which is a constant for a given soil; c) between this zone of minimum porosity and the bulk of soil, porosity increases exponentially; d) the exponent of this relation includes a constant of the soil, which was estimated by this author (Dexter 1987) to be around 0.5, multiplied by the relative distance from the root; e) the distance from the root to which soil density is affected depends on the root diameter.

A few years later, Bruand *et al.* (1996) applied Dexter's model to data obtained with corn roots growing in a silty clay loam, and found that the constant in the exponent was much higher (4.3), which means that the soil compression by roots extended to a shorter distance than that predicted by Dexter (1987). Bruand *et al.* (1996) attributed this difference to the fact that Dexter (1987) had used remolded soil, whereas they used structured soil.

Several studies have looked at the consequences of root growth on soil micro structure. Greacen *et al.* (1968) determined that the effect of a pea radicle in increasing soil density extended to a distance of 8-10 times the root radius, although most of the influence was restricted to a distance of three times the root radius.

Dexter *et al.* (1983) studied the influence of cumulative rainfall and the presence of a wheat crop on the structure of a soil managed with two tillage systems. They found that the wheat reduced the volume of pores higher than 0.5 mm by 24 % compared to the uncropped areas, at the same time as the mean aggregate size was increased by 33 %. This was attributed to unknown factors.

However, these results by Dexter *et al.* (1983) could be at least partly explained by later findings by Misra *et al.* (1986). These authors, working with pea, cotton and sunflower radicles with radii between 0.4 and 1.0 mm, determined that the distance at which the roots caused plastic failure in the surrounding soil extended for up to at least 15 mm, the maximum aggregate size used. They estimated that even with larger aggregates, it could be safely concluded that growing roots always cause plastic deformation of soil. If this is the case, and if soil aggregates are fairly small, most of the volume occupied by roots would be at the expense of macropores between aggregates.

Blevins *et al.* (1970) had also demonstrated that there was a decrease in the volume of pores higher than 50 μm within a distance of 0.4 mm from the root surface of trees. Bruand *et al.* (1996) also detected a 24 % reduction in porosity, mainly in the range from 100 to 500 μm in diameter. Using a different approach, Guidi *et al.* (1985) demonstrated that the porosity of soil adhering to corn roots was 13 % lower than that of the bulk soil.

The effect of growing plant roots on soil structure has also been observed macroscopically. Waldron and Dakessian (1982) studied the effect of several plant species on soil shearing resistance, with the purpose of stabilizing soil against downslope displacement. Alfalfa and several grass species were the most effective, causing respectively a four-fold and three-fold increase in shearing strength, compared to uncropped soil. In this case, the effects of plant roots resulted mainly from the presence of roots that resist shearing (Waldron and Dakessian 1981). However, increased soil cohesion, due to higher inter-particle contact, may have also contributed to the observed increase in soil strength.

Willatt and Sulistyaningsih (1990) also demonstrated that rice plants caused an increase in soil shearing strength, measured with a vane shear tester, from 2.7 to 4.9 kPa. The bearing capacity of the soil, determined with a laboratory penetrometer, was increased from

71 to 161 kPa. There was a positive correlation between root weight and soil bearing capacity.

2.4. PLANT RESPONSES AND ADAPTION TO STRESS CAUSED BY SOIL COMPACTION

Plants respond in various ways to hostile soil physical environment. Both subterranean organs, which directly sense these conditions, and aerial parts, which receive signals from the subsoil, are equally affected. It has been known for a long time that this synchrony between shoot and root growth, as well as the compensatory growth of unaffected portions of the root systems, are a consequence of the action of growth regulators (Russell 1977). However, very little is known about the detailed mechanisms involved in the various responses.

Tardieu (1994) proposed that plant responses to soil compaction would be governed by multiple physical and chemical signals acting simultaneously. Such signals would be: a) the mechanical process of soil resistance opposing root turgor pressure; b) a chemical message, probably involving ethylene, which causes root thickening as a means of overcoming soil resistance; c) another chemical message, probably involving ABA, which induces stomatal closure in response to root clumping, and helps conserve soil water even when soil moisture levels are high (Tardieu *et al.* 1992); and d) still another chemical message, consisting of soluble sugar buildup, which reduces photosynthesis rate. Ternesi (1994) provided evidence that confinement of roots also inhibited shoot growth of sunflower, a response that was presumably mediated by a chemical signal.

These signals sent by the roots are emitted very promptly, even before the onset of adverse situations. Passioura and Stirzaker (1993) described these preventive mechanisms as 'feedforward' responses of plants, and demonstrated that conditions such as reduced soil volume ('Bonsai effect'), soil compaction, incipient soil drying, excessively large pores, and reduced soil temperature, all trigger conservative responses by plants.

Most of the knowledge in plant responses to soil compaction is based on what happens below ground. The reaction of roots to their physical environment, namely high mechanical impedance and reduced aeration, are analysed in the following sections, after providing a brief description of roots growing in favourable soil conditions.

2.4.1. Normal Root Morphology and Physiology

Most studies on roots have focussed on monocots, in particular the grass family, very likely due to their economic importance. In these species, most of the root growth occurs from apical meristems, whereas in dicots, besides extension and branching from the meristems, growth also occurs by thickening as a consequence of cambial activity. From the standpoint of water and nutrient absorption functions, the growth associated with meristematic activity is of most interest.

Several types of roots coexist in single plants. Grasses have seminal and nodal or adventitious roots. The former include both the embryo root and others arising from the embryonic nodes, whereas the latter include those emerging after plant establishment from stem nodes. Both types differ in their morphology (Waisel and Eshel 1991) and physiology. Bole (1977) found that nodal roots in wheat were more efficient than seminal roots in absorbing water and phosphorus.

A difference can also be made between primary axes and laterals. Main root axes usually are thicker and grow faster than branches. Russell (1977) indicated that typical growth rates of cereal roots grown in favourable conditions are 2.0 cm day^{-1} (root axes), 0.5 cm day^{-1} (primary laterals) and 0.1 cm day^{-1} (secondary laterals). Longevity is also higher for primary axes than for branches (Fusseder 1987). Because of their more rapid growth, the distance between the root apex and the root zone where complete suberization of the endodermis occurs is higher for primary roots than laterals. This makes primary axes more permeable to water and less selective for nutrients than laterals (Waisel and Eshel 1991). Nodal roots have usually less branching than seminal roots, and this may be related to their higher efficiency for absorbing water and nutrients as stated above.

Fitter *et al.* (1991) established the existence of two extreme topological models for describing root systems: the herringbone (branching is restricted to the main axis) and the dichotomous (every node has the same probability of branching) types. They concluded that the herringbone type has higher construction, maintenance and transport costs, but higher soil exploitation efficiency (volume of soil explored per unit mass of roots), particularly for highly mobile resources (water, nitrogen) than the dichotomous type. In this sense, Fitter and Stickland (1991) found that dicots growing under low-nutrient levels and species native to poor soils tended to have long links (distance between laterals) and root systems closer to the herringbone type, whereas annual, highly-demanding species had root systems closer to the dichotomous type (Fitter 1991).

Yamauchi *et al.* (1987) compared the root structures of several species of cereals. Based on their morphological characteristics, they identified four groups of species. Rice and other species were classified in one of the extremes ('concentrated type'), with large number of nodal roots (more than 100 per plant) which had low insertion angles and relatively short and slender laterals. On the other extreme ('scattered type'), wheat, maize, barley, sorghum, rye and oats were all included in the group of plants with relatively small number of nodal roots (less than 80) with wide insertion angles, and long, vigorous, profusely-branched laterals. The concentrated type was correlated with waterlogging tolerance, whereas the scattered type provided high water deficit tolerance. The concentrated and scattered types of roots may be associated with the herringbone and dichotomous types, respectively, as discussed in previous paragraph.

Roots growing in soils with no restrictions can achieve very high extension rates. Hackett and Rose (1972) developed a model for describing the growth of a seminal root of barley. In favourable conditions, 23 days after seeding, the total length of one single seminal root was 720 cm. First- and second-order laterals comprised 60 and 34 % of the total length, respectively. As it is discussed below, growth rates found in normal field conditions are much less than those simulated in this study.

2.4.2. Root Growth in Soil

The growth of roots is driven by the turgor pressure in the meristematic cells. This pressure has to overcome two opposing forces: that offered by the rigidity of the cell walls, and the mechanical resistance of the soil (Dexter 1987b, Greacen and Oh 1972).

The maximum pressure that roots can exert is restricted to about 0.7 to 1.3 MPa in the axial direction and to 0.4 to 0.6 MPa in the radial direction (Gill and Bolt 1955, Misra *et al.* 1986b), and therefore, no growth could be expected when the resistance of the medium surpasses those limits. However, the actual process is much more complex due to the porous nature and heterogeneity of soils.

The pressure exerted by roots depends upon external factors. It has been shown that it increases with strength of the soil (Schuurman 1965) and size of aggregates being penetrated (Misra *et al.* 1986a). The resistance offered by the medium can be very much reduced by the presence of large, continuous pores, even if the strength of the soil matrix is very large (Goss *et al.* 1984). Pore sizes in soil range from $2\text{-}3 \times 10^{-3}$ µm (distance between clay plates) to a few centimetres (cracks). Roots can penetrate through pores larger than their diameter or enlarge smaller pores by radial compaction (Dexter 1987a) providing the soil strength is not too large. Root diameters vary between 20 µm (second order laterals in grasses) and 1 cm (tap roots of dicotyledons) (Hamblin 1985). Since roots cannot force their passage through narrow pores by reducing their diameter (Wiersum 1957), the minimum pore size useful for root growth is determined by the root diameter and the soil compressibility. The proportion of pores larger than 100 µm (Gibbs and Reid 1988) or 50 µm (Goss 1977) has been proposed as parameters associated with root movements in soil.

Although root enlargement is the direct consequence of the axial pressure, force in the radial direction also has a number of important functions: a) it is responsible for the enlargement of pores that are somewhat smaller than the root diameter (Greacen *et al.* 1968, Dexter 1987a, Schuurman 1965); b) it causes the soil to fail by tension, and if the failure propagates ahead of the root tip, it may reduce the resistance of the soil (Abdalla *et al.* 1969, Whiteley *et al.* 1981) depending on the tensile strength of the soil and the distance from the point of radial pressure and the elongating zone of the root; c) radial thickening is a mechanism of enlarging the total force applied in the axial direction by expanding the cross sectional area (Abdalla *et al.* 1969, Barley *et al.* 1965, Gill and Bolt 1955); and d) the skin friction provides anchorage to the axial forces and is an additional component of the force exerted (Stolzy and Barley 1968). The anchorage is also dependent on the size of the void in which the proximal part of the root is located (Dexter 1978).

2.4.3. Mechanical Impedance and Root Growth

Soil strength, as measured by a penetrometer, has been shown to be uniquely related to root penetration, through a wide range of soil moisture contents and bulk densities (Taylor and Gardner 1963) and soils (Taylor *et al.* 1966) all fitting the same relationship. Even though resistance to cone penetration is an empirical determination, it integrates many, although not all, of the factors involved in the mechanical resistance of the soil.

Considerable attention has been given to the critical cone indexes that completely inhibit root growth in soils or artificial media. For a wide range of soil types, plant species and experimental techniques, values reported for critical penetration resistance vary between 1.0 and 5.6 MPa (Bengough and Mullins 1991, Camp and Lund 1968, Cockroft *et al.* 1969, Ehlers *et al.* 1983, Gerard *et al.* 1982, Grimes *et al.* 1975, Martino and Shaykewich 1994 Taylor and Gardner 1963, Taylor *et al.* 1966, Vepraskas and Wagger 1989, Yapa *et al.* 1990). Even after making allowance for variations due to the different types of penetrometers and different species used in these studies, there is still a wide variation. This result indicates that cone index does not combine all the soil physical factors that affect root development.

Gerard *et al.* (1982) determined that the critical cone index decreased as the clay content of the soil increased, while the opposite was found by Vepraskas and Wagger (1989). This suggests that the relation between clay content and penetration resistance is not causal, and it can be speculated that some other factor related to the clay content, such as the pore size distribution, is the fundamental variable causing the critical cone index to vary. If the soil exhibits a continuous system of large pores through which roots can move, growth will occur even at large soil strengths. This would be the reason why critical cone index seems to be higher in the surface than in deep soil horizons (Gerard *et al.* 1982, Grimes *et al.* 1975, Vepraskas and Wagger 1989).

The values of critical strengths mentioned above represent pressures two to six times larger than the maximum pressures that roots can apply. Whiteley *et al.* (1981) used penetrometers of similar size and shape to roots and determined that penetration resistance were three to five times larger than root pressures. The difference can be attributed to the ability of roots to deflect when encountering high strength obstacles (Whiteley and Dexter, 1983), the low friction between root and soil (Cockroft *et al.* 1969), and the capability of the roots to exert radial pressures.

Below the critical strength level, the rate of root elongation is lessened by increases in penetration resistance. This effect begins at very low values of soil strength (Bengough and Mullins 1991, Taylor and Gardner 1963, Taylor *et al* 1966) and there seems to be large variability among species in the sensitivity to mechanical impedance. Taylor and Ratliff (1969) found that increasing the cone index from 0 to 1 MPa reduced the elongation rates of cotton and peanut roots by 62 and 29%, respectively. Soils at different water potentials all produced the same response curve to soil strength for each crop. Voorhees *et al* (1975) reported similar reductions for pea seedlings. In this case, different water potentials fitted the same relationship in a sand, but not in a clay where reductions in the rate of root elongation were more severe at high moisture contents, probably because of aeration problems. If very high water potentials are needed to achieve low penetration resistance, adequate aeration of the roots is impaired, and the rate of elongation increases rather than decreases at low cone indexes (Bar-Yosef and Lambert 1981, Warnaars and Eavis 1972). Barley *et al* (1965) also found differences between species: changing the penetration resistance from 0.9 to 3.4 MPa caused a decline in root length per plant from 14.2 to 2.1 cm (pea) and from 9.4 to 4.8 cm (wheat). Since the force exerted by plants seems to vary only within narrow limits (Gill and Bolt 1955, Misra *et al* 1986b), the interspecific variability in sensitivity to mechanical resistance would relate to the root diameter and the interaction with the pore geometry. Fibrous roots, because of their smaller diameter, seem to be able to grow better than taproots in conditions of high impedance.

In studies where penetration resistance was varied by modifying the soil water potential, the effect of mechanical impedance on root elongation may have been distorted either by a decline in water availability at high resistance (Mirreh and Ketcheson 1973) or by the depletion of oxygen caused by roots accumulating immediately above a compacted soil layer (Asady and Smucker 1989). The restriction in oxygen diffusion at high moisture contents, as already mentioned, is an additional factor increasing variability in response of root growth to soil strength.

A number of studies in which roots were grown on pressurized cells containing artificial media, have shown a very sharp decline in root elongation with externally applied pressures of less than 0.1 MPa (Abdalla *et al* 1969, Goss 1977, Russell and Goss 1974). These studies relied on the assumption that the applied pressure was equal to the pressure acting on the roots. However, it has been demonstrated that this assumption is grossly misleading in a non fluid medium, and underestimates the real pressures on the roots. Richards and Greacen (1986) developed a model based on elastic stiffness and plastic yield parameters of the soil, and predicted that the pressures on the roots are about one order of magnitude larger than the external pressures. Bengough and Mullins (1990) estimated that difference to be between 10 and 40 times, depending on the method used.

Despite all the complexities arising from the rigidity of the metal probes, and their different shape, size and speed of movement with respect to roots, cone penetrometers have proven to be a valuable experimental tool that provides satisfactory empirical estimations of the soil mechanical resistance to root growth, particularly if combined with information about the porosity and pore size distribution.

2.4.4. Plant Responses to High Mechanical Impedance

Roots, when subject to soil mechanical impedance, reduce their extension rates and increase their diameter (Atwell 1990a, Barley 1963, Wilson *et al.* 1977), become distorted (Kirkegaard *et al.* 1992) and at times tend to grow horizontally (Taylor and Burnett 1964). The production of lateral roots is highly stimulated (Veen 1982), particularly on the convex side of the curvature (Goss and Russell 1980). Veen (1982) found that corn root laterals formed in response to soil compaction were longer and more branched than the main axes. Goss and Russell (1980) demonstrated that barley plants subjected to high soil strength produced more tillers and nodal root axes than non-stressed plants. Atwell (1990a), however, reported that wheat plants suffering high soil compaction delayed the formation of tillers compared to plants in non-compacted soil.

The internal concentration of various elements and compounds is also altered by soil compaction. In a study with wheat plants during early tillering, Atwell (1990b) found that concentration of sugars near the root tips was increased, and that of amino acids was decreased as a consequence of soil compaction. The buildup of sugars was likely due to reduced root elongation, and caused an increase in the turgor pressure. The concentration of sugars in the shoots was 21 % higher in plants subjected to high compaction than in unaffected plants. High mechanical impedance also stimulates root exudation of different substances. Boeuf-Tremblay *et al.* (1995) found an increased leakage of nitrogenous compounds in corn plants subjected to compaction.

Several facts support the hypothesis that morphological changes in roots subjected to high soil resistance are not the consequence of just mechanical processes, but also regulated by hormonal mechanisms. Goss and Russell (1980) found that corn radicles markedly reduced their elongation rate during the 10-minute period after their tips contacted the soil matrix, and a few minutes later recovered their initial growth rate. This slowing down did not occur when root caps were excised. In another experiment, the same authors applied external pressure to barley and sugar beet roots for four days, causing a decrease in their elongation rate. When pressure was relieved, recovery of normal growth was achieved after a lag period of three days. These responses strongly suggest the involvement of hormones.

Wilson *et al.* (1977) analysed the modifications in the various tissues of barley roots subjected to high mechanical impedance. Their results can be summarized as follows: a) xylem vessels were not affected, except near the root tip, where their diameter was somewhat reduced; diameter of phloem was increased, mainly because of a higher number of cells; c) the radial length of endodermis cells was dramatically reduced by up to 80 % of that of unimpeded roots, and the volume of endodermis cells decreased by half; d) the tangential length of endodermis cells increased, and consequently, so did the surface area of endodermis per unit length of root; e) the number and total volume of cortical cells was increased, but there was a decrease in the size of cells in the inner cortex layer; and finally, f) both number and size of epidermis cells increased. Similar results were reported by Atwell (1990a).

Working also with spring barley, Lipiec *et al.* (1991) found that impeded roots had roots with rougher surfaces than those growing in non-compacted soils. Such roughness was attributed to distortion in the shape of epidermal cells by incrusted soil particles.

Soil compaction also causes changes at the intracellular level. Veen (1982) found that soil compaction, besides changing the shape of cortical cells of corn nodal roots, produced the deposition of longitudinal cellulose microfibrils on the inside of cell walls. In unimpeded roots, these microfibrils were deposited in radial direction. Roots with axially-oriented microfibrils would restrict longitudinal growth and favour lateral expansion. This change in the orientation of cellulose depositions on cell walls in response to mechanical impedance, could have only be caused, the authors argued, by the action of ethylene.

The role of endogenous ethylene in these responses to mechanical impedance was suggested by Dawkins *et al.* (1983), who observed higher levels of this gas in impeded than in unimpeded roots. The external application of ethephon, a substance that is readily converted to ethylene, produced similar responses to those observed when high mechanical resistance occurs (Jackson 1983). Ethylene is formed in plants by oxidation of ACC (1-amino-cyclopropane-1-carboxylic acid) in response to environmental stresses or hormonal signals which stimulate the synthesis of ACC synthase (Yang and Hoffman 1984). Lachno *et al.*

(1982) had found that high mechanical impedance was associated with increased auxin (indol-propylacetic acid) concentration in the root tips. Auxin formation in the root caps could well be the first reaction of the plant to mechanical impedance, although this has not been documented so far.

2.4.5. Plant Responses to Low Aeration

Oxygen is the normal electron acceptor in the respiratory process occurring in soils. In waterlogged conditions, oxygen is consumed very rapidly, and other electron acceptors have to be used, bringing about the accumulation of a number of substances such as organic acids, methane, ethylene, sulphide and carbon dioxide, which may be toxic for plants (Cannell and Jackson 1981, Russell 1977). As a consequence of the low efficiency of anaerobic respiration, the energy availability for plants is greatly reduced (Vartapetian 1993).

This anaerobic condition triggers a number of morphological and physiological changes in plants growing in such soils (Kawase 1981). Morphological responses include wilting, epinasty, chlorosis of leaves, premature senescence, reduced stem elongation, reduced root growth, and aerenchyma formation (Russell 1977). Roots subjected to flooding are straighter, shorter and more profusely branched than in soils with adequate supply of oxygen (Feldman 1984). Wetland plants such as rice present special adaptations both morphological (congenital aerenchyma) and physiological (a more efficient energy metabolism) to tolerate anaerobic soil (Vartapetian 1993).

Nodal roots of wheat grown in well-aerated soil have pore spaces higher than those of seminal roots and may be more important for survival in conditions of intermittent waterlogging (Erdmann *et al.* 1986). Thomson *et al.* (1990) found that both seminal and nodal roots of wheat shorter than 100 mm developed aerenchyma tissue after being exposed to anaerobic soil for several hours, but longer roots did not. Aerenchyma is formed all along the roots by two different processes: by cell lysis, which occurs mainly in the proximal regions, where cell walls are already rigid, and by radial enlargement of cells in the distal region of the roots (Erdmann *et al.* 1986).

The ability to increase root porosity in response to anoxia differs between (van Noordwijk and Brouwer 1993) and within species. Yu *et al.* (1969) studied the effects of flooding on the roots of several crop species. Respiration rate per unit mass of root tissue was highest for wheat and lowest for barley, whereas corn and sunflower had intermediate values. This was inversely related to root porosity, which was only 2.4 in barley and more than 10 % by volume in the other crops. Of the two wheat cultivars tested, one showed a remarkably high capacity to form aerenchyma in response to anoxia. Erdmann and Wiedenroth (1986) demonstrated that modern wheats and their predecessor and relative species all reduce their root and shoot growth when subjected to flooding, but the former are the least affected because of their enhanced capacity to adapt to these conditions mainly by developing aerenchyma in response to anoxia.

As a consequence of low soil aeration, wheat plants have been shown to accelerate the appearance of nodal roots, and the branching of proximal regions of seminal roots (Wiedenroth and Erdmann 1985). This can be interpreted as a mechanism for renovating the root system, with new roots growing near the soil surface, where oxygen availability is likely to be highest.

There is solid evidence to affirm that ethylene plays a central role in regulating the plant responses to anoxia (Jackson 1985). Ethylene is normally produced by roots, and in well-aerated soils, it easily diffuses away from the roots. It has been suggested that in flooded conditions, however, diffusion is restricted and root growth inhibition occurs along with other adaptive responses (Feldman 1984). Ethylene is also produced in flooded soils (Smith and Robertson 1969), and this soil-borne ethylene may also play a role in plant responses. A more recent study (Jackson *et al.* 1994) showed that the amount of ACC, the biosynthetic precursor of ethylene, transferred from roots to shoots in tomato plants was sharply increased 6 hours after the onset of flooding, immediately causing symptoms such as petiole epinasty, thus suggesting that ACC was readily oxidized to ethylene in the shoots.

In monocots, however, the evidence for ACC or ethylene levels being related with adaptive responses to anoxia seems to be weaker. Larsen *et al.* (1986) did not find any changes in the concentrations of ACC nor ethylene in flooded, compared to well-aerated barley plants. Jackson (1994) on the other hand, proved a connection between ethylene and aerenchyma formation in corn.

Crops may suffer serious grain yield losses due to waterlogging. Cannell *et al.* (1984) reported that winter barley and winter wheat yielded 30 and 24 % less with winter waterlogging than crops growing on well-drained soil. In Australia, Watson *et al.* (1976) reported yield losses due to intermittent waterlogging of 40, 39 and 48 % for wheat, barley and oats, respectively.

2.5. ALLEVIATION OF STRESS IN DIRECT-DRILLING SYSTEMS

Traditionally, diverse tillage practices have been the main tool for mitigating soil compaction problems. However, the improvement in structure achieved by tilling the soil is only transient, because there is not a buildup of stable aggregates by chemical bonding, particularly in soils with low organic matter contents and poor aggregate stability (Dexter 1991).

The current trend to the worldwide adoption of direct-drilling systems, which as discussed above will bring about increased compaction problems, makes it necessary to find alternative ways of dealing with the problem. Current knowledge, and trends for future developments are discussed in this section.

2.5.1. Subsoiling: the Paraplow

Subsoilers have been used to reduce soil compaction for a long time. Conventional subsoilers cause a great deal of soil disturbance and, consequently, are not compatible with conservation-tillage systems.

The effectiveness of subsoiling operations, that has been repeatedly demonstrated in tilled soils (Vepraskas and Miner 1986), would still be greater in conservation tillage, as shown by Busscher and Sojka (1987). This may be related to the thixotropic property of soils, as noted by Dexter (1991), by which soils that have been sheared or moulded by tillage or traffic wheels, are weaker than undisturbed soil, even at the same water content and density.

The Paraplow, a subsoiling tool developed in England two decades ago, can be used to loosen compacted soil up to 50-cm depth with very little surface disturbance, therefore allowing direct drilling. It was first introduced by Pidgeon (1982), and also described later by Mukhtar *et al.* (1985), Erbach *et al.* (1992) and others.

2.5.1.1. *Description of the Paraplow*

The Paraplow consists of shanks or legs mounted on a tool bar which is tilted 45° with respect to the direction of advance on the horizontal plane (Fig. 2.1). The shanks are also slanted 45° from the vertical, and have chisel points slightly wider than the shanks. Each leg has also an adjustable shatter plate located above and behind the point (Fig. 2.1). Large disk coulters for cutting through surface residue are also mounted on the tool bar.

The slanted leg lifts the soil as the Paraplow moves forward, causing soil fracturing by planes of natural weakness, and leaving the surface minimally disturbed. The shatter plates provide additional lifting and also certain twisting of soil, which after the implement has passed, falls back acquiring a new structure with no soil inversion.

Draft power requirement as stated by makers of Paraplow vary between 20 and 30 kW per shank. There are not many scientific studies evaluating draft requirements. Karlen *et al.* (1991) studied the energy requirements and performance of different deep tillage implements, including a Paratill, which is similar to the Paraplow, on a loamy sand soil. This implement, passed at 40-cm depth in dry conditions, required a draw bar power of 16.2 kW at a forward speed of 0.84 $m.s^{-1}$. Fuel consumption was 22.7 $L.ha^{-1}$. The energy requirement would be expected to be less at higher moisture contents, and higher in finer textured soils.

The Paraplow has been tested in a wide variety of soils from loamy sands to clay loams (Table 2.1). The working depth of this implement is up to 50 cm. However, most studies have used between 30 and 35 cm. Leg spacing is usually 50 cm, and some workers have reported using up to 76 cm, probably to fit with distance between crop rows. Almost all reports listed in Table 2.1 have demonstrated some positive effect of this subsoiler on soil physical properties, which lasted for several months.

Figure 2.1. Diagram of the Paraplow viewed from different angles. Adapted from commercial brochures.

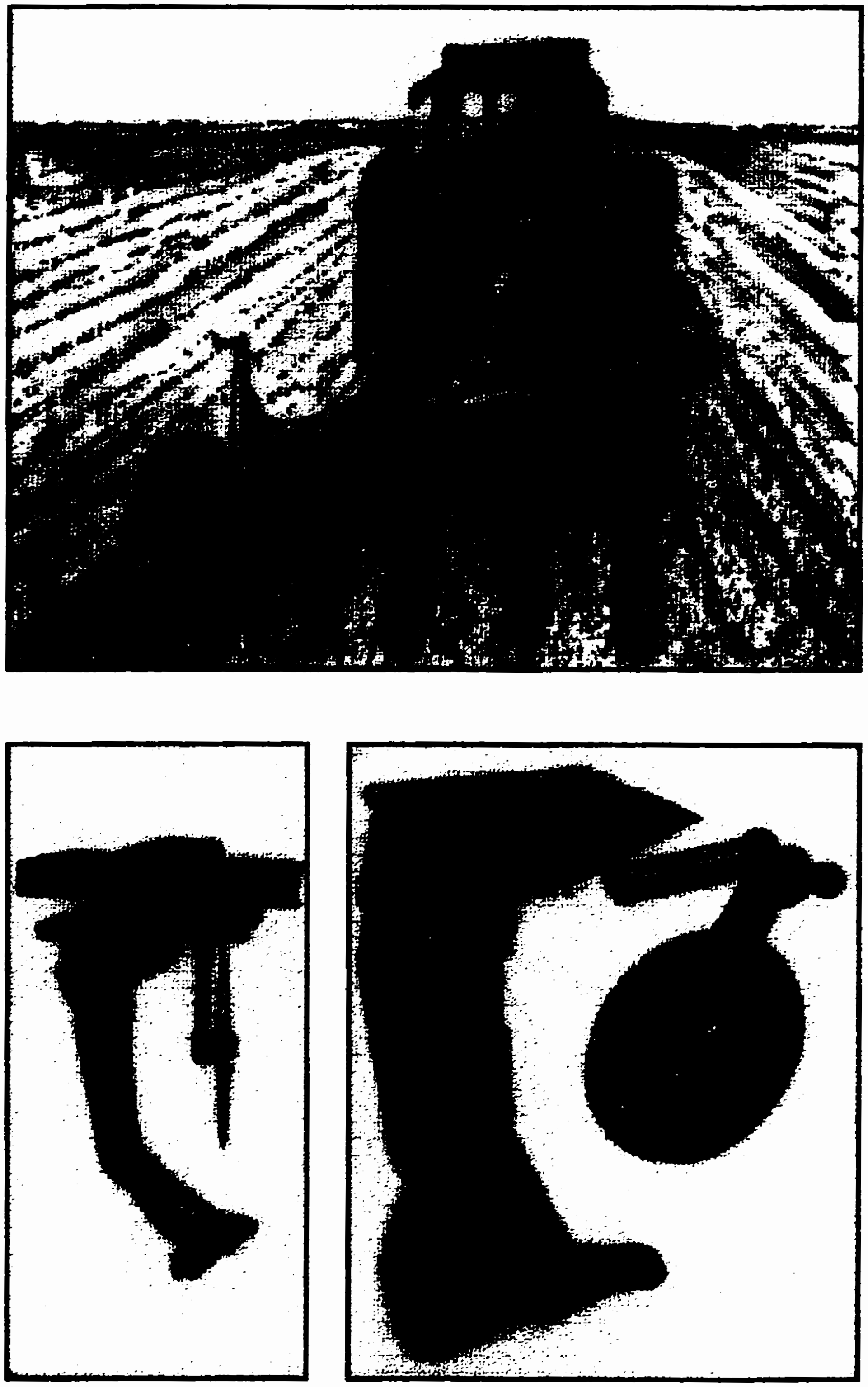


Table 2.1 List of published papers reporting on the Paraplow, including soil types used, leg spacing, depth of operation and time residuality of effects.

Soil Type	Leg Spacing	Depth (cm)	Time Residuality (Months)	Authors
Sandy clay loam	50	35	> 7	Braim *et al.* 1984
Silty clay loam Silt loam Loam	50	30	—	Erbach *et al.* 1984
Silty clay loam Silt loam Loam	50	25-30	—	Mukhtar *et al.* 1985
Sandy clay loam	50	29-35	> 7	Hipps and Hodgson 1987
Loamy Sand	76	45	6	Busscher *et al.* 1988
Silt loam	50	35	> 9	Ehlers and Baeumer 1988
Sandy clay loam	50	35	20	Hipps and Hodgson 1988 a
	50	33-35	.	Hodgson *et al.* 1989
Sandy loam	50	43	—	Touchton *et al.* 1989
Expansive clay soil	62	45	—	Chambers *et al.* 1990
Silt loam	50	20-25	> 5	Pikul *et al.* 1990
Loamy sand	76	40	—	Karlen *et al.* 1991
Silt clay loam Loam Silt loam	50	30	—	Erbach *et al.* 1992
Clay loam	50	30	—	Radford *et al.* 1992
Clay loam	61	30	< 12	Clark *et al.* 1993
Loam	50	35	—	Mc Conkey *et al.* 1997

2.5.1.2. *Effect of Paraplow on Soil Porosity*

The most obvious effect of paraplowing would be a decrease in soil bulk density associated with the increase in pore space. Nine months after passing the Paraplow on a silt loam, Ehlers and Baeumer (1988) measured a decrease in bulk density due to subsoiling from 1.4 to 1.3 Mg m^{-3} at 350-mm depth. Erbach *et al.* (1992) detected similar effects on four poorly drained soils in Iowa.

However, a large number of reports indicate little or no effect of paraplowing on bulk density (Braim *et al.* 1984, Erbach *et al.* 1984, Mukhtar *et al.* 1985, Hipps and Hodgson 1988a), even though other soil physical properties were affected. This could have been related with the lack of a suitable method for bulk density determination in loosened soil which, in all cases, was based on soil cores of relatively small size. Measuring density by using these methods immediately after paraplowing would be virtually impossible due to the abundance of soil cracks.

The increase in porosity caused by the Paraplow is almost exclusively due to the effect on large pores. Hipps and Hodgson (1988a) reported an increase from 7.8 to 13.3 % in the volume of a sandy clay loam soil with pores higher than 60 μm. Pikul *et al.* (1990) measured an increase in soil macroporosity in the spring due to fall-paraplowing on a silt loam. The no-till treatment had less than 1% of soil volume occupied by macropores, while the Paraplowed plots had between 7 and 17 %, depending on soil depth.

2.5.1.3. *Effect of Paraplow on Soil Water Infiltration Capacity*

Another consistent effect of paraplowing is the increase in water infiltration capacity. As shown by Hipps and Hodgson (1988a) many of the cracks formed in the soil profile after passing the Paraplow could be traced up to the soil surface. The increase in macroporosity and the continuity of this pore system would be the main reasons for the improved infiltration capacity.

Mukhtar *et al.* (1985) studied the effect of various tillage systems on soil water infiltration on four different soils at several dates during one cropping season. Averaged over all sites and sampling dates, 1-minute cumulative water infiltration was 2.44, 1.24 and 0.80 cm for Paraplow, moldboard-plow and no-tillage, respectively. Values for 30-minute cumulative infiltration were 28.6, 11.7 and 8.5 cm, respectively. The values were higher for Paraplow in spite of higher soil moisture contents for this treatment. These trends were observed in all four soils. Similar treatments were evaluated by Pikul *et al.* (1990) on a silt loam. In this case, the final infiltration rates were 23.5, 22.8 and 9.3 mm h^{-1} for Paraplow, chisel-plow, and no-tillage, respectively.

Clark *et al.* (1993) evaluated the influence of the Paratill (a subsoiler very similar to the Paraplow) frequency on physical properties of a fine-textured, eroded soil. Steady-state infiltration rates were 8.6, 4.2 and 1.4 cm h^{-1} for the Paratill passed one, two and three years earlier, respectively.

Conventional subsoilers, and even paraplowing in combination with conventional tillage (McConkey *et al.* 1997), also improve infiltration capacity. However, due to low aggregate stability, slaking of soil by rain tends to clog the macropores (Dexter *et al.* 1987), and infiltration rate decreases rapidly with time. Ehlers and Baeumer (1988) found that constant infiltration rate in the spring on a silt loam was 20 and 0 cm day^{-1} for fall-Paraplow and fall-mouldboard-plow treatments, respectively.

2.5.1.4. *Effect of Paraplow on Soil Moisture*

The changes in porosity caused by the Paraplow influence the water dynamics of soil in several opposing ways. Firstly, the positive effects on infiltration rate discussed in the previous section will affect the amount of water that enters the soil. Secondly, root activity is enhanced, promoting an increase in the use of water by crops, provided there is available water in the soil. Finally, the increased porosity favours the dissipation of energy as latent heat by water evaporation, which would in turn affect the soil's thermal regime.

Even though the Paraplow preserves the residue cover to a large extent, some destruction is inevitable. Erbach *et al.* (1984) determined that the soil coverage by residues was 83 % for no-tillage, compared with 75 % for Paraplow. This reduction in residue coverage would also increase the amount of radiation energy reaching the soil and therefore, increase the probability of water loss by evaporation. The same authors did not find significant differences between treatments in surface roughness, although values for Paraplow were higher than for the rest. This increased roughness of the soil surface would lead to more turbulence in the soil's boundary layer, and may cause additional evaporation.

Paraplowing would thus increase simultaneously the intensity of evapotranspiration and infiltration. The balance between these opposing processes determines the soil moisture content at a given time. Probably because of this, there is an apparent inconsistency in the effects of paraplowing on soil moisture data found in the literature. Some authors (Braim *et al.* 1984, Hipps and Hodgson 1988) have found the Paraplow to be effective in reducing the incidence of waterlogging in wet climates. Others (McConkey *et al.* 1997) have noted the advantages of the Paraplow for capturing moisture in dry environments.

The results obtained by Ehlers and Baeumer (1988) illustrate these effects well. On one field experiment, soil moisture content at the beginning of the growing season was higher for reduced-tillage than Paraplow, particularly near the soil surface. A month later, after a dry period, both treatments had similar moisture contents. And two weeks later, after a 60-mm rain, the Paraplow treatment had more soil moisture stored below 30-cm depth. This was attributed to its improved infiltration rate.

Pikul *et al.* (1990) determined a higher overwinter water storage capacity for soil with Paraplow than undisturbed soil. They also noticed that during periods of dry, warm winds, evaporation from soil was also higher from the Paraplow treatment.

Clark *et al.* (1993) found lower soil moisture in the upper 30 cm of soil when a Paratill was passed one year before compared to subsoiling two and three years prior to the determination. This was attributed to increased water uptake by the crop.

A number of published papers report no effects of the Paraplow on soil moisture. Mukhtar *et al.* (1985) and Erbach *et al.* (1992) did not find any differences in volumetric soil moisture between no-tillage and Paraplow in various soil types and sampling dates. Similarly, Radford *et al.* (1992) also reported lack of any effect of paraplowing on soil moisture in a dry area in Australia.

2.5.1.5. *Effects of Paraplow on Soil Strength*

Since the Paraplow modifies soil density and moisture content which, as shown in section 2.2.1, are the main factors determining soil strength, an effect on the latter is also to be expected. Indeed, most works in the literature report decreases in soil penetration resistance (PR) on paraplowed as compared to untilled soil (Braim *et al.* 1984, Erbach *et al.*

1984, Hipps and Hodgson 1987, Hipps and Hodgson 1988a, Ehlers and Baeumer 1988, Touchton *et al.* 1989, Hodgson *et al.* 1989, Chambers *et al.* 1990, Clark *et al.* 1993).

Braim *et al.* (1984) determined that the Paraplow was as effective as the moldboard plow in reducing soil penetration resistance up to 35 cm depth. Immediately after passing the Paraplow, penetration resistance was 0.3 MPa, compared to 1.2 MPa for the undisturbed soil. Seven months later, the treatments had PR of 0.6 and 1.1 MPa, respectively.

Characterizing the effects of paraplowing on soil strength is made difficult by the spatial and temporal variability of this parameter. Hipps and Hodgson (1988a) measured the volume of soil in different penetration resistance classes eight months after passing the Paraplow on a sandy clay loam. Subsoiling increased the volume of the top 30 cm of soil with penetration resistance lower than 1.5 MPa from 35 to 87 %. Another way of expressing the effects is by the depth to certain threshold level. Hodgson *et al.* (1989) determined that paraplowing increased the maximum rooting depth, measured as the depth at which penetration resistance reaches 2 MPa, from 23 to 32 cm.

Penetrometers are very convenient for assessing the spatial variability of Paraplow effects, and several workers have used them for this purpose. Maximum soil loosening has usually been observed to occur at 20 to 30 cm depth (Braim *et al.* 1984, Busscher *et al.* 1988, Ehlers and Baeumer 1988, Hipps and Hodgson 1988a). There is some disagreement regarding the horizontal position of maximum loosening effect. Busscher *et al.* (1984) found minimum soil strength values right below the insertion point of the Paratill into soil. Hipps and Hodgson (1988a) on the other hand, reported that maximum effect of the Paraplow in the plane at right angles from the direction of travel occurred in an elliptical trough of soil located above and to the right of the spot where the shanks had passed.

Busscher *et al.* (1988) compared the effect of a Paratill with two other subsoilers, in combination with either conventional or reduced tillage, on soil strength of a loamy sand. Averaged over two seasons and four sampling dates, the Paratill was the most effective treatment in reducing soil strength in the direct-seeding system. Another implement ('Super Seeder') was superior to the Paratill in tilled-soil conditions.

2.5.1.6. *Effects of Paraplow on Crops*

Several studies have shown that paraplowing may be beneficial for crop establishment in various circumstances. Hipps and Hodgson (1988b) found that Paraplow passed 11 months before seeding caused a 7 % increase in plant density of barley in two consecutive years. The effect was attributed to better seed-soil contact and in one year to improved soil drainage. Similar results were obtained by Braim *et al.* (1984). Erbach *et al.* (1992) working with four medium-to-fine textured, poorly-drained soils in Iowa reported that corn plants emerged faster with Paraplow than with no-till, but final plant population was not affected. They credited this effect to a reduced residue cover, which may have increased soil temperature in paraplowing conditions. On the other hand, Hipps and Hodgson (1987), working on a sandy clay loam soil, found no effect of the Paraplow on winter wheat plant population, compared to direct drilling without Paraplow.

Nutrient availability for plants has also been shown to increase due to paraplowing. Braim *et al.* (1984) found that in subsoiled plots spring barley increased the amount of N absorbed. This effect was also shown by Hipps and Hodgson (1988b), and may have been associated with the fact that paraplowing, as shown in previous sections, increases soil aeration and water infiltration, eventually promoting soil organic matter mineralization. In other studies, P and K absorption was also shown to increase after subsoiling, mainly due to better soil exploration by roots (Ide *et al.* 1984).

A major effect of paraplowing is the promotion of root development due to reduced soil strength. This has been demonstrated for winter wheat (Ehlers and Baeumer 1988, Hipps and Hodgson 1987, Hodgson *et al.* 1989), and spring barley (Braim *et al.* 1984, Hipps and Hodgson 1988a).

The work by Hipps and Hodgson (1988a) provided a comprehensive illustration of the effects of paraplowing on roots. In this study, spring barley at the beginning of tillering had more root density at 25 cm depth with Paraplow passed either 7 or 18 months before seeding than the control. At this crop stage, the effect was the higher the longer the soil had been under no tillage, and Paraplow plots had less root density than those tilled with the moldboard plow. At the end of tillering, paraplowing increased root density by up to 3000 axes m^{-2} (about 100 % increase), but the effect was restricted to the 5-20 cm depth soil layer. Total root length at the end of tillering was increased by 12 % on average of two years (from 6900 to 7700 m m^{-2}). This effect was attributed to reduced soil strength; increase in volume of pores higher than 60 and 300 μm diameter; and higher plant density due to better drainage.

As a consequence of the positive effects of the Paraplow on soil physical properties and crop establishment and root growth, this subsoiler has usually improved crop productivity. Yield gains have been reported for several crops. In two separate studies, spring barley yields increased by 5 (Hipps and Hodgson 1988b) and 19 % (Braim *et al.* 1984), and this effect was entirely due to improved tiller survival and reduced spikelet abortion, both factors having resulted in a higher number of grains per unit area.

Paraplowing produced an increase in corn yields of 7 to 14 % in poorly-drained soils of Iowa (Erbach *et al.* 1992). In this case, the reason for the effect was an improved plant emergence due to higher soil temperature. Reeder *et al.* (1993) measured a slight improvement in corn yields due to Paraplow passed 18 months before seeding. In this same study, grain yield of soybean grown immediately after subsoiling was raised by 6 %.

The effect on wheat yields have been fairly variable, and mainly dependant on the soil moisture regime. Hipps and Hodgson (1987) reported a winter wheat yield increase of 6 % in one season, associated with reduced waterlogging, and no effect in the other season studied. Two studies conducted in relatively dry areas (McConkey *et al.* 1997, Radford *et al.* 1992) reported no effect of Paraplowing on spring wheat grain yields. Hodgson *et al.* (1989) found that Paraplow passed on a soil that had been more than three years without any tillage caused a 6 % decrease in winter wheat yields, whereas no effect was detected on plots where no-tillage had just been started.

Sojka *et al.* (1997) working on Australian soils susceptible to compaction by grazing cattle in a moist climate, reported that paraplowing increased forage oat yield by 18 %. Again, avoidance of waterlogging was the main reason for this outcome.

2.5.2. Biological Tillage

Another approach to overcome soil physical constraints under direct drilling would be to exploit the ability of certain plant species to develop roots in soils with high compaction levels. This would create a system of channels in the soil which may be later used by roots of other crops susceptible to compaction. Dexter (1991) proposed the term biological tillage for this process, including also the action of soil organisms like earthworms.

Several plant species have been reported to be suitable for this purpose: alfalfa (Blackwell *et al.* 1990, Radcliffe *et al.* 1986), rapeseed (Shaffer *et al.* 1990), *Melilotus alba* Medik (Bowen 1981), and *Lupinus sp.* (Atwell 1988). The mechanisms responsible for this ability are not known. Materechera *et al.* (1991) suggested that roots of dicots, which have large diameters, are more able to penetrate hard soils than roots of monocots. These authors (Materechera *et al.* 1991) compared the responses of 22 plant species to high soil compaction, and found that root elongation was reduced by 97 % in barley, wheat and oats, the three most susceptible species, and by 88 % in lupin, the species that showed the most tolerance.

The stability of the root channels would relate to their predominantly vertical orientation, which would protect them against sealing by compaction forces, which are also vertical. The localized compression of channel walls by the radial pressure exerted by roots would also contribute to the longevity of the channels if the soil is not tilled. Lack of tillage, the degree of verticality of the root system, and the radial pressures exerted by roots lead to the creation of adequate, long-lived biochannels in soils.

The process of biological tillage is undoubtedly very positive in that it improves soil water infiltration and gaseous exchange between soil and atmosphere, and also allows for a deeper root penetration into the soil. However, whether the created biochannels would support adequate plant growth in highly-compacted soils or not still remains a matter of speculation.

The doubts on the efficacy of root channels are based on a number of facts. Firstly, as shown by Whiteley and Dexter (1983), roots 'prefer' to grow through cracks or pores rather than through high-strength aggregates. This suggests that the volume of soil that is effectively explored by a root system growing in a compacted soil would be limited. Secondly, it is possible to assume that roots of successive crops growing through the same paths may deplete low-mobility nutrients in localized regions of the soil profile. In the third place, it has been shown that root tips growing in large pores may sense a poor contact with soil and send certain signals to the shoot that cause growth inhibitions (Stirzaker *et al*. 1996, Passioura and Stirzaker 1993). A large research effort is needed to elucidate these questions

2.5.3. Exploiting genetic variability

Certain traits associated with resistance or tolerance to high mechanical impedance or low oxygen availability would have genetic variability. These traits could be identified to select cultivars to be used in environments with soil physical restrictions.

The genetics of root systems is only poorly understood due to the relatively reduced research efforts that have been made in the past. Zobel (1991) indicated that there is wide genetic variability both in root traits and in their response to varying environmental conditions, which are generally controlled by several genes. He stressed the need for new statistical tools to separate the genotype by environment interaction and estimate the heritability of various root traits. Sharma and Lafever (1992) revealed the existence of large variability in several root traits among 42 spring wheat cultivars, and that root length was controlled by additive genetic mechanisms. Masle (1992) also showed important variability among modern cultivars and landraces of wheat and barley in root traits associated with tolerance to high soil penetration resistance.

Mechanical and aeration stresses cause similar effects on root morphology, probably because they both induce the production of ethylene by the plant (Sections 2.4.3 and 2.4.4). Since the pathway of ethylene synthesis in plants is well known, and the enzymes ACC synthase and ACC oxidase are regulated by single genes, Ecker (1995) suggested the possibility of genetically manipulating plants to control ethylene biosynthesis and therefore, induce or prevent certain plant responses.

The methodological difficulties for measuring roots, and the fact that sampling of roots may destroy valuable plant materials, are major obstacles for including root traits in plant breeding programs. An alternative approach would be the selection of cultivars best adapted to direct-seeding conditions. However, due to large genotype by environment interactions, the prospects of achieving substantial progress following this approach are only meagre (Cox 1991, Hwu and Allan 1992).

3. SOIL LOOSENING BY PARAPLOW IN DIFFERENT DIRECT-SEEDING-BASED CROPPING SEQUENCES

ABSTRACT

Crops grown in direct-seeding systems in Uruguay may be affected by excessive soil compaction, caused by livestock and machinery traffic in wet conditions. The Paraplow is a subsoiler that loosens the soil without inverting it, thus permitting direct seeding. The ability of the Paraplow to mitigate soil compaction in a fine textured soil managed with direct-seeding, and the Paraplow by crop-sequence interaction on soil physical properties were studied during 1991-1994 in four field experiments.

Subsoiling resulted in up to 2 MPa decrease in soil penetration resistance (PR), most notably in dry soil, in increased water infiltration capacity and reduced frequency of waterlogging. Soil loosening occurred over virtually all soil volume up to 450 mm depth, with maximum effect at the 200 to 300 mm depth. Spring and fall treatments were equally effective, despite differences in initial soil moisture content. Oxygen diffusion rate at 50-mm depth, three days after soil was saturated in the winter time, was 0.13, 0.14, 0.17 and 0.25 μg O_2 cm^{-2} min^{-1} for no-Paraplow, spring Paraplow, fall Paraplow, and double (spring and fall) Paraplow treatments, respectively. The effects of paraplowing on soil physical properties lasted for more than 20 months. The first crop in the rotation affected soil physical properties, in addition to Paraplow treatments. The results obtained provided evidence of decreased water infiltration after sunflower, as compared to corn, 19 months after these crops were harvested, for some Paraplow treatments, suggesting that benefits of paraplowing would be more lasting if crops with fibrous root systems were grown.

3.1. INTRODUCTION

Crops grown in direct-seeding systems in Uruguay may be affected by soil physical constraints arising from a combination of several factors including high rainfall, low-permeability soils, grazing livestock and machinery traffic in wet conditions. Soil mechanical loosening has been the traditional method of alleviating excess compaction (Vepraskas and Miner 1986). Conventional subsoilers are not compatible with conservation-tillage systems because they tend to mix the crop residues with soil and leave large aggregates on the surface.

The Paraplow (Fig. 2.1) is a slant-legged subsoiler that loosens the soil without inverting it, thus permitting direct drilling (Pidgeon 1982). This implement has been successful in improving the soil physical environment for root growth in a wide range of soils. The most direct effect of Paraplow on soil is an increase in porosity (Erbach *et al.* 1992), particularly in the macropore size range (Pikul *et al.* 1990). Because the continuity of the macropores is also improved, even reaching to the soil surface (Hipps and Hodgson 1988a), the water infiltration capacity of soil is greatly increased (Mukhtar *et al.* 1985, Clark *et al.* 1993). The effect of Paraplow on infiltration capacity can also be more long lasting than that of the mouldboard plow (Ehlers and Baeumer 1988).

Besides improving water infiltration into soil, paraplowing also enhances water availability as compared to undisturbed soil (Pikul *et al.* 1990). The effect on soil moisture content will depend on the balance between these two opposing processes.

A major consequence of paraplowing is a reduction in soil strength (Braim *et al.* 1984, Hipps and Hodgson 1987). In a study comparing four subsoilers in conservation-tillage systems, Busscher *et al.* (1988) found that the Paratill, an implement having the same soil-working tool as the Paraplow, was the most effective in reducing soil penetration resistance.

The extent of soil loosening by Paraplow treatment varies with depth and horizontal position. Maximum effect has been consistently observed at 200-300 mm depth (Braim *et al.* 1984), and either right below the point of insertion into the soil (Busscher *et al.* 1988) or above and to the right of the shanks (Hipps and Hodgson 1988a).

Soils loosened by the Paraplow tend to consolidate back to their original state by the action of natural agents and traffic. The residual effect of Paraplow on soil has been from a few months to three years (Hipps and Hodgson 1988b). From the relatively scarce information available in the literature (Table 2.1) it is not possible to establish what factors determine this residuality.

The objectives of this paper are: (1) to assess the effectiveness of Paraplow in mitigating soil compaction in a fine textured soil, managed with different cropping sequences with direct-seeding; (2) to evaluate the time residuality of Paraplow effects; and (3) to study the possible Paraplow by crop-sequence interaction on soil physical properties.

3.2. MATERIALS AND METHODS

Several experiments were conducted during the period 1991-94 on a silty-clay loam (fine, mixed, superactive, thermic Oxyaquic Argiudoll, or 'Brunosol éutrico típico' in the Uruguayan classification) in SW Uruguay (INIA La Estanzuela Experimental Station, 34°20' S, 57°41' W), to study effects of soil compaction on crop productivity under zero tillage. Four of these experiments (named as *RTN*, *C13*, *C14* and *C15*) were selected for the present study. The experiments were physically near one another on the same soil type (Table A1).

3.2.1. Experiment Description

The first experiment (*RTN*) had a randomized complete-block design with split-plots and 4 replicates. Four treatments were established on main plots: treatment A (paraplowing in Oct. 1991), treatment B (paraplowing in May 1992), treatment ABC (paraplowing in Oct. 1991, May 1992 and May 1993), and treatment O (control). Four three-crop sequences (Table 3.1), including corn (*Zea mays* L.) or sunflower (*Helianthus annus* L.) as summer crops, and wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.) as winter crops, constituted subplots. Subplots were 4 m x 10 m.

Experiment *C14* was identical, but was started one year later. Both *RTN* and *C14* sites had grown forage crops (a mixture of red clover and tall fescue) for three years prior to initiation of experiments. Crops on *RTN* were cut for hay, while those on *C14* were grazed by beef cattle.

The other experiments (*C13* and *C15*) were conducted to evaluate the effect of paraplowing in spring immediately prior to corn crop establishment. These experiments were on the same field as experiment *C14*, and had the same previous crops. Only two treatments (A and O) were imposed in a complete randomized block design.

In *C13* there were three replicates, and plot size was 11 m x 100 m. In experiment *C15* four blocks were established, and plots were 10 m x 80 m (treatment A) and 5 m x 80 m (treatment O). In both experiments, the longest plot axis was perpendicular to the main slope in the field. Experiment *C13* was established in Oct. 1992, and *C15* in Oct. 1993. Residual effects of paraplowing in 1992 were evaluated in successive crops in experiment *C13* (Table 3.1), whereas experiment *C15* was terminated at corn harvest. Crop sequences for all

Table 3.1. Diagram of crop sequences in the four experiments. Symbols before crops indicate times at which Paraplow was passed.

1991	1992	1993	1994
(A) Corn	(B) Wheat	(C) Barley	
(A) Corn	(B) Barley	(C) Wheat	
(A) Sunflower	(B) Wheat	(C) Barley	
(A) Sunflower	(B) Barley	(C) Wheat	
		C 14	
	(A) Corn	(B) Wheat	(C) Barley
	(A) Corn	(B) Barley	(C) Wheat
	(A) Sunflower	(B) Wheat	(C) Barley
	(A) Sunflower	(B) Barley	(C) Wheat
		C 13	
	(A) Corn	Wheat / Sunflower	Canola
		C 15	
		(A) Corn	

(A) Spring - Paraplow
(B) (C) Fall - Paraplow

experiments are shown in Table 3.1.

3.2.2. Field Operations

A 'Howard' Paraplow with three shanks spaced at 0.5 m was used. Tractor speed was 3.8 km/h, and working depth was 0.45 m. A 'Semeato' PS-8 direct-drilling, triple-disc seeder was used to plant the corn and sunflower, whereas wheat and barley were seeded by using a 'Semeato' TD-220 direct-drilling, triple-disc seeder.

In experiments *RTN* and *C14* corn cv. '*Estanzuela Bagual*' and sunflower cv. '*Estanzuela Yatay*' were seeded in the first spring. Wheat cv. '*Estanzuela Benteveo*' and barley cv. '*Estanzuela Quebracho*' were seeded in the following fall. The soil was fallowed with no tillage after wheat and barley harvest in Dec. 1992 (*RTN*) and 1993 (*C14*), until the Paraplow was used again on treatment ABC plots in June 1993 (*RTN*) and May 1994 (*C14*). The same cultivars of wheat and barley were then seeded again.

In experiment *C13*, paraplowing was performed on 22 Oct. 1992, and corn cv. "*Estanzuela Bagual*" was seeded one day later. The crop was harvested on 24 Mar. 1993. Wheat cv. "*Estanzuela Cardenal*" was seeded on 30 June 1993, and harvested on 6 Dec. 1993. Sunflower cv. "*Estanzuela Yatay*" was seeded on 10 Jan. 1994. Sunflower plants did not reach maturity and were chopped on 25 May 1994. Finally, canola cv. "*Topas*" was seeded on 1 June 1994 and harvested on 5 Dec. 1994.

In experiment *C15* only one crop was grown. The Paraplow was passed on 7 Oct. 1993, and corn cv. "*Estanzuela Bagual*" was seeded on 13 Nov. 1993. Because of waterlogging after seeding, the crop failed and had to be reseeded 12 days later.

Soil moisture content at the times of Paraplow treatments varied between 15.1 and

29.9% by weight (Table 3.2). Spring-paraplowing was usually performed with drier soil than fall-paraplowing.

3.2.3. Penetration Resistance Determinations

Sampling dates for soil physical properties in all experiments are detailed in Table 3.3. Penetration resistance (PR) was measured by using a Rimik CP10 hand-held recording cone penetrometer. The cone used had an included semiangle of 15° and a base diameter of 12.8 mm. PR was recorded up to 450 mm depth in 15-mm increments. Rate of penetration was about 10 mm s^{-1}. The number of replicates varied among sampling dates, but was usually between two and four per plot in selected plots (experiments *RTN* and *C14*), and between 10 and 20 per plot in all treatments (experiments *C13* and *C15*). In one case (25 June 1993, experiment *C14*) PR profiles were determined on four 8-m transects across Paraplow passes, at 0.1-m intervals. Transects were laid on plots corresponding to treatment A, crop sequence sunflower-wheat-barley, one on every block.

3.2.4. Soil Moisture and Bulk Density Determinations

Soil moisture was measured by the gravimetric method, generally paired with PR determinations. Soil cores were taken from within 0.1 m of the PR measurement points. In one case (14 Oct. 1992), soil cores were extracted from the same spots where PR was measured. Before Nov. 1993, samples were taken by using either a hand-driven soil auger (when bulk density was not measured) or a Uhland-type soil corer. After that date, a truck-mounted Concorde mechanical corer harnessed with 45-mm-internal-diameter tubes was used. Sampling depths were generally from 0 to 150; 150 to 300; and 300 to 450 mm. In a few cases, samples were taken at 0-75 and 75-150 mm depth (Table 3.3). Soil samples were dried

Table 3.2. Soil moisture content (mean of 0-450 mm depth) at the times of passing the Paraplow

Time of Paraplow	Soil moisture (% by weight)
	RTN
A	22.0
B	26.8
C	25.2
	C14
A	15.8
B	24.0
C	29.9
	C13
A	15.1
	C15
A	21.6

Table 3.3. Sampling dates for soil physical properties in the four experiments.

Date	Penetration Resistance	Soil Moisture	Bulk Density	Oxygen Diffusion Rate
		RTN		
22 May 1992		x (†)		
11 June 1992				x
11-14 July 1992				x
27 July 1992	x	x		
17 Aug. 1992	x	x		
17 Sep. 1992 ‡	x	x		
14 Oct. 1992 ‡	x	x		
25 June 1993	x	x (†)	x (†)	
29 Nov. 1993	x	x	x	
		C14		
24 June 1993	x	x (†)	x (†)	
25 June 1993	x			
25 Nov. 1993	x	x	x	
7 June 1994	x	x	x	
13-19 July 1994				x
19 Aug. 1994		x	x	
29 Dec. 1994 §	x	x	x	
		C13		
6 May 1993	x			
24 Nov. 1993	x	x	x	
21 Jan. 1994	x	x	x	
1 June 1994	x	x	x	
		C15		
6 Oct. 1993	x	x	x	
23 Nov. 1993	x	x	x	
20 Jan. 1994	x	x	x	
4 Mar. 1994		x	x	
13 May 1994	x	x	x	

† Measured at 0-75 and 75-150 mm only

‡ In Paraplow treatments A and ABC, measurements were taken only in plots that had been seeded to sunflower.

§ Measurements were taken only in plots that had been seeded to sunflower.

for 48 hours, and weighed again. Soil moisture content was calculated on a weight basis. Soil bulk density was estimated in the same samples by dividing the dry soil weight by the sample volume (98 cm^3 for Uhland-type sampler or 239 cm^3 for the Concorde sampler).

3.2.5. Soil Oxygen Diffusion Rate Determinations

The flow rate of oxygen to a platinum microelectrode with a potential of -0.65 V with respect to a Ag/AgCl electrode, was derived from the intensity of the electric current generated, according to the method proposed by Lemon and Erickson (1952). Electrodes were buried into the soil to a depth of 50 mm. The equilibration time was 4.5 minutes. Oxygen diffusion rate (ODR) was determined on 11 June and 11-14 July 1992 (experiment *RTN*) by placing 40 equally-spaced micro electrodes in each plot on 1-m transects across Paraplow passes. Soil temperature at 50-mm depth was determined by a digital thermometer placed on each extreme of the transects.

In experiment *C14*, ODR was measured during the wheat emergence period on plots corresponding to the crop sequence sunflower-barley-wheat between 13 and 19 July 1994. In this case, two 1-m transects per plot were established across Paraplow passes, with microelectrodes equally spaced at 0.1 m.

3.2.6. Statistical Analyses

Analyses of variance were performed by using the GLM procedure (SAS Institute 1985). Penetration resistance, soil moisture and bulk density data were analysed separately for each soil depth. Means were compared by the LSD test at the 95% level of significance.

3.3. RESULTS AND DISCUSSION

The different Paraplow treatments modified soil structure and interacted with cropping sequences. Soil penetration resistance was the main variable used to assess the degree of soil loosening by Paraplow. The statistical significance of the various treatment effects on soil penetration resistance for all experiments is presented in Tables B1 through B17 (Appendix). The value of PR varied with time. Experiment mean values for the various sampling dates in the four experiments are shown in Fig 3.1. Soil density and water dynamics were also affected by Paraplow and crop sequence treatments. The statistical significance of treatment effects on soil moisture and bulk density is presented in Tables B18 through B35 (Appendix).

3.3.1. Spatial Pattern of Paraplow Effects on Soil

The Paraplow affected most of the soil volume in the upper 450 mm of soil. Repeated measurements of ODR and PR at close space intervals in transects across Paraplow passes showed spatial variability in the degree of loosening (Figs. 3.2 and 3.4). Measurements were done on sampling dates when the soil moisture content was high enough to ensure that there was no interference of the effect of soil moisture on PR measurements (Chapter 5) and to allow ODR determination, since high soil water content is a requirement of the method used.

3.3.1.1. *Oxygen Diffusion Rate (Experiment RTN)*

Soil ODR at 50-mm depth was dependent on both Paraplow treatment and spatial position (Fig. 3.2). Aeration status was best at the midpoint between Paraplow shanks, and poorest in the region where shanks were inserted into the soil. This pattern was clearly visible in treatments with a single Paraplow pass (Oct. 91 and May 92) and indicated that maximum soil loosening near the surface occurred between Paraplow shanks. Double-Paraplow treatment presented the same trend, but there were some high ODR values near the insertion point as well.

Figure 3.1. Experiment means of penetration resistance (PR) profiles for various sampling dates. a) *RTN*; b) *C14*; c) *C13*; d) *C15*.

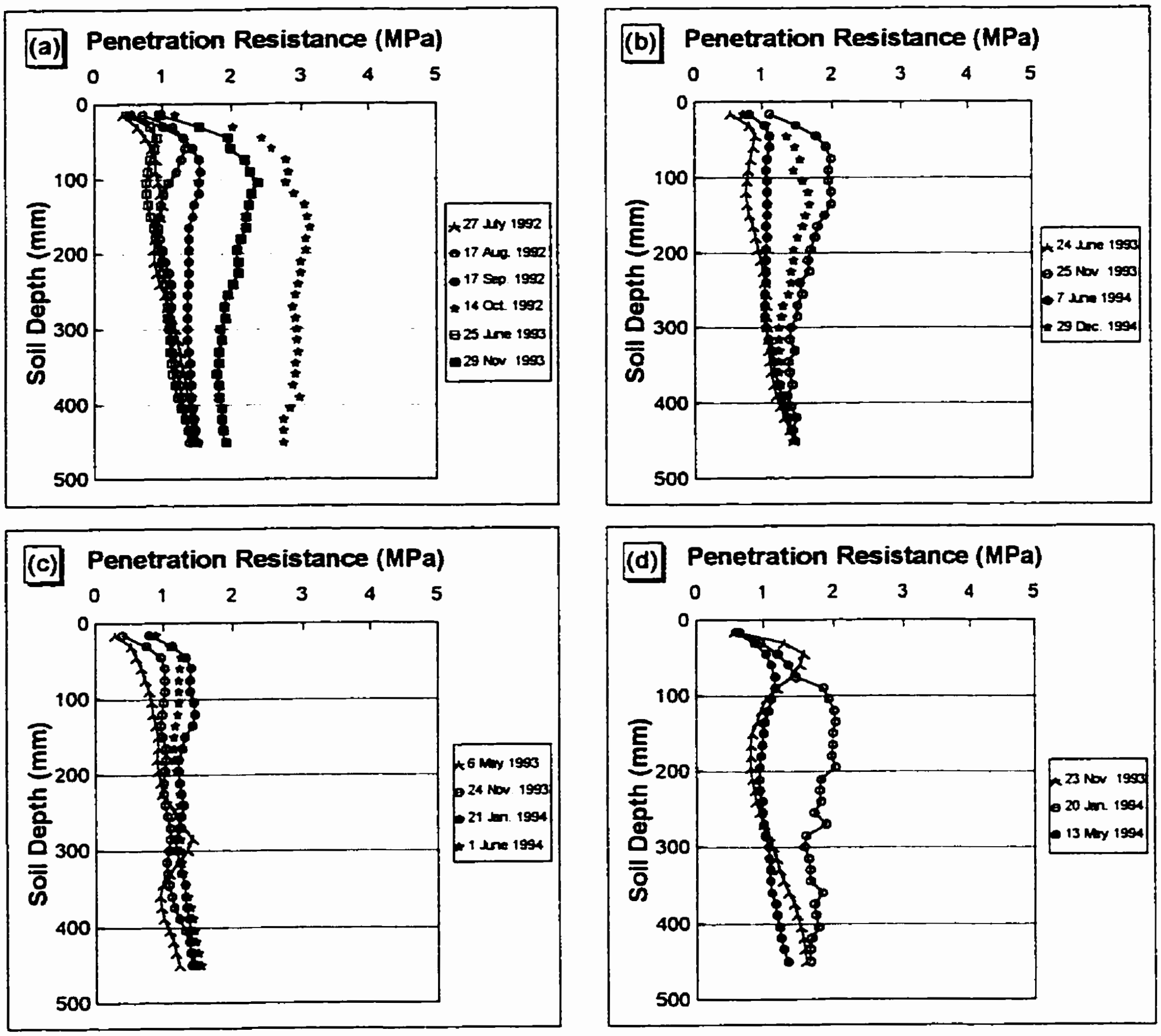
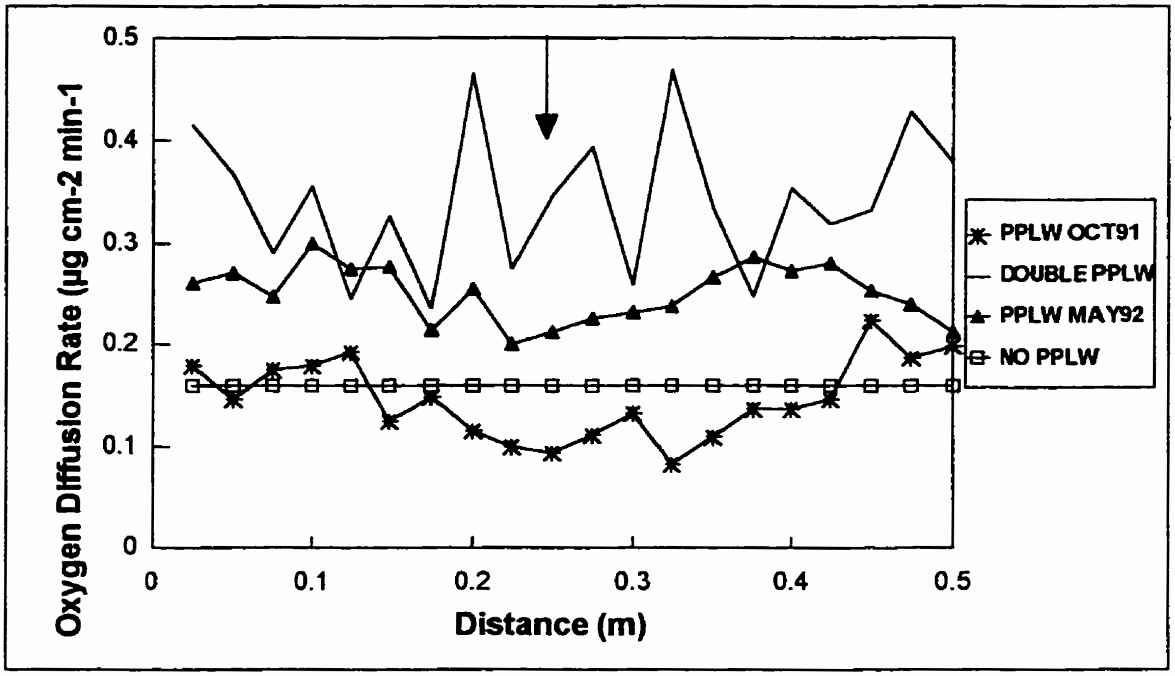


Figure 3.2. Effect of Paraplow (PPLW) treatment on soil oxygen diffusion rate measured on transects perpendicular to Paraplow passes. Experiment *RTN*, 11 June 1992. The arrow indicates the insertion point of the Paraplow shank into the soil.



Both fall-Paraplow treatments had ODR values higher than the undisturbed treatment at all positions. Treatment A (Paraplow in Oct. 91) had values higher than the check only in the hilltops between Paraplow legs, whereas in the depressions associated with Paraplow passes, ODR values were lower than in the no-Paraplow check.

3.3.1.2. *Penetration Resistance (Experiment C14)*

Soil PR profiles at different positions for treatment A, eight months after paraplowing, are shown in Fig. 3.3. The Paraplow loosened the soil at all positions and all depths considered. The curve representing the difference in PR between the control and treatment A, which is a measure of degree of soil loosening, had a similar shape for all positions. The difference was small in the upper soil, with a minimum near zero around 100 mm depth, and a maximum at depths varying between 200 and 350 mm. The maximum difference varied between 0.5 and 0.6 MPa, depending on the position. These results are consistent with most reports in the literature (Braim *et al.* 1984, Busscher *et al.* 1988, Ehlers and Baeumer 1988, Hipps and Hodgson 1988a).

The difference between the control and treatment A is presented in a manually-drawn contour diagram perpendicular to the direction of travel (Fig. 3.4). Maximum loosening occurred at 250-350 mm depth, right below and to the left of the spots where the Paraplow shanks passed, which is the depth at which the lifting wings of the Paraplow were running. The minimum effect was at 100 mm, right below where the soil surface depressions were located, and where the vertical portions of the shanks were moving. With legs spaced at 500 mm, a complete coverage of the soil was achieved, and the spatial pattern of soil disturbance was similar to the one reported by Hipps and Hodgson (1988a), and differed from that found

Figure 3.3. Soil penetration resistance profiles for treatments A (paraplowing in Oct. 1992) and O (control), and their difference, measured at different positions on transects perpendicular to Paraplow passes. Experiment *C14*, 25 June 1993. Position 0 m corresponds with the insertion point of Paraplow shanks into soil.

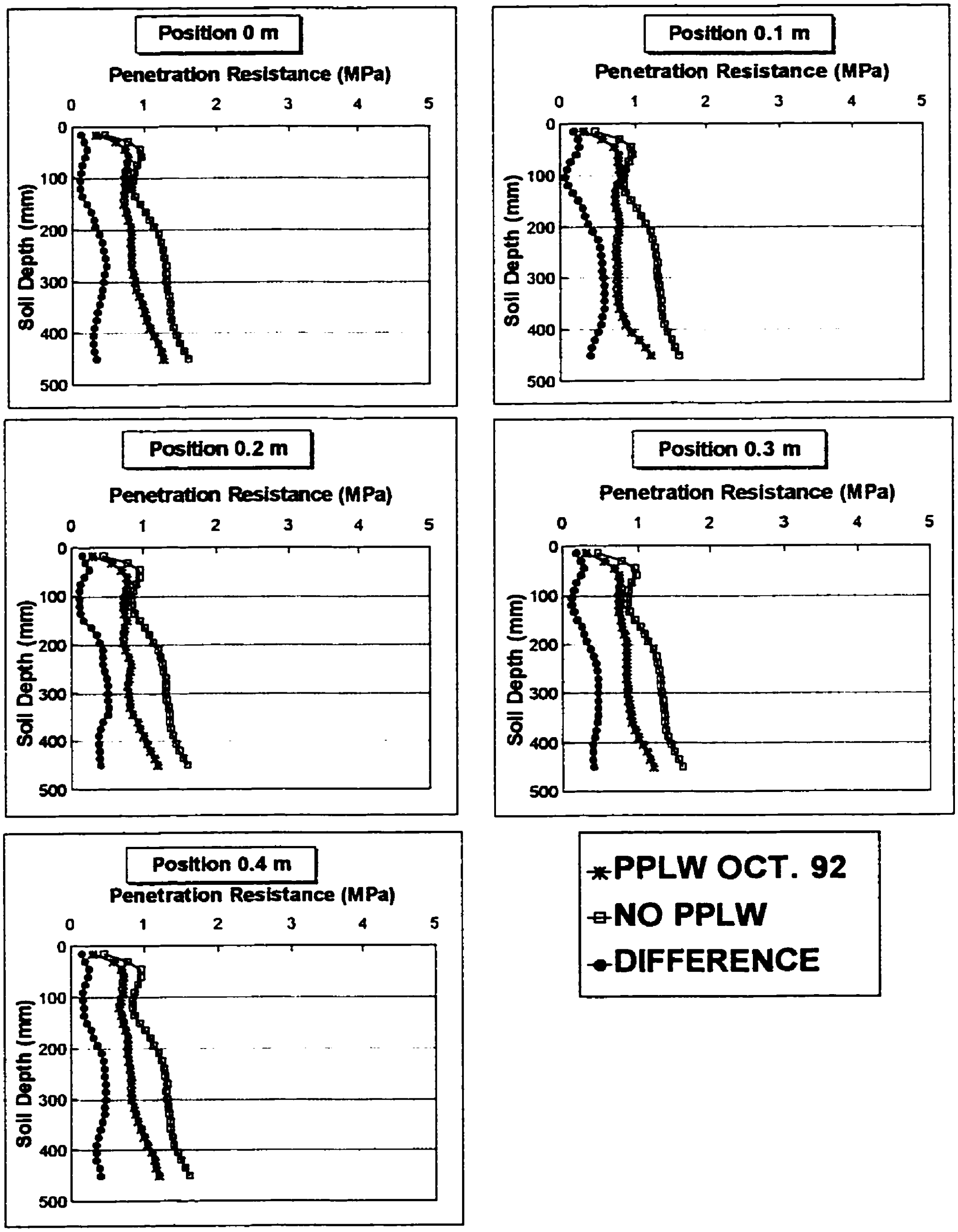
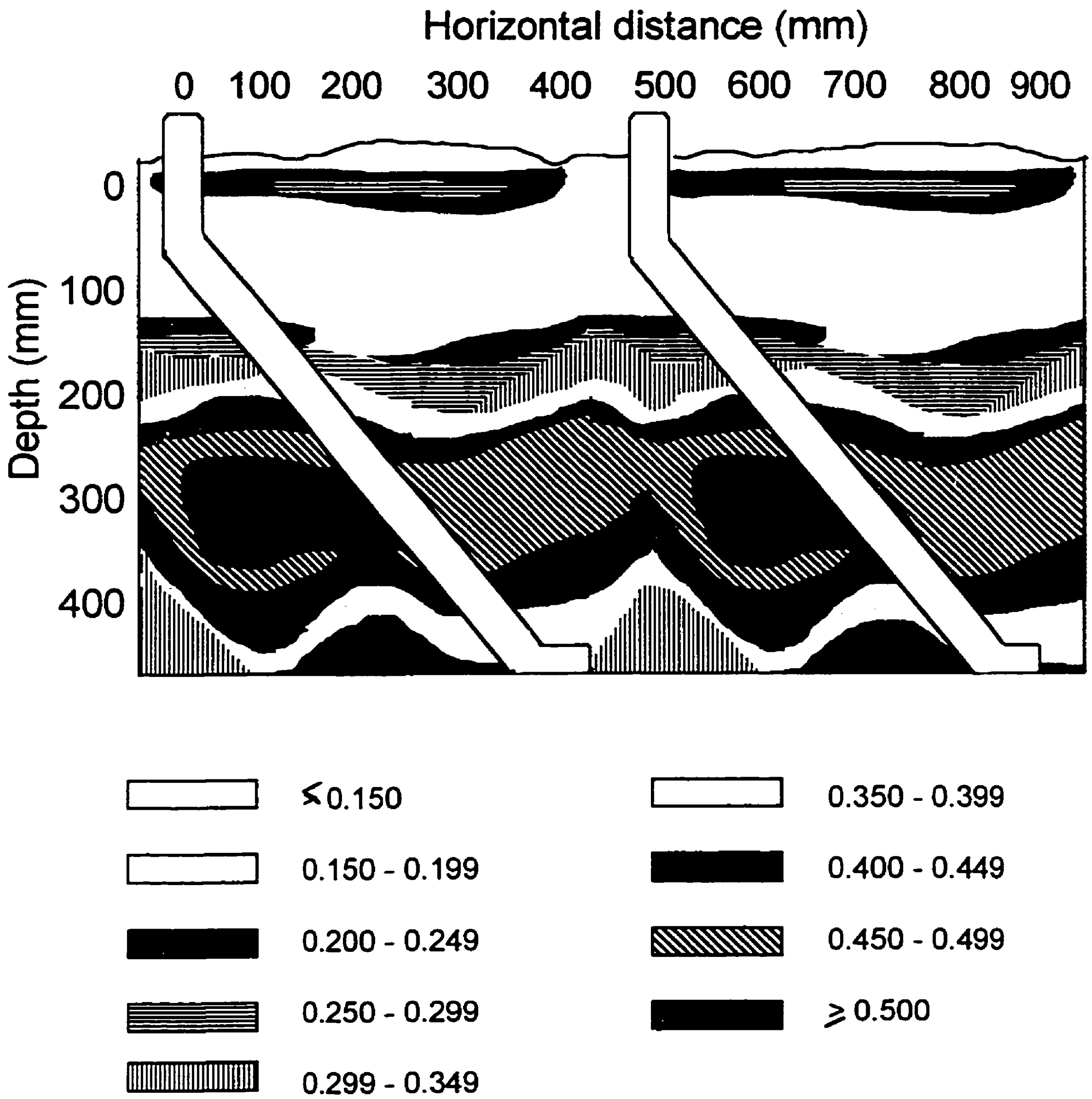


Figure 3.4. Contour diagram of the difference in soil penetration resistance (MPa) between treatments A and the control on a plane at right angles to the direction of travel of Paraplow. Experiment *C14*, 25 June 1993.



by Busscher *et al.* (1988) (Section 2.5.1.5).

3.3.2. Paraplow Effects on Soil Strength

When wet, the soil type used in the experiments had PR values lower than the usually accepted threshold level for root growth of 2 MPa (Taylor *et al.* 1966, Martino and Shaykewich 1994) in the portion of the soil profile considered. In dry conditions, soil strength could reach up to more than 4 Mpa (Fig. 3.1). Paraplowing caused substantial reductions in soil PR, thus facilitating root development.

3.3.2.1. *Experiments RTN and C14*

The effects of paraplowing on soil strength varied with time, and had very similar patterns in these two experiments (Figs. 3.5 and 3.6). The control had generally higher PR levels than all Paraplow treatments, particularly within the top 300 mm of soil. Exceptions to this general behaviour occurred. In experiment *RTN*, treatment A had higher PR than the control between 60 and 120 mm depth two months after wheat and barley seeding (Fig. 3.5c); and treatment B had the highest PR three months after seeding (14 Oct. 1992) between 120 and 285 mm depth (Fig. 3.5d). Also, in both experiments, at maturity of the last crop, some Paraplow treatments had higher PR values than the control near the soil surface (Fig. 3.5f and 3.6d).

These exceptions may have reflected differences between treatments in the patterns of water extraction from the soil profile. Variations in soil moisture content caused by Paraplow treatments lead to changes in soil strength (Greacen 1960), making it difficult to use PR to assess soil loosening by the Paraplow. One could avoid this problem by comparing PR profiles when the soil was saturated with water. The condition closest to this ideal was

Figure 3.5. Soil penetration resistance profiles for each Paraplow (PPLW) treatment at different sampling dates in experiment *RTN*. a) 27 July 1992; b) 17 Aug. 1992; c) 17 Sep. 1992; d) 14 Oct. 1992; e) 25 June 1993; and f) 29 Nov. 1993.

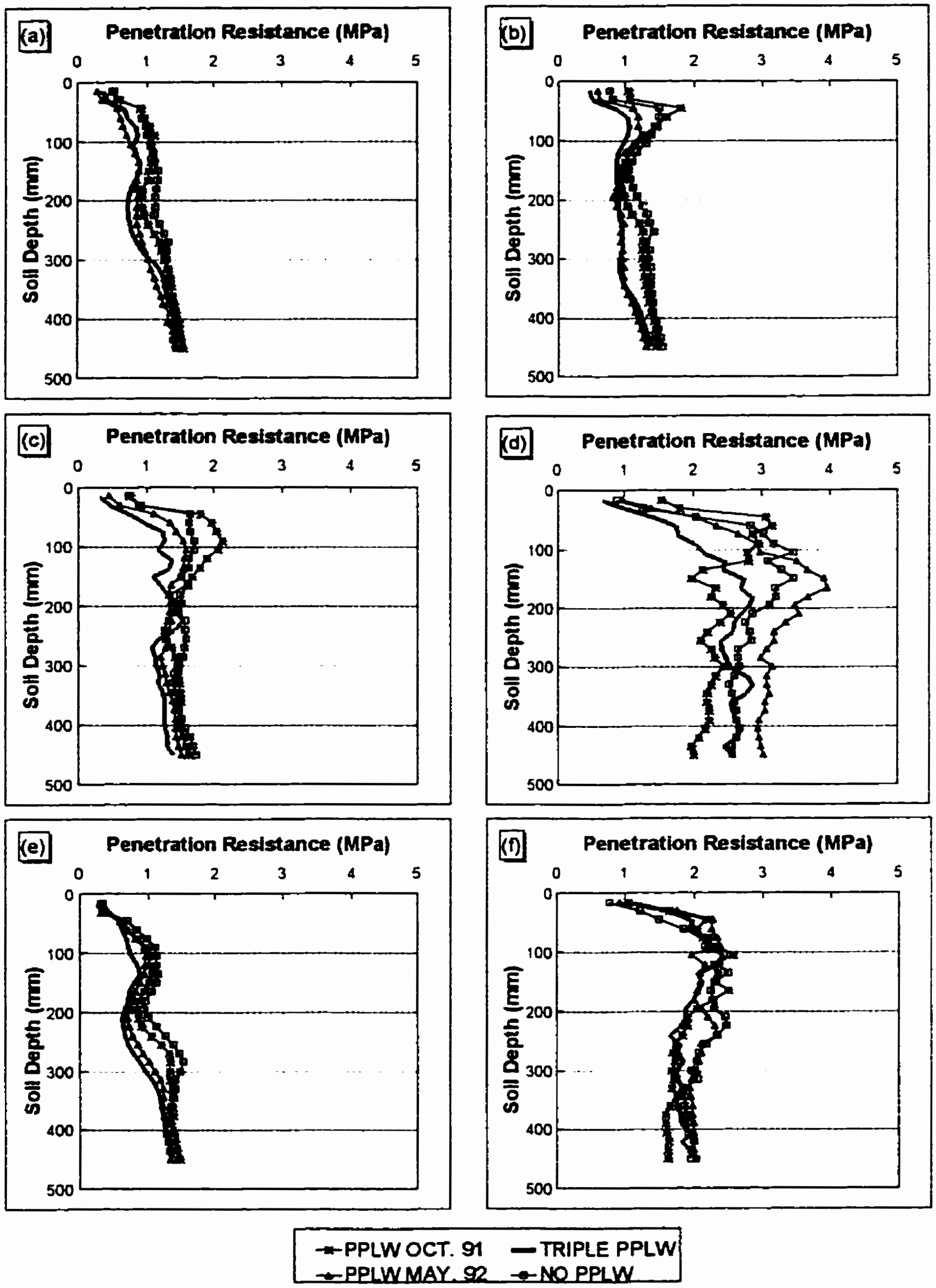
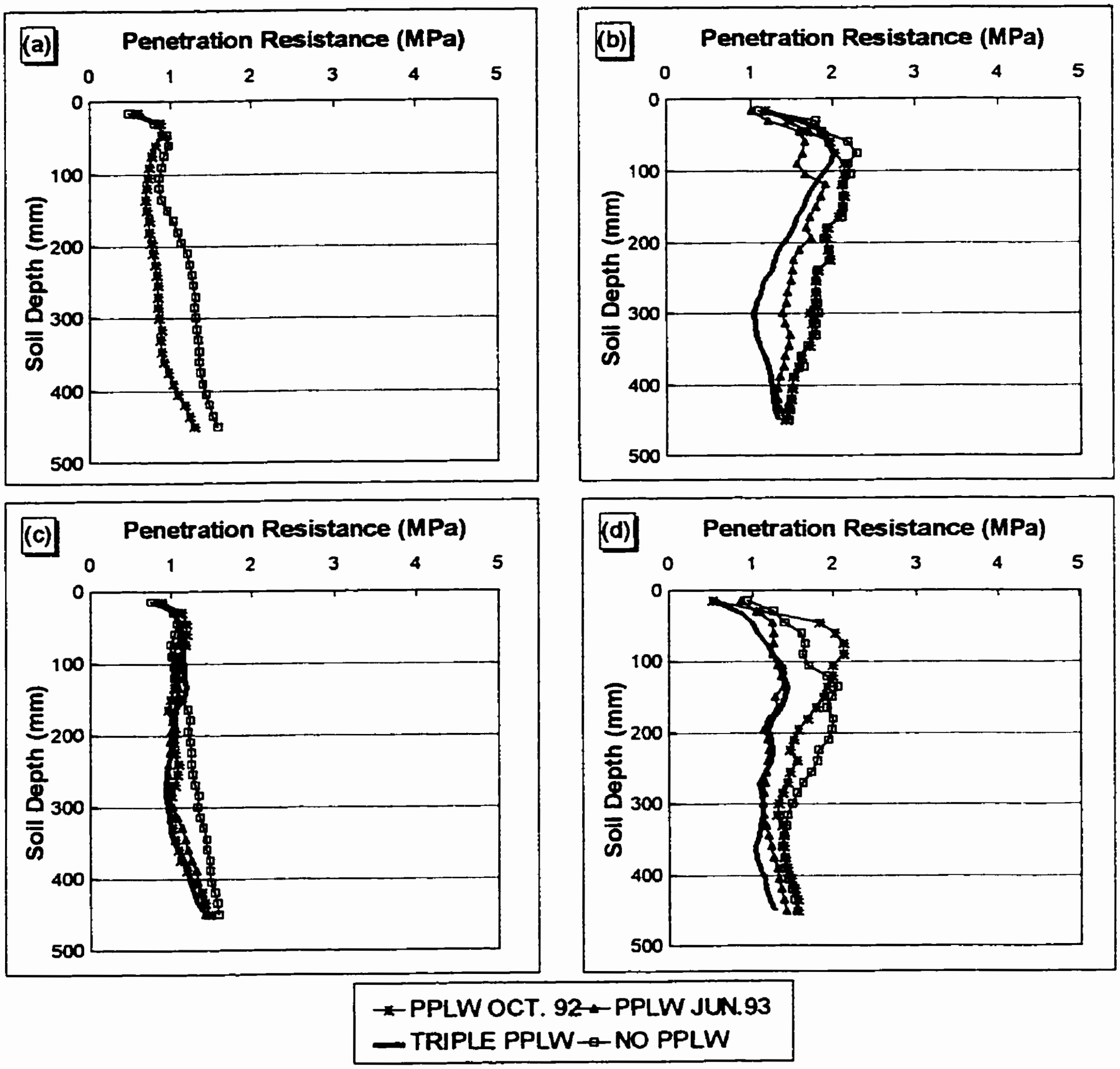


Figure 3.6. Soil penetration resistance profiles for each Paraplow (PPLW) treatment at different sampling dates in experiment *C14*. a) 24 June 1993; b) 25 Nov. 1993; c) 7 June 1994; and 29 Dec. 1994.



probably at the beginning of the wheat and barley seasons, when soil moisture was usually at or above field capacity throughout the soil profile, and differences in soil PR should have reflected differences in soil loosening status. In these cases, all Paraplow treatments had lower PR values than the control (Figs. 3.5a, 3.5e, 3.6a, 3.6c).

Double paraplowing in spring and fall (treatment ABC) significantly reduced PR, beyond the effect of single Paraplow in the fall (Figs. 3.5c, 3.5d and 3.6b). This difference was visible only in advanced stages of crop development, suggesting that it was more likely due to an effect on water dynamics than to a real difference in loosening.

Tillage operations are usually more effective when the soil is dry, although higher traction is required. Soils were drier when the Paraplow was passed in the spring than in the fall. However, the quality of subsoiling did not sem better in the spring than in the fall.

3.3.2.2 *Experiments C13 and C15*

In experiment *C13*, PR after spring-paraplowing was consistently lower than in the undisturbed check (Fig. 3.7). The difference was evident at least until 1 June 1994, 19 months after Paraplow treatment, particularly between 200 and 350 mm, the depth at which effects of paraplowing on soil strength were shown to be maximal (Section 3.3.1.2).

The effects of Paraplow in experiment *C15* were similar to those observed in experiment *C13*. Paraplow in the spring significantly reduced PR (Fig. 3.8). The effect was very large (0.6 MPa on average), affecting the whole soil profile at the beginning of the growing season (23 Nov. 1993), and tended to decline with time. After harvest (13 May 1994) PR for the control was still higher than for treatment A between 60 and 150 mm depth

Figure 3.7. Soil penetration resistance profiles for each Paraplow (PPLW) treatment at different sampling dates in experiment *C13*. a) 6 May 1993; b) 24 Nov. 1993; c) 21 Jan. 1994; and 1 June 1994.

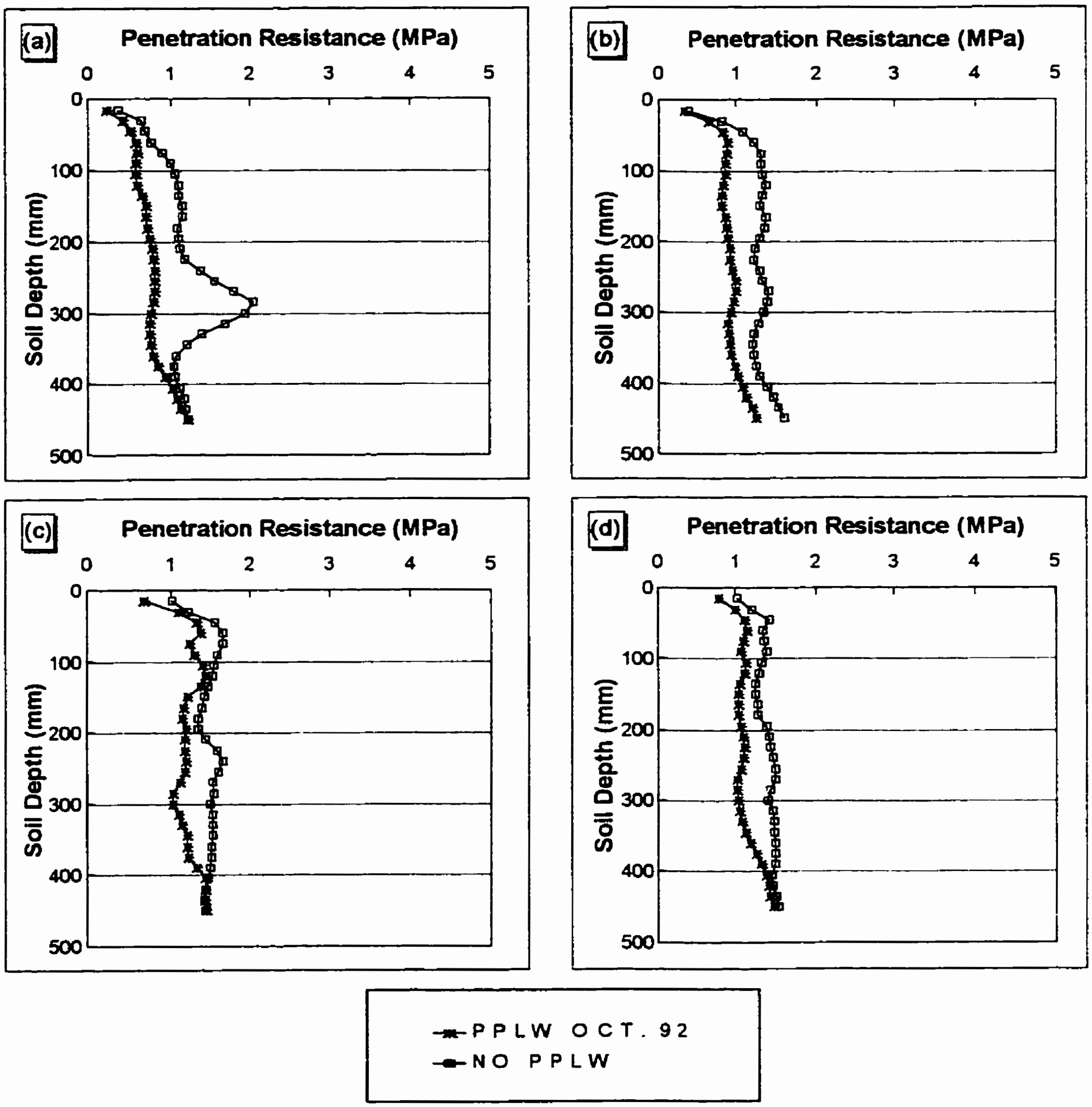
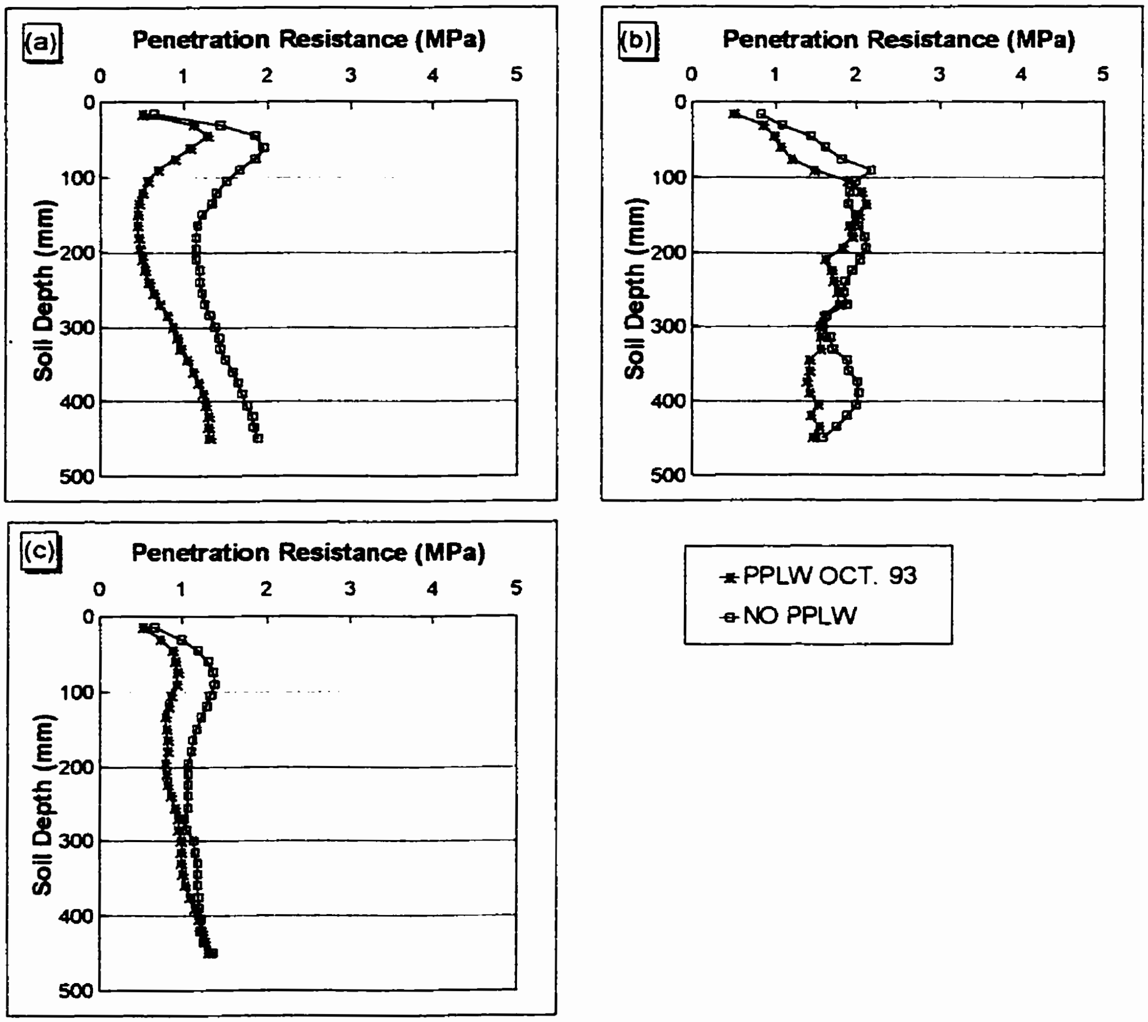


Figure 3.8. Soil penetration resistance profiles for each Paraplow (PPLW) treatment at different sampling dates in experiment *C15*. a) 23 Nov. 1993; b) 20 Jan. 1994; and c) 13 May 1994.



(Fig 3.8c).

3.3.3. Paraplow Effects on Soil Water and Air Dynamics

3.3.3.1. *Experiments RTN and C14*

Paraplowing affected soil porosity (Tables 3.4 and 3.5) and moisture content (Tables 3.6 and 3.7), and these effects were highly variable, depending on the sampling date. Soil bulk density was usually significantly higher for the control than Paraplow treatments, and this effect was restricted to the upper soil layers. No effects ofParaplow treatment on bulk density were recorded in June 1993 and June 1994, when soil moisture contents were high. This lack of effect may have been caused by sample compression effect, which, as shown by Zwarich and Shaykewich (1969), is a drawback of the core sampler method for determining bulk density used in the present work.

Even though water infiltration was not measured directly, the observed variability in soil moisture contents after the heavy rainfalls of Nov. 1993 (90 mm two days before measurement, and over 400 mm in the previous four weeks, Fig. A3, Appendix) reflected variations in the amount of water entering the soil and provided an indirect measurement of water infiltration capacity of the soil. In experiment *RTN*, the total amount of water contained in the top 450 mm of soil was 136, 142, 131 and 128 mm for treatments ABC, B, A and the control, respectively (as calculated from data in Tables 3.4 and 3.6). The values for experiment *C14* were, respectively, 141, 142, 137 and 118 mm (Tables 3.5 and 3.7). The effect on available soil moisture was still more dramatic: assuming that water content at wilting point for the soil in experiment *C14* was 86 mm in 450 mm of soil (Table A1), available water was respectively, 55, 56, 49, and 31 mm.

Table 3.4. Soil bulk density ($Mg\ m^{-3}$) at different sampling dates and depths. Experiment *RTN*.

	Depth (mm)				
	25 June 1993		29 Nov. 1993		
	0 -75	75-150	0-150	150-300	300-450
No Paraplow (O)					
Corn - Barley	1.30	1.33	1.31	1.18	1.22
Corn - Wheat	1.31	1.33	1.37	1.20	1.14
Sunf. - Barley	1.32	1.34	1.34	1.20	1.19
Sunf. - Wheat	1.32	1.35	1.32	1.30	1.10
Mean	**1.31**	**1.34**	**1.34**	**1.22**	**1.16**
Paraplow Oct. 1991(A)					
Corn - Barley	----	----	1.22	1.18	1.13
Corn - Wheat	----	----	1.24	1.17	1.25
Sunf. - Barley	1.35	1.33	1.31	1.13	1.09
Sunf. - Wheat	----	----	1.36	1.19	1.10
Mean	**1.35**	**1.33**	**1.29**	**1.17**	**1.14**
Paraplow May 1992(B)					
Corn - Barley	1.32	1.31	1.29	1.22	1.16
Corn - Wheat	1.27	1.34	1.18	1.22	1.24
Sunf. - Barley	1.26	1.32	1.34	1.27	1.13
Sunf. - Wheat	1.27	1.35	1.36	1.12	1.28
Mean	**1.28**	**1.33**	**1.29**	**1.21**	**1.20**
Triple Paraplow(ABC)					
Corn - Barley	----	----	1.16	1.19	1.09
Corn - Wheat	----	----	1.26	1.23	1.22
Sunf. - Barley	1.26	1.30	1.28	1.19	1.22
Sunf. - Wheat	----	----	1.26	1.24	1.07
Mean	**1.26**	**1.30**	**1.24**	**1.21**	**1.15**
LSD ($p<0.05$)					
Paraplow	0.13	0.11	0.09	0.16	0.24
Crop sequence	0.05	0.06	0.07	0.11	0.17

Table 3.5. Soil bulk density ($Mg\ m^{-3}$) at different sampling dates and depths. Experiment *C14*.

	DEPTH (mm)							
	24 June 1993		**25 Nov. 1993**			**7 June 1994**		
	0-70	**70-140**	**0-150**	**150-300**	**300-450**	**0-150**	**150-300**	**300-450**
No Paraplow (O)								
Corn - Barley	1.30	1.28	1.36	1.28	1.09	1.26	1.31	1.37
Corn - Wheat	—	—	1.34	1.30	1.16	1.22	1.25	1.31
Sunflower - Barley	1.30	1.26	1.31	1.17	1.21	1.25	1.31	1.34
Sunflower - Wheat	—	—	1.22	1.20	1.32	1.34	1.28	1.32
Mean	**1.30**	**1.27**	**1.31**	**1.24**	**1.20**	**1.27**	**1.28**	**1.33**
Paraplow Oct. 1992 (A)								
Corn - Barley	1.28	1.30	1.32	1.26	1.14	1.25	1.30	1.35
Corn - Wheat	—	—	1.27	1.17	1.11	1.33	1.31	1.39
Sunflower - Barley	1.27	1.27	1.25	1.22	1.17	1.29	1.31	1.40
Sunflower - Wheat	—	—	1.34	1.27	1.25	1.35	1.26	1.32
Mean	**1.28**	**1.29**	**1.30**	**1.23**	**1.17**	**1.32**	**1.29**	**1.36**
Paraplow June 1993 (B)								
Corn - Barley	—	—	1.15	1.15	1.25	1.28	1.31	1.34
Corn - Wheat	—	—	1.07	1.18	1.17	1.30	1.24	1.35
Sunflower - Barley	—	—	1.18	1.24	1.21	1.27	1.30	1.36
Sunflower - Wheat	—	—	1.24	1.18	1.18	1.25	1.28	—
Mean	—	—	**1.16**	**1.19**	**1.20**	**1.24**	**1.26**	**1.35**
Triple Paraplow (ABC)								
Corn - Barley	—	—	1.13	1.17	1.12	—	—	—
Corn - Wheat	—	—	1.15	1.14	1.18	—	—	—
Sunflower - Barley	—	—	1.02	1.07	1.17	—	—	—
Sunflower - Wheat	—	—	1.29	1.24	1.24	—	—	—
Mean	—	—	**1.15**	**1.15**	**1.18**	—	—	—
LSD ($p<0.05$)								
Paraplow	0.03	0.06	0.08	0.07	0.13	0.11	0.08	—
Crop sequence	0.02	0.04	0.06	0.05	0.09	0.06	0.07	—

Table 3.5. (continued)

	Depth (mm)					
	19 Aug. 1994			29. Dec. 1994		
	0-150	150-300	300-450	0-150	150-300	300-450
No Paraplow (O)						
Corn - Barley	1.26	1.32	1.33	—	—	—
Corn - Wheat	—	—	—	—	—	—
Sunflower - Barley	1.28	1.31	1.36	1.27	1.30	1.35
Sunflower - Wheat	—	—	—	1.23	1.31	1.36
Mean	**1.27**	**1.31**	**1.35**	**1.25**	**1.31**	**1.35**
Paraplow Oct. 1992 (A)						
Corn - Barley	1.23	1.28	1.36	—	—	—
Corn - Wheat	—	—	—	—	—	—
Sunflower - Barley	1.21	1.21	1.23	1.18	1.30	1.31
Sunflower - Wheat	—	—	—	1.19	1.29	1.30
Mean	**1.22**	**1.24**	**1.30**	**1.19**	**1.30**	**1.30**
Paraplow June 1993 (B)						
Corn - Barley	1.21	1.28	1.33	—	—	—
Corn - Wheat	—	—	—	—	—	—
Sunflower - Barley	1.19	1.24	1.34	1.14	1.20	1.31
Sunflower - Wheat	—	—	—	1.11	1.24	1.31
Mean	**1.20**	**1.26**	**1.34**	**1.12**	**1.22**	**1.31**
Triple Paraplow (ABC)						
Corn - Barley	1.23	1.27	1.29	—	—	—
Corn - Wheat	—	—	—	—	—	—
Sunflower - Barley	1.18	1.24	1.32	1.24	1.15	1.35
Sunflower - Wheat	—	—	—	1.16	1.25	1.36
Mean	**1.21**	**1.25**	**1.30**	**1.20**	**1.20**	**1.35**
LSD ($p<0.05$)						
Paraplow	0.06	0.07	0.10	0.07	0.08	0.06
Crop sequence	0.05	0.05	0.05	0.05	0.04	0.06

Table 3.6. Soil moisture content (% by weight) at different sampling dates and depths. Experiment *RTN*.

	Depth (mm)							
	27 July 1992			14 Aug. 1992			17 Sep. 1992	
	0-150	150-300	300-450	0-150	150-300	300-450	0-150	150-300
No Paraplow (O)								
Corn - Barley	28.5	29.5	29.1	23.9	28.3	30.7	26.9	23.8
Corn - Wheat	—	—	—	—	—	—	26.6	23.1
Sunflower - Barley	28.1	29.8	31.2	24.9	28.9	31.0	25.5	22.3
Sunflower - Wheat	—	—	—	—	—	—	26.8	25.5
Mean	**28.3**	**29.7**	**30.2**	**24.5**	**28.6**	**30.9**	**26.5**	**23.7**
Paraplow Oct. 1991(A)								
Corn - Barley	27.7	29.2	31.9	24.5	30.6	31.9	—	—
Corn - Wheat	—	—	—	—	—	—	—	—
Sunflower - Barley	28.3	29.0	30.6	24.7	30.6	31.7	27.0	21.8
Sunflower - Wheat	—	—	—	—	—	—	26.9	23.2
Mean	**28.0**	**29.1**	**31.3**	**24.6**	**30.6**	**31.8**	**27.0**	**22.5**
Paraplow May 1992 (B)								
Corn - Barley	29.2	29.5	31.3	25.7	28.6	29.8	26.2	23.9
Corn - Wheat	—	—	—	—	—	—	27.5	23.6
Sunflower - Barley	28.9	28.8	31.8	25.3	30.1	32.3	26.9	22.8
Sunflower - Wheat	—	—	—	—	—	—	21.8	23.9
Mean	**29.1**	**29.2**	**31.6**	**25.5**	**29.4**	**31.1**	**25.6**	**23.6**
Triple Paraplow(ABC)								
Corn - Barley	29.2	30.4	31.8	25.1	31.7	32.1	—	—
Corn - Wheat	—	—	—	—	—	—	—	—
Sunflower - Barley	29.3	30.0	32.0	25.2	28.7	33.0	27.7	23.5
Sunflower - Wheat	—	—	—	—	—	—	27.0	25.1
Mean	**29.3**	**30.2**	**31.9**	**25.2**	**30.2**	**32.6**	**27.4**	**24.3**
LSD ($p<0.05$)								
Paraplow	5.4	3.1	3.0	1.9	3.9	3.7	2.7	2.5
Crop sequence	2.8	2.2	1.9	1.5	2.8	2.5	1.3	1.3

Table 3.6 (continued)

	Depth (mm)						
	14 Oct. 1992		**28 June 1993**		**29. Nov. 1993**		
	0-150	**150-300**	**0-150**	**75-150**	**0-150**	**150-300**	**300-450**
No Paraplow (O)							
Corn - Barley	15.7	15.9	22.9	23.1	25.7	21.2	15.4
Corn - Wheat	15.0	16.3	23.9	24.0	28.1	24.3	16.5
Sunflower - Barley	14.9	15.7	23.2	23.0	27.8	25.9	17.4
Sunflower - Wheat	16.4	19.4	23.1	23.7	28.5	25.7	16.4
Mean	**15.5**	**16.8**	**23.3**	**23.5**	**27.5**	**24.3**	**16.4**
Paraplow Oct. 1991 (A)							
Corn - Barley	—	—	—	—	20.9	26.6	24.6
Corn - Wheat	—	—	—	—	23.4	26.3	23.7
Sunflower - Barley	15.3	16.4	23.7	22.3	29.6	26.7	19.3
Sunflower - Wheat	15.6	17.0	—	—	28.9	21.8	19.0
Mean	**15.5**	**16.7**	**23.7**	**22.3**	**25.7**	**25.4**	**21.3**
Paraplow May 1992 (B)							
Corn - Barley	15.4	16.6	23.0	23.2	22.2	30.0	34.6
Corn - Wheat	16.2	16.0	23.1	21.6	23.4	28.1	24.2
Sunflower - Barley	15.9	17.0	22.9	21.8	27.3	27.4	19.4
Sunflower - Wheat	15.5	15.5	23.2	22.7	26.6	26.9	17.7
Mean	**15.8**	**16.3**	**23.1**	**22.3**	**24.8**	**28.1**	**23.9**
Triple Paraplow (ABC)							
Corn - Barley	—	—	—	—	23.7	31.2	26.8
Corn - Wheat	—	—	—	—	21.7	24.8	23.8
Sunflower - Barley	16.3	16.9	—	23.1	22.1	27.7	23.4
Sunflower - Wheat	15.8	16.4	—	—	22.1	26.8	27.3
Mean	**16.1**	**16.7**	**25.1**	**23.1**	**22.4**	**27.6**	**25.3**
LSD ($p<0.05$)							
Paraplow	2.1	3.4	2.8	3.0	6.8	5.6	6.7
Crop sequence	1.4	2.7	1.6	1.6	4.8	4.1	4.3

Table 3.7. Soil moisture content (% by weight) at different sampling dates and depths. Experiment *C14*.

	Depth (mm)							
	24 June 1993		25 Nov. 1993			7 June 1994		
	0-70	70-140	0-150	150-300	300-450	0-150	150-300	300-450
No Paraplow (O)								
Corn - Barley	22.8	24.1	24.8	23.5	16.4	29.6	34.4	30.4
Corn - Wheat	—	—	25.5	18.1	18.3	29.6	32.4	28.6
Sunflower - Barley	23.1	24.3	24.9	27.8	16.8	30.6	32.7	29.6
Sunflower - Wheat	—	—	21.5	16.2	16.6	29.0	31.4	31.6
Mean	**23.0**	**24.2**	**24.2**	**21.4**	**17.0**	**29.6**	**32.6**	**30.4**
Paraplow Oct. 1992 (A)								
Corn - Barley	23.2	24.8	30.7	26.4	17.7	28.8	32.2	30.6
Corn - Wheat	—	—	30.3	29.6	18.8	26.7	31.6	29.0
Sunflower - Barley	24.1	23.5	31.4	25.6	17.3	28.9	28.6	28.6
Sunflower - Wheat	—	—	27.4	20.0	17.9	26.8	30.0	32.8
Mean	**23.7**	**24.2**	**30.0**	**25.4**	**17.9**	**27.5**	**30.6**	**30.3**
Paraplow June 1993 (B)								
Corn - Barley	—	—	27.4	27.9	25.5	28.1	31.4	30.5
Corn - Wheat	—	—	26.0	28.9	28.0	29.7	29.3	30.2
Sunflower - Barley	—	—	25.7	23.9	24.9	27.2	30.0	31.6
Sunflower - Wheat	—	—	24.8	29.7	26.3	29.9	29.4	—
Mean	—	—	**26.0**	**27.6**	**26.2**	**29.1**	**29.8**	**30.8**
Triple Paraplow (ABC)								
Corn - Barley	—	—	28.6	29.7	26.3	—	—	—
Corn - Wheat	—	—	27.2	30.5	25.3	—	—	—
Sunflower - Barley	—	—	27.6	27.9	22.2	—	—	—
Sunflower - Wheat	—	—	24.7	27.6	25.7	—	—	—
Mean	—	—	**27.1**	**28.9**	**24.9**	—	—	—
LSD ($p<0.05$)								
Paraplow	4.4	2.6	3.4	5.0	3.1	1.9	3.1	6.2
Crop sequence	3.2	1.8	2.4	3.5	2.6	1.6	1.8	4.5

Table 3.7. (continued)

	Depth (mm)					
	19 Aug. 1994			29 Dec. 1994		
	0-150	150-300	300-450	0-150	150-300	300-450
No Paraplow (O)						
Corn - Barley	28.3	31.2	31.4	—	—	—
Corn - Wheat	—	—	—	—	—	—
Sunflower - Barley	27.6	31.6	30.8	16.8	26.7	29.1
Sunflower - Wheat	—	—	—	20.0	27.2	28.7
Mean	**28.0**	**31.4**	**31.1**	**18.4**	**26.6**	**28.9**
Paraplow Oct. 1992 (A)						
Corn - Barley	26.2	31.4	31.0	—	—	—
Corn - Wheat	—	—	—	—	—	—
Sunflower - Barley	24.0	31.5	32.3	18.7	24.7	29.4
Sunflower - Wheat	—	—	—	19.8	26.7	30.1
Mean	**25.1**	**31.4**	**31.7**	**19.2**	**25.7**	**29.8**
Paraplow June 1993 (B)						
Corn - Barley	28.4	29.1	31.6	—	—	—
Corn - Wheat	—	—	—	—	—	—
Sunflower - Barley	27.8	29.9	31.0	20.0	26.6	29.6
Sunflower - Wheat	—	—	—	22.2	27.5	29.4
Mean	**28.1**	**29.5**	**31.3**	**21.1**	**27.1**	**29.5**
Triple Paraplow (ABC)						
Corn - Barley	28.2	32.5	33.4	—	—	—
Corn - Wheat	—	—	—	—	—	—
Sunflower - Barley	29.5	32.4	31.5	19.5	25.1	28.4
Sunflower - Wheat	—	—	—	24.3	28.5	29.9
Mean	**28.8**	**32.4**	**32.4**	**21.9**	**26.8**	**29.2**
LSD ($p<0.05$)						
Paraplow	2.9	4.4	3.9	2.3	3.8	2.4
Crop sequence	1.3	2.3	1.2	1.8	1.5	1.7

In Nov. 1993, the time interval since the last paraplowing had varied from 5 months (treatment ABC in both experiments) to 25 months (treatment A in experiment *RTN*). As shown above, all Paraplow treatments were able to capture a larger proportion of the precipitation than did the undisturbed soil. Also, a higher proportion of the water present in soil reached deeper horizons, in particular in treatments B and ABC. In experiment *RTN*, the proportion of the total water present in the 300-450 mm soil layer was 32, 30, 28 and 22 % for treatments ABC, B, A and the control, respectively. In experiment *C14* corresponding figures were 31, 33, 23 and 26 %. The deep percolation of water, even where soil moisture contents near the soil surface were below field capacity, suggests a mechanism of preferential flow through a continuous system of macropores and cracks in the Paraplow treatments. Previous reports have shown that a major effect of Paraplow is an increase in the volume of soil occupied by large pores (Hipps and Hodgson 1988a, Pikul *et al.* 1990).

Paraplowing also improved soil aeration in excess moisture conditions, which is in agreement with previous reports (Braim *et al.* 1984, Hipps and Hodgson 1988a). In experiment *RTN*, ODR immediately after wheat and barley seeding was higher for treatments B and ABC than for treatment A and the control, except one day after a heavy rainfall occurred on 10 July 1992 (Table 3.8). Similarly, at the time of emergence of the last crop in experiment *C14*, both B and ABC treatments had better aeration status and higher soil temperature than the treatment without Paraplow, and also had higher ODR than treatment A immediately after a 41-mm rainfall on 17 July 1994 (Table 3.9). The improvement in ODR may have arisen either from increased evaporation from the soil surface, or improved deep percolation of excess water in treatments with Paraplow. The rapid increase in ODR occurring

Table 3.8. Soil oxygen diffusion rate at 50-mm depth for different Paraplow treatments and previous crops, at two dates after wheat and barley seeding in experiment *RTN*.

Paraplow Treatment	**Oxygen Diffusion Rate ($\mu g\ O_2\ cm^{-2}\ min^{-1}$)** 11 June 1992	11 July 1992	14 July 1992
B †	0.25 b #	0.02 a	0.25 a
ABC ‡	0.34 a	0.02 a	0.17 b
A §	0.15 c	0.01 a	0.14 c
O ¶	0.16 c	0.02 a	0.13 c
Previous Crop			
Corn	0.16 a	0.02 a	0.19 a
Sunflower	0.13 b	0.02 a	0.18 a

† Paraplow in May 1992
‡ Paraplow in Oct. 1991 and May 1992.
§ Paraplow in Oct. 1991
¶ No Paraplow
# Means followed by the same letter within sampling dates were not statistically different ($p<0.05$)

Table 3.9. Soil oxygen diffusion rate and temperature at 50-mm depth for different Paraplow treatments at three dates, after wheat and barley seeding in experiment *C14*.

Treatment	**13 July 1994**	**16 July 1994**	**19 July 1994**
	Oxygen diffusion rate ($\mu g\ O_2\ cm^{-2}\ min^{-1}$)		
ABC †	0.07 a #	0.08 a	0.02 a
B ‡	0.07 a	0.08 a	0.02 a
A §	0.07 a	0.08 a	0.00 b
O ¶	0.05 b	0.06 b	0.00 b
	Temperature (° C)		
ABC	8.5 a	12.8 a	—
B	8.2 ab	12.9 a	—
A	8.1 ab	12.6 a	—
O	7.9 b	12.7 a	—

† Paraplow in Oct. 1992 and May 1993.
‡ Paraplow in May 1993
§ Paraplow in Oct. 1992
¶ No Paraplow
# Means followed by the same letter within sampling dates were not statistically different ($p<0.05$)

from 11 to 14 July 1992 (Table 3.8) was an indication of improved infiltration, rather than evaporation.

3.3.3.2 *Experiments C13 and C15*

In experiment C13, soil moisture was at levels near field capacity at all sampling dates (Table 3.10). At wheat maturity (24 Nov. 1993), treatment A had 29.0 % soil moisture in the upper 150 mm, which was significantly lower ($p<0.05$) than that of the control (31.0%). This is an additional evidence of the increase in infiltration capacity by paraplowing, since the field capacity of this soil is around 29 % by weight (Table A1). The same effect was observed in Jan 1994, where soil moisture content was higher in the surface soil and lower in the subsurface soil in the control s compared to the Paraplow treatment (Table 3.10). There was a transient effect of Paraplow on soil bulk density measured in 150-mm depth increments (Table 3.11). On 24 Nov. 1993, 12 months after paraplowing, the control had a higher density (1.34 Mg m^{-3}) than treatment A (1.28 Mg m^{-3}) in the layer between 150 and 300 mm depth. No differences between Paraplow treatments were detected in subsequent sampling dates.

In experiment C15, soil moisture was generally higher for treatment A than the control (Table 3.12), indicating increased infiltration capacity. Soil bulk density was also decreased by paraplowing (Table 3.13). On 23 Nov. 1993, soil bulk density between 0 and 450 mm in treatments O and A was 1.25 and 1.13 Mg m^{-3}, respectively. The difference decreased progressively, presumably due to soil sitting and on 13 May 1994 values were 1.26 and 1.21 Mg m^{-3}, respectively.

Table 3.10. Soil moisture (% by weight) at different sampling dates and depths. Experiment *C13*.

	24 Nov. 1993			21 Jan. 1994			1 June 1994		
	0-150	150-300	300-450	0-150	150-300	300-450	0-150	150-300	300-450
No Paraplow (O)	31.0	27.5	28.0	29.1	26.1	25.7	27.6	28.6	28.3
Paraplow Oct. 1992 (A)	29.0	29.4	28.8	27.4	28.7	26.4	27.3	30.3	29.1
LSD ($p<0.05$)	1.7	2.2	2.9	1.5	2.6	2.4	2.0	2.9	3.3

Table 3.11. Soil bulk density (Mg m^{-3})at different sampling dates and depths. Experiment *C13*.

	24 Nov. 1993			21 Jan. 1994			1 June 1994		
	0-150	150-300	300-450	0-150	150-300	300-450	0-150	150-300	300-450
No Paraplow (O)	1.22	1.34	1.38	1.23	1.33	1.35	1.23	1.31	1.36
Paraplow Oct. 1992 (A)	1.19	1.30	1.38	1.24	1.37	1.36	1.28	1.29	1.37
LSD ($p<0.05$)	0.04	0.04	0.06	0.06	0.05	0.06	0.07	0.05	0.06

Table 3.12. Soil moisture (% by weight) at different sampling dates and depths. Experiment *C15*.

	23 Nov. 1993			20 Jan. 1994		
	0-150	150-300	300-450	0-150	150-300	300-450
No Paraplow (O)	30.2	30.5	26.5	17.8	16.7	16.9
Paraplow Oct.1992 (A)	33.7	32.6	28.5	17.9	16.5	16.8
LSD (p<0.05)	4.2	2.1	2.3	3.0	3.3	2.9

	4 May 1994			13 May 1994		
	0-150	150-300	300-450	0-150	150-300	300-450
No Paraplow (O)	12.9	11.7	14.6	34.5	30.9	26.2
Paraplow Oct.1992 (A)	13.1	14.8	16.9	35.2	31.2	26.1
LSD (p<0.05)	2.1	2.6	2.3	2.1	2.0	1.6

Table 3.13. Soil bulk density (Mg m^{-3}) at different sampling dates and depths. Experiment *C15*.

	23 Nov. 1993			20 Jan. 1994		
	0-150	150-300	300-450	0-150	150-300	300-450
No Paraplow (O)	1.18	1.21	1.37	1.19	1.20	1.35
Paraplow Oct.1992 (A)	1.01	1.11	1.26	1.12	1.15	1.26
LSD (p<0.05)	0.07	0.08	0.07	0.06	0.04	0.04

	4 May 1994			13 May 1994		
	0-150	150-300	300-450	0-150	150-300	300-450
No Parap low (O)	1.21	1.24	1.32	1.18	1.21	1.39
Parap low Oct. 1992 (A)	1.13	1.26	1.24	1.11	1.16	1.36
LSD (p<0.05)	0.06	0.04	0.07	0.03	0.04	0.04

3.3.4. <u>Residual Effects of Paraplowing</u>

Paraplowing affected the various soil physical properties measured for relatively long periods. Soil PR after paraplowing was consistently lower than in the control in all experiments and all sampling dates (Figs. 3.5 through 3.8). As discussed in Section 3.3.2, comparison of PR between Paraplow treatments may be invalidated by variations in soil moisture content, and to avoid this, only PR measurements taken in the winter time, when the soil profile was uniformly wet, should be used. Considering only PR measurements taken at seeding time of wheat and barley, effects on soil strength of paraplowing 20 months before were still visible in experiments *RTN* (Fig. 3.5e), *C14* (Fig. 3.6c) and *C13* (Fig. 3.7d). At the end of experiments *RTN* and *C14*, treatment A (paraplowing 26 months before) still had lower PR than the control at certain soil depths, but this difference could have been due to higher water extraction from soil in treatment A. However, in experiment *RTN*, treatment A evidenced a higher water infiltration capacity than the control (Section 3.3.3.1) in Nov. 1993, indicating that effects of paraplowing lasted for at least 25 months.

Effects of paraplowing on soil bulk density were still visible at the end of experiments *RTN* (Table 3.4) and *C14* (Table 3.5). However, treatment A did not differ from the control in any sampling date. The most lasting effect of paraplowing on this variable was recorded for treatment B in experiment C14, which differed significantly from the control 18 months after paraplowing (Table 3.5).

An additional evidence of the residual effect of paraplowing was derived from ODR measurement in experiment *C14*. Even 20 months after paraplowing, treatment A had higher ODR values than the control (Table 3.9).

Summarizing, paraplowing caused improvements in soil structure, which lasted for at least six months in experiment *C15*, 20 months in *C14* and *C13*, and 25 months in *RTN*. Among several studies that have looked at the time residuality of Paraplow effects (Table 2.1), persistency has varied from six (Busscher *et al.* 1988) to 20 months (Hipps and Hodgson 1988a).

Persistence of effects is important considering the high energy cost of paraplowing. Karlen *et al.* (1991) determined that for a loamy sand, a Paraplow passed at 400-mm depth had a fuel requirement of 22.7 L ha^{-1}. In our work we estimated a consumption of 25 L ha^{-1} operating at 450 mm depth. It would take a yield increase of 300 to 500 kg/ha of corn or wheat to pay for this. Based on the results obtained, it can be concluded that there would be no need for subsoiling every year in the type of soil and system of production represented by the present study.

3.3.5. Crop Sequence and its Interaction with Paraplow Treatment

Soil PR profiles were markedly affected both by crops currently growing and their predecessors in experiments *RTN* (Figs. 3.9 through 3.14) and *C14* (Figs. 3.15 through 3.18). This effect was generally small when soil was wet (measurements taken in June to August), and very large in advanced stages of the crops, when soil moisture was lacking. This suggests that the differences in PR between crops would have been mainly due to differences in water consumption patterns by the crops. In this sense, early in the season in experiment *RTN*, PR under barley was higher than under wheat in the upper 165 mm of soil (Fig. 3.11), very likely reflecting a higher water consumption by barley. On the other hand, the opposite was observed in experiment *C14* very late in the season (Fif. 3.18). In this case, PR below 180 mm

Figure 3.9. Effect of previous crop on soil penetration resistance profiles for different Paraplow (PPLW) treatments. Experiment *RTN*, 27 July 1992: a) treatment A (Paraplow in Oct. 1991); b) treatment B (Paraplow in May 1992); c) treatment ABC (Paraplow in Oct. 1991 and May 1992); d) treatment O (control).

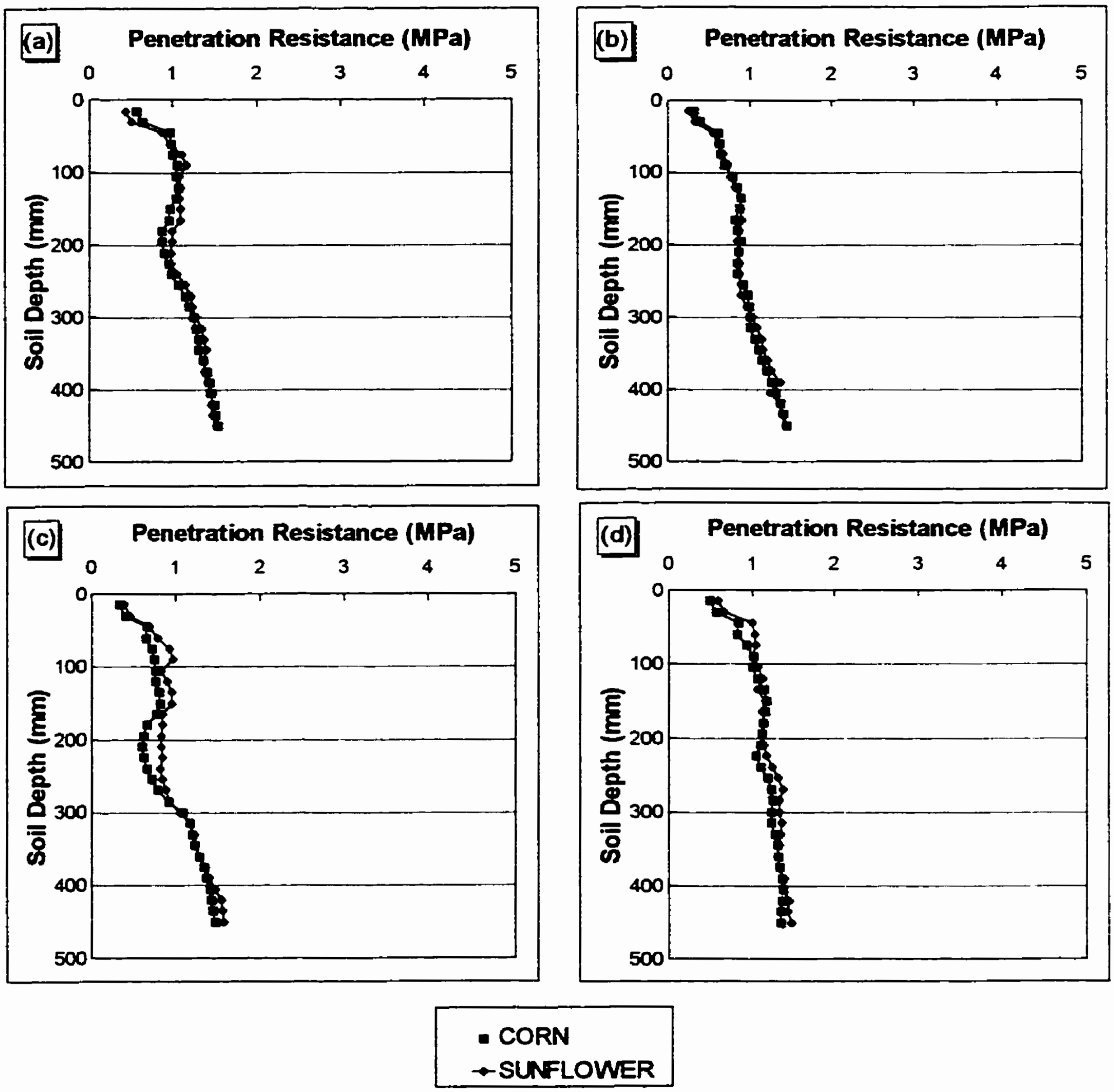


Figure 3.10. Effect of previous crop on soil penetration resistance profiles for different Paraplow treatments. Experiment *RTN*, 17 Aug. 1992: a) treatment A (Paraplow in Oct. 1991); b) treatment B (Paraplow in May 1992); c) treatment ABC (Paraplow in Oct. 1991 and May 1992); d) treatment O (control).

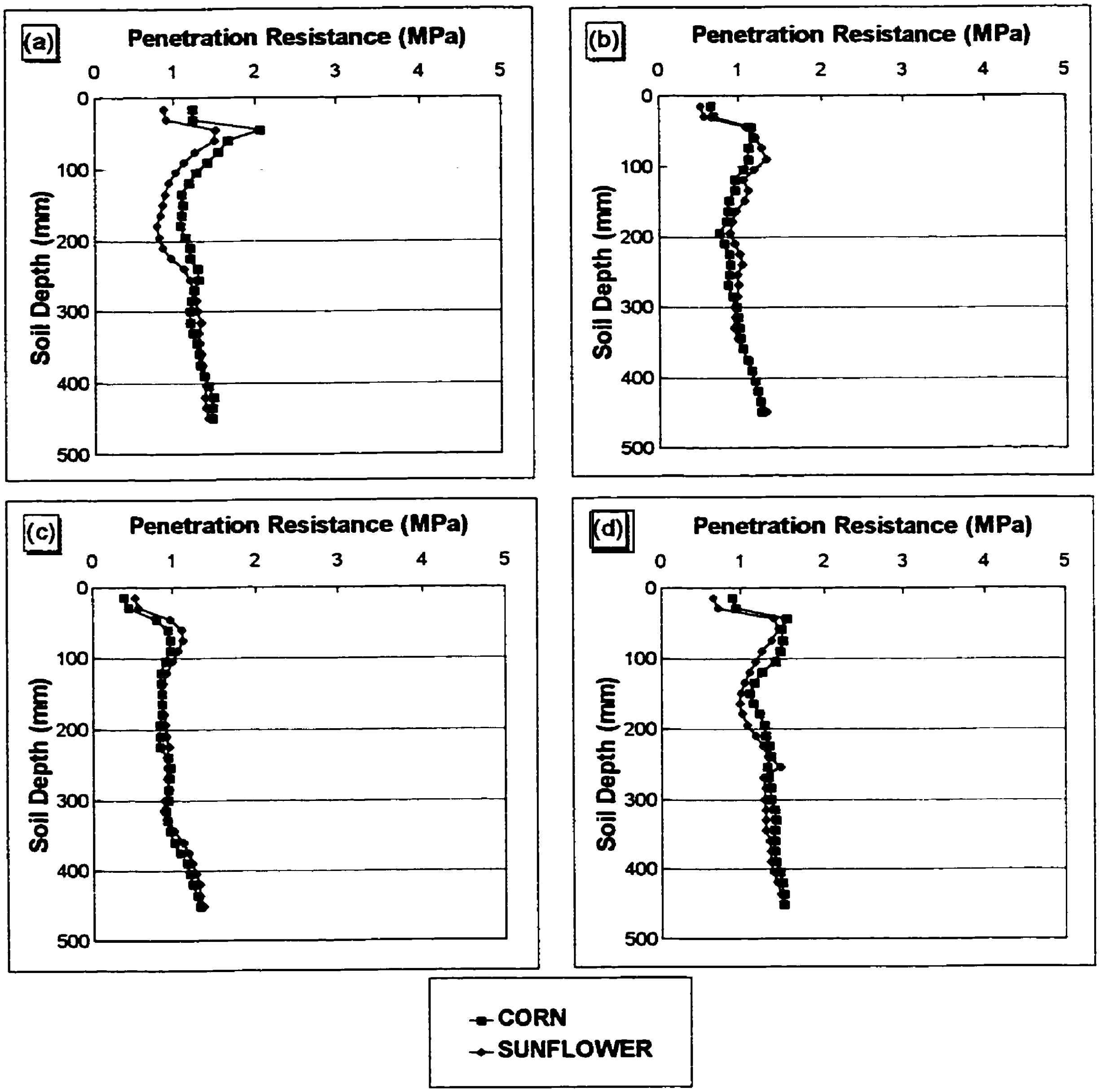


Figure 3.11. Effect of crop sequence on soil penetration resistance profiles for different Paraplow treatments. Experiment *RTN*, 17 Sep.1992: a) treatment A; b) treatment B; c) treatment ABC; d) treatment O.

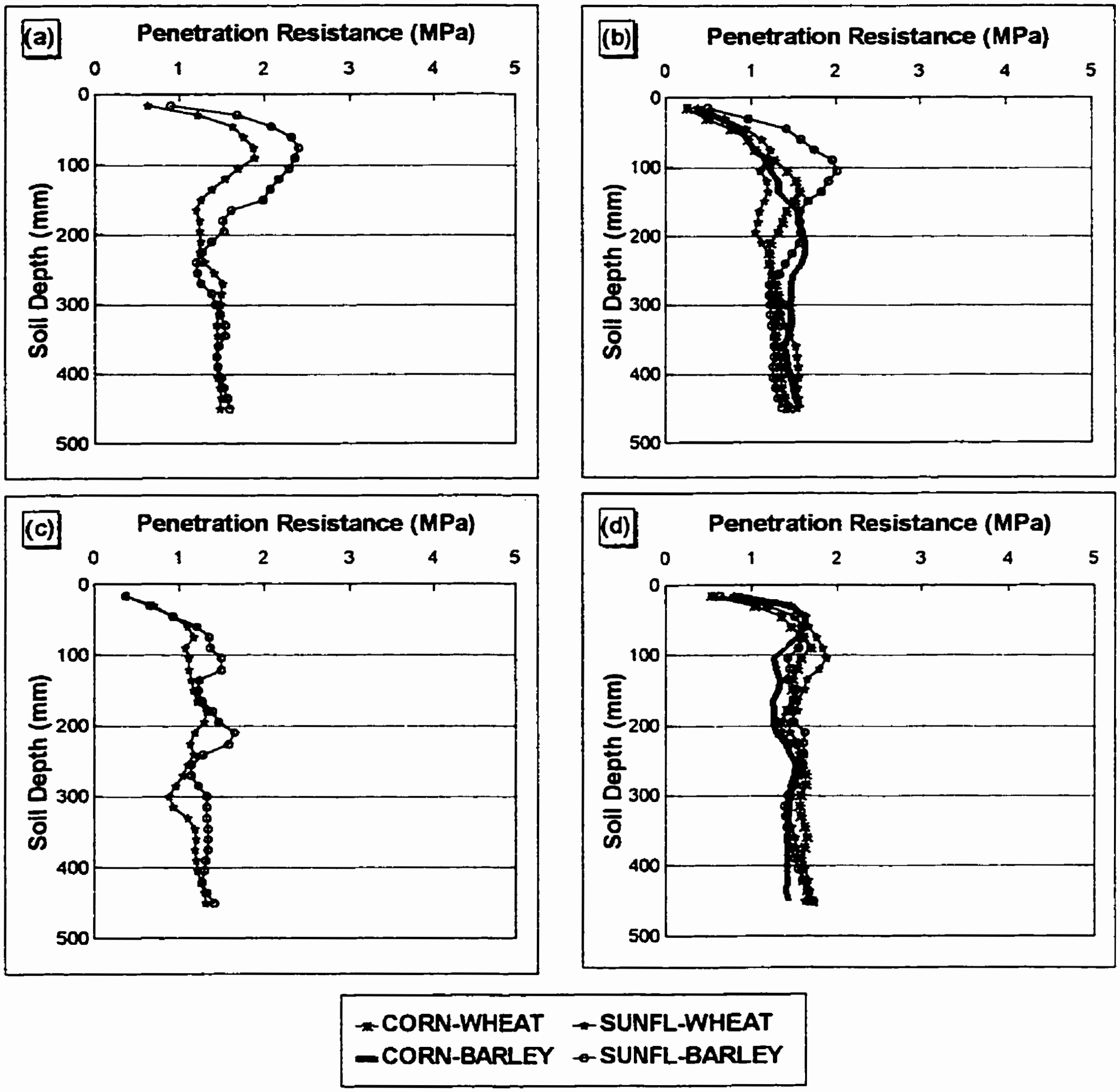


Figure 3.12. Effect of crop sequence on soil penetration resistance profiles for different Paraplow treatments. Experiment *RTN*, 14 Oct. 1992: a) treatment A (Paraplow Oct. 1991); b) treatment B (Paraplow May 1992); c) treatment ABC (Paraplow Oct. 1991 and May 1992); d) treatment O (control).

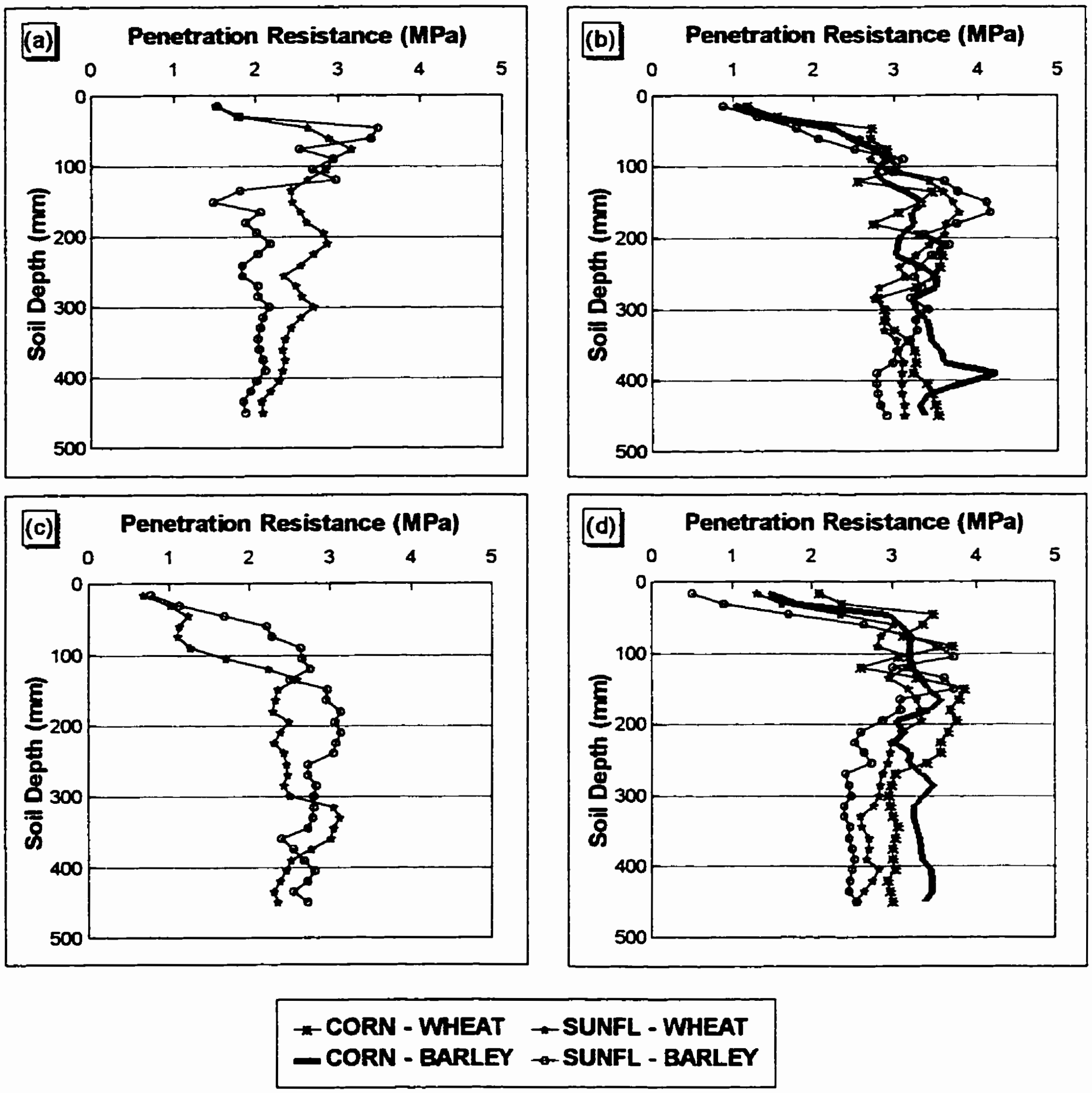


Figure 3.13. Effect of crop sequence on soil penetration resistance profiles for different Paraplow treatments. Experiment *RTN*, 28 June 1993: a) treatment A; b) treatment B; c) treatment ABC; d) treatment O.

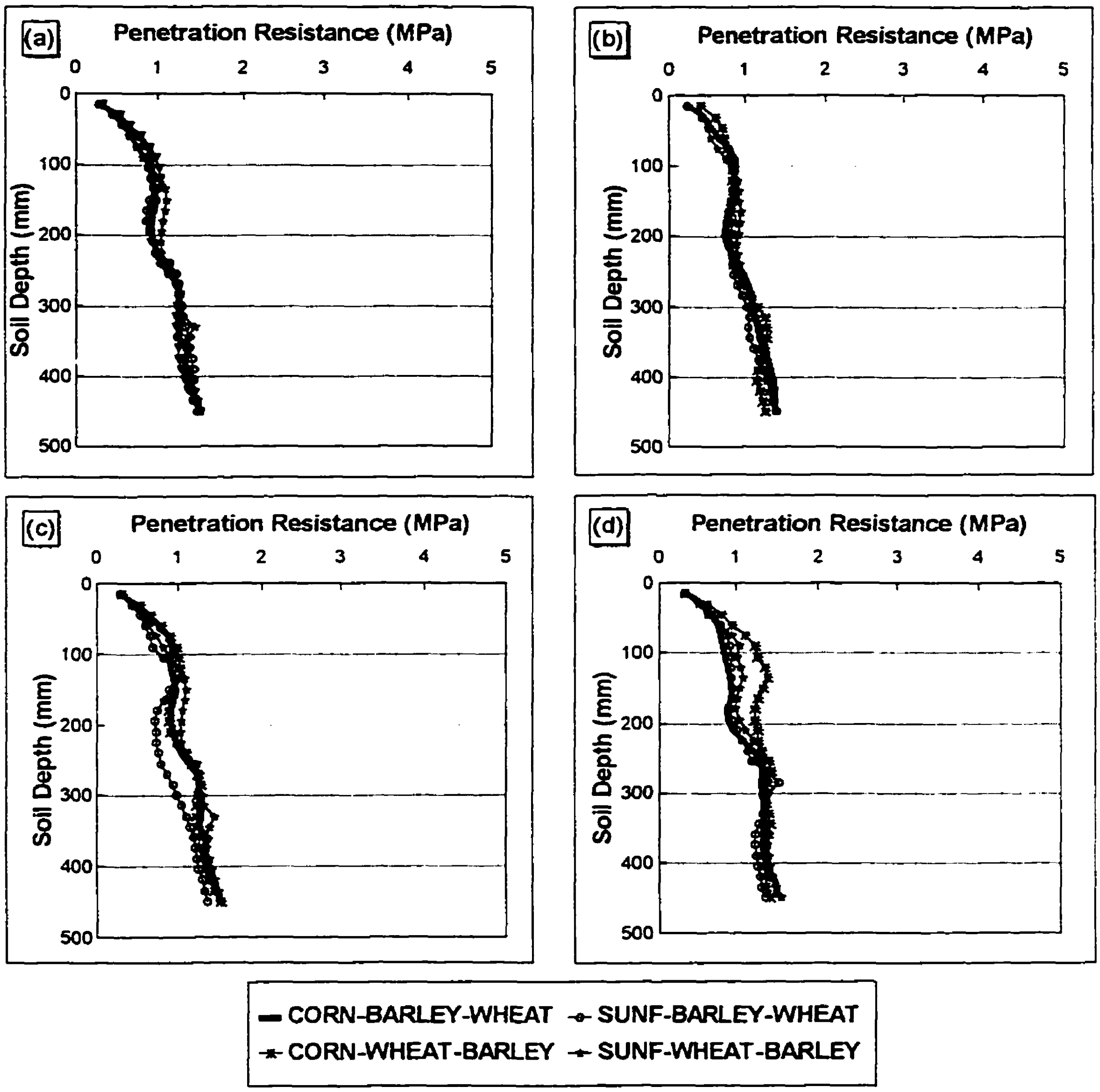


Figure 3.14. Effect of crop sequence on soil penetration resistance profiles for different Paraplow treatments. Experiment *RTN*, 29 Nov. 1993: a) treatment A (Oct. 91); b) treatment B (May 92); c) treatment ABC (Oct. 91, May 92, June 93); d) treatment O (control).

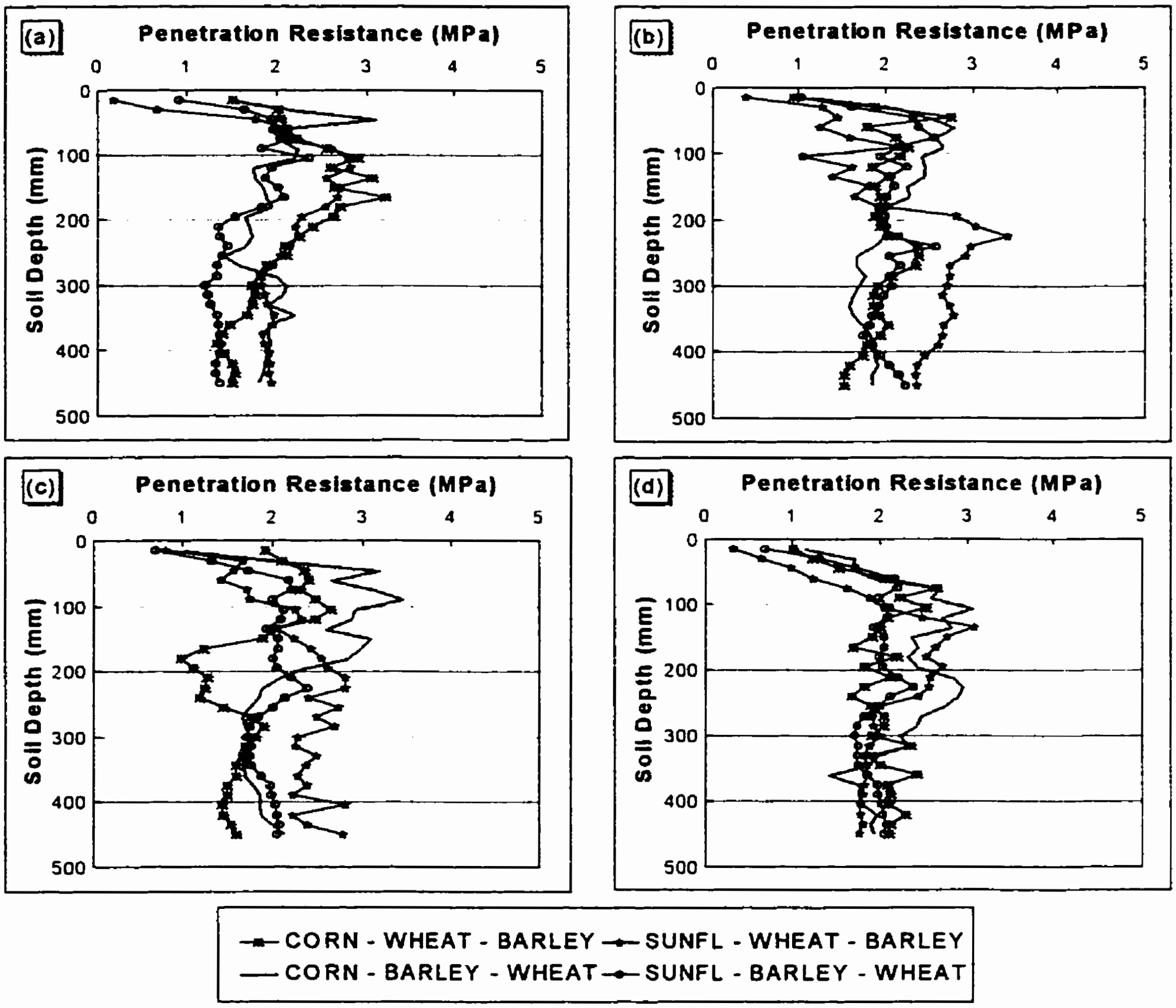


Figure 3.15. Effect of previous crop on soil penetration resistance profiles for different Paraplow treatments. Experiment *C14*, 24 June 1993: a) treatment A (Oct. 92); b) treatment O (control).

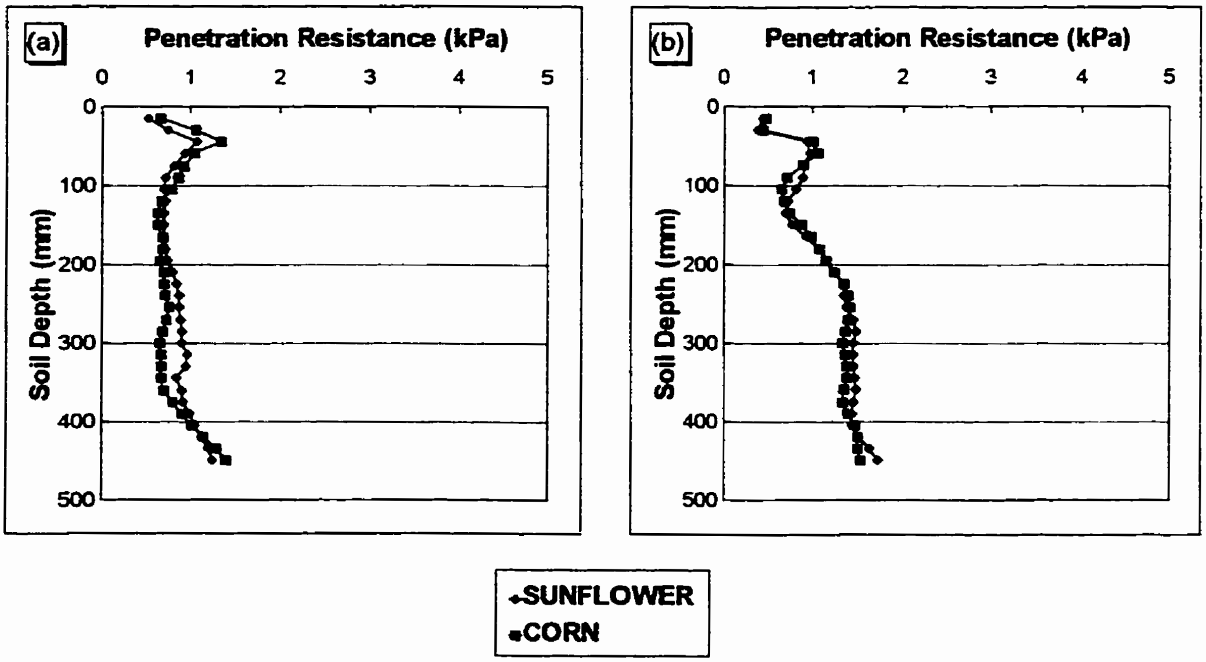


Figure 3.16. Effect of crop sequence on soil penetration resistance profiles for different Paraplow treatments. Experiment *C14*, 25 Nov. 1993: a) treatment A (Oct. 92); b) treatment B (June 93); c) treatment ABC (Oct. 92, June 93); d) treatment O (control).

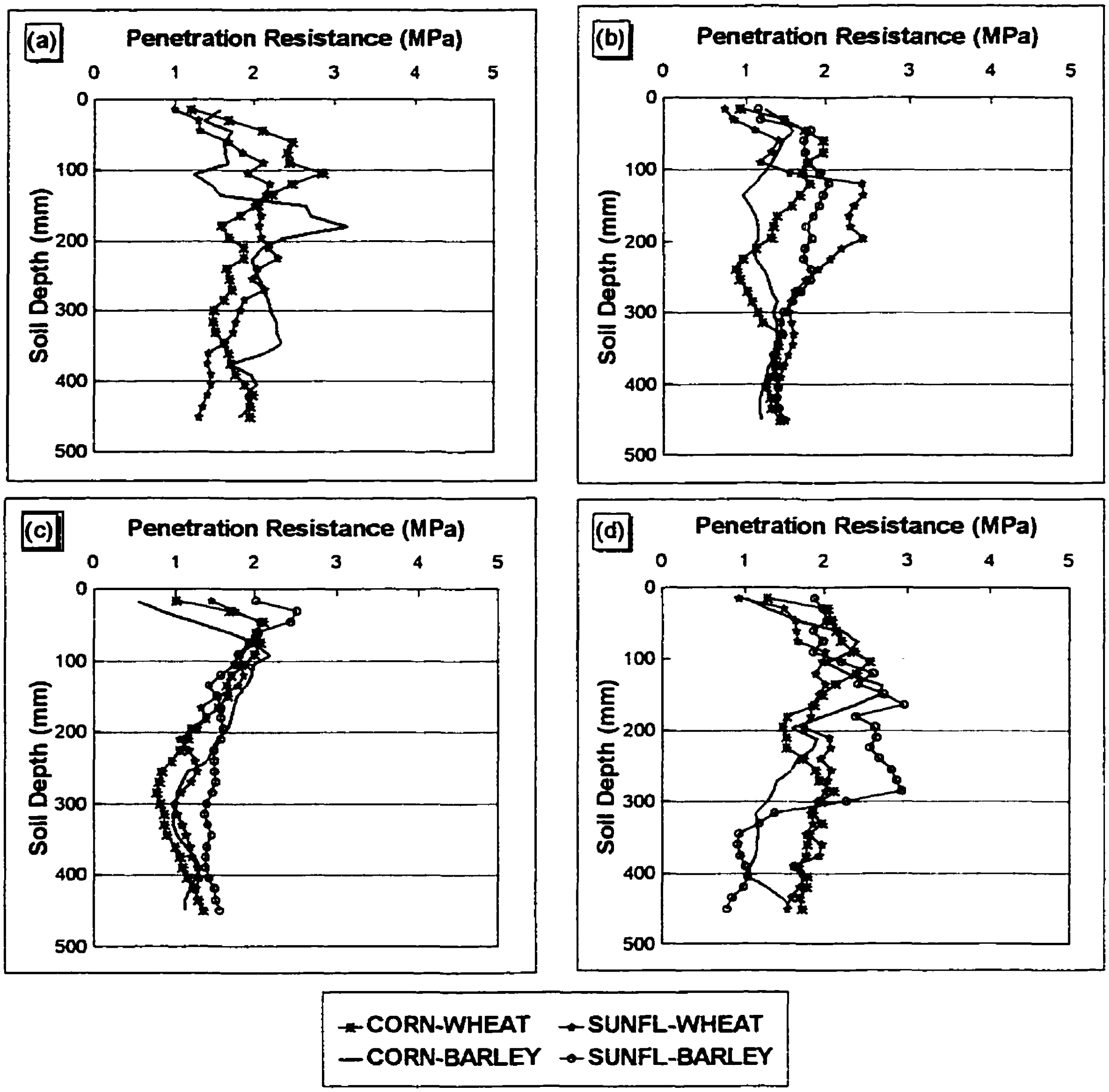


Figure 3.17. Effect of crop sequence on soil penetration resistance profiles for different Paraplow treatments. Experiment *C14*, 7 June 1994: a) treatment A (Oct. 92); b) treatment B (June 93); c) treatment ABC (Oct. 92, June 93, May 94); d) treatment O (control).

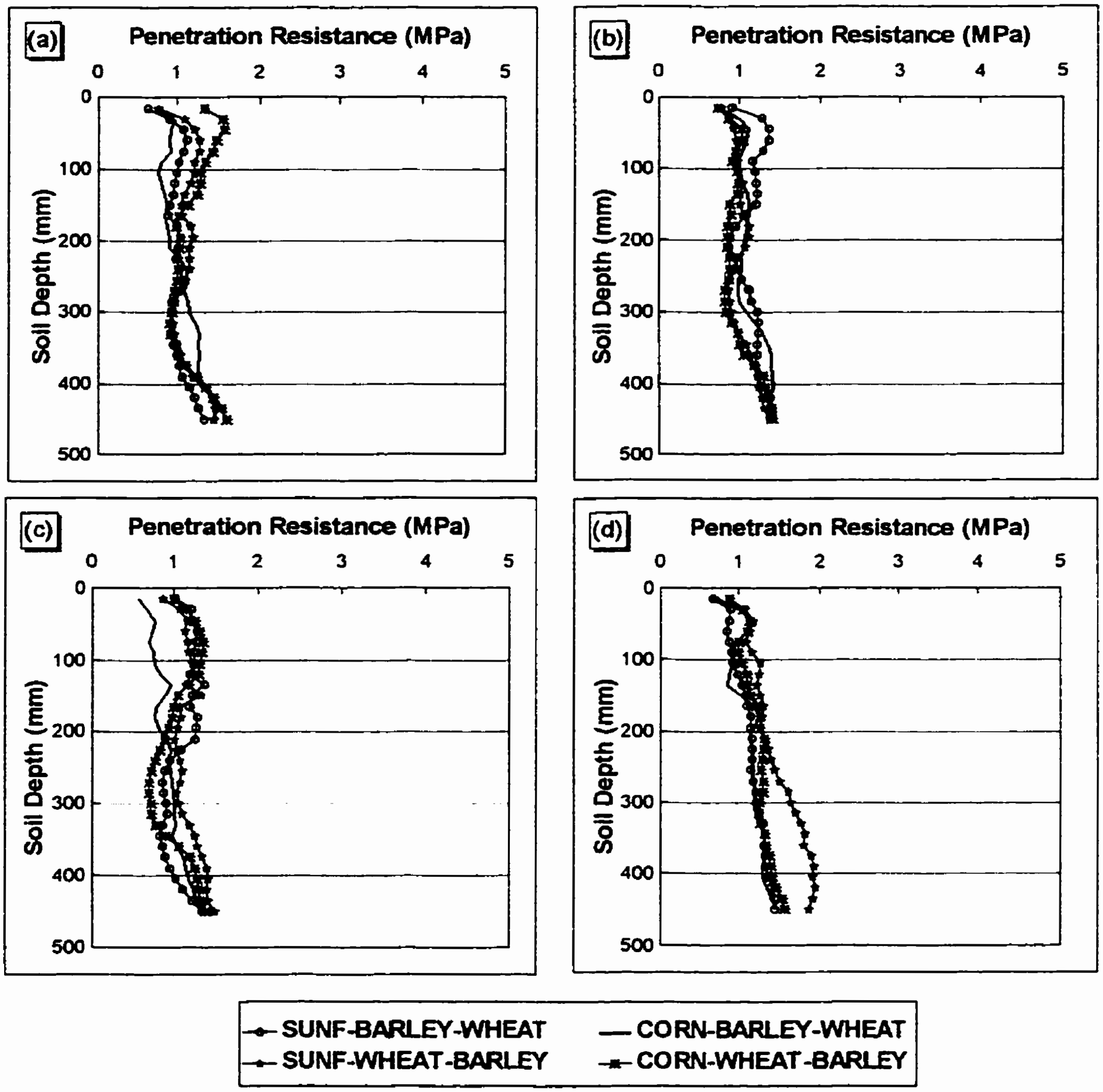
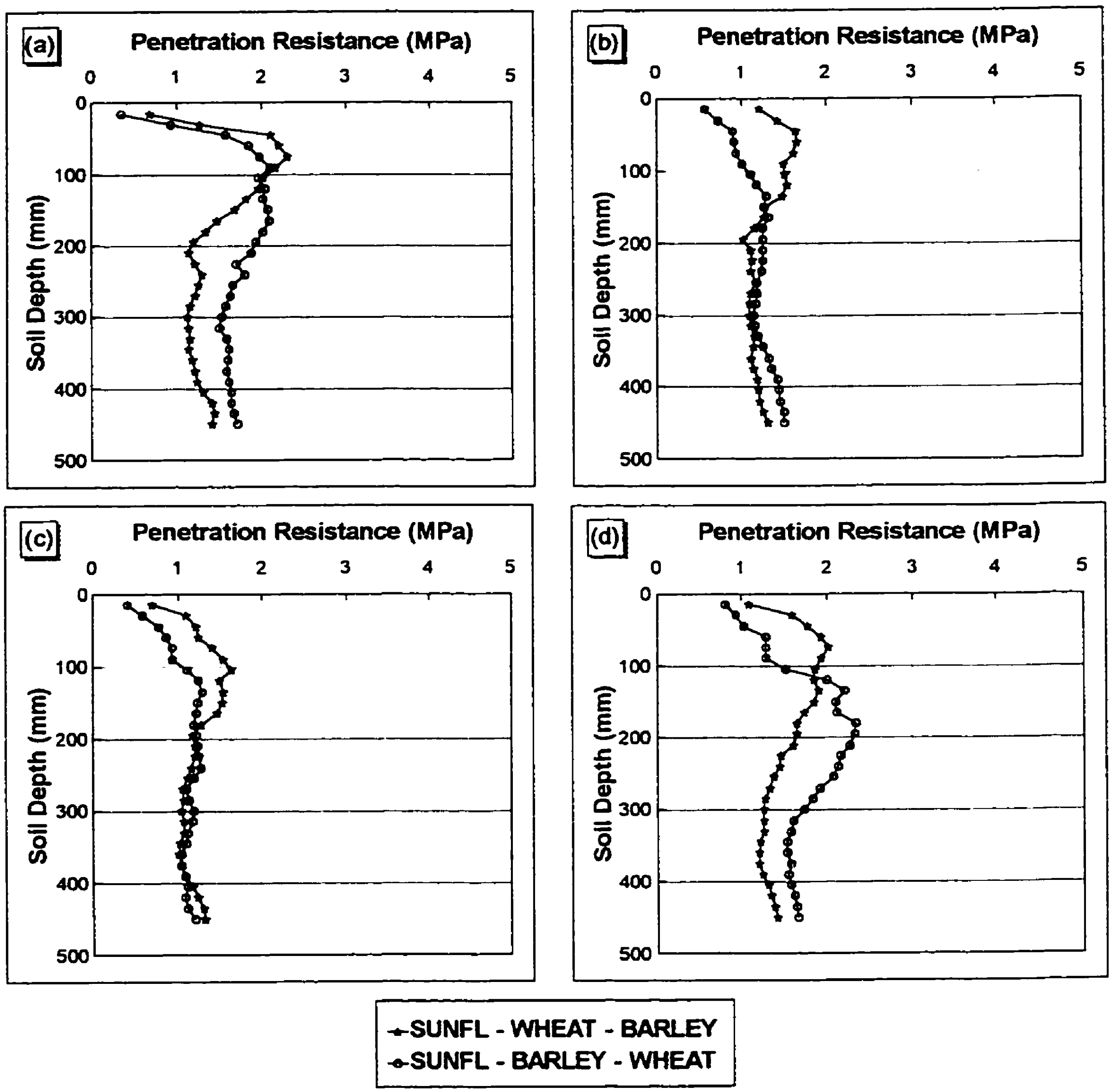


Figure 3.18. Effect of crop sequence on soil penetration resistance profiles for different Paraplow treatments. Experiment *C14*, 29 Dec.1994: a) treatment A (Oct. 92); b) treatment B (June 93); c) treatment ABC (Oct. 92, June 93, May 94); d) treatment O (control).



was higher under wheat than barley, probably reflecting the fact that the latter had stopped extracting water a few days earlier than the former.

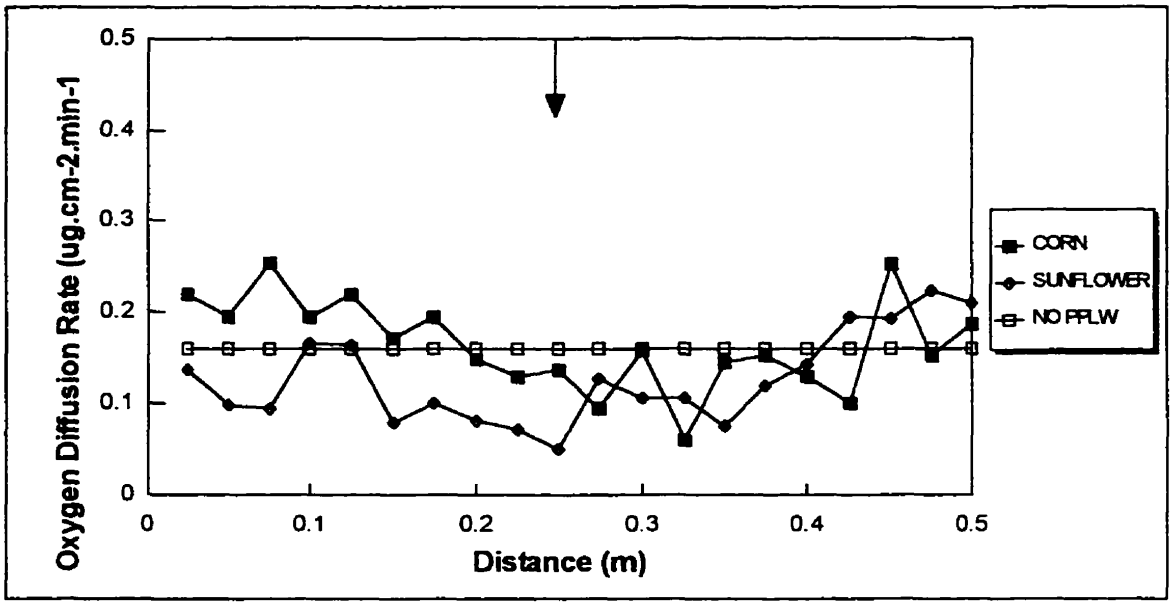
The first crop in the rotation (corn or sunflower) significantly affected PR at various sampling dates throughout the duration of the experiments. In experiment *RTN*, after seeding the second crop in the rotation, soil PR after sunflower was significantly higher than after corn at 60-75 mm and 165-240 mm (Fig. 3.9). The same occurred in Sep. 1992 at 45-90 mm depth (Fig. 3.11). Similarly, in experiment *C14*, PR values after corn were lower than after sunflower in June 1993 (at 270 to 375 mm soil depth, Fig. 3.15), Nov. 1993 (at most depths between 60 and 300 mm, Fig. 3.16) and June 1994 (around 200 mm depth, Fig. 3.17). On the other hand, there were also cases, particularly in advanced stages of wheat and barley crops in experiment *RTN*, where PR values after corn were higher than after sunflower (Figs. 3.10, 3.12 and 3.14). If it is assumed that differences in PR were caused mainly by differences in soil moisture content, it can be concluded that at times when water infiltration into the soil was the dominant process (mainly in the winter time, and in Nov. 1993), soil after sunflower tended to have lower soil moisture content than after corn. These results suggest that corn left the soil in a condition more favourable for water infiltration than sunflower.

Soil moisture content was also affected by crop sequence. By the time of fall paraplowing in experiment *RTN* (22 May 1992), soil moisture content after corn (25.3 %) was higher than after sunflower (23.8 %) in the surface 150 mm. In Nov. 1993, soil moisture in the 0-150 mm soil layer for treatments A and B (Table 3.6) was higher when sunflower was the first crop in the rotation (28.1 %) than in plots that had grown corn (22.5 %). The opposite occurred in the 300-450 mm soil horizon, where soil moisture values for sunflower and corn were 18.9 and 26.7 %, respectively. In experiment *C14*, also in Nov. 1993, soil moisture after corn (25.5%) was higher than after sunflower (24.0%) throughout the whole soil profile (Table 3.7). Considering the abundant rainfall just before sampling in both experiments in Nov. 1993, it can be concluded that water infiltration capacity was lower after sunflower than corn.

The lower soil moisture frequently observed after sunflower could have been due either to improved internal soil drainage, presumably because of vertical macropores created by tap roots; or to impaired water infiltration into the soil due to some factor associated with the nature of sunflower plants. The available data are not sufficient to indicate which of these mechanisms prevailed. The first possibility, improved drainage, was not very likely, because the tap roots were probably still intact by the time the measurements were made. The second mechanism, impaired infiltration, could have been caused in turn by some degree of soil compaction caused either by sunflower tap roots, or by soil slaking by rain drops falling on land with relatively low residue coverage. The higher ODR observed after corn (Fig 3.19), in spite of higher moisture content, would support the hypothesis of higher soil compaction after sunflower.

There are no studies in the literature reporting on compaction caused by roots affecting water infiltration. Willatt and Sulistyaningsih (1990) determined an increase in soil strength caused by the presence of rice roots. Several workers have shown that radial growth of roots cause reductions in the macropores in a volume of soil surrounding them (Blevins *et al.* 1970, Guidi *et al.* 1985, Bruand *et al.* 1996), and it is well known that water flow in a

Figure 3.19. Effect of previous crop on oxygen diffusion rate measured on transects perpendicular to Paraplow passes in treatment A. Experiment *RTN*, 11 June 1992. The arrow indicates the point of insertion of the Paraplow shank into the soil.



porous medium is directly proportional to the pore size squared. Dexter (1987) developed a model, later validated by Bruand *et al.* (1996), which predicted that the extent of the soil volume affected by roots was a function of root diameter. It may be speculated that sunflower tap roots would compact a larger soil volume than corn roots. The uncertainty remains as to whether this may have an impact on a macroscopic soil property such as infiltration capacity.

The effects of crop sequence on soil water dynamics often interacted with Paraplow treatments. As discussed above, in the winter after harvest of the first crop, in both *RTN* and *C14* experiments, soil moisture content after corn was higher than after sunflower, and this difference was evident only in treatment A (Figs. 3.9 and 3.15). Roots and shoots of both crops grew more extensively in Paraplow treatment than the control (Chapter 4), and therefore, the effects of these crops on soil properties would have been augmented by paraplowing.

In Sep. 1992, PR under barley was significantly higher than under wheat, particularly in treatments B and A after sunflower, between 45 and 200 mm depth (Fig. 3.11). This would have been caused by higher water extraction from soil in this combination of Paraplow treatment and previous crop, which, as shown in Chapter 4, was the one with highest growth of wheat and barley crops. No differences between wheat and barley were observed in the no-Paraplow treatment.

The soil moisture data collected in Nov. 1993 in experiment *RTN* (Table 3.6), 19 months after corn and sunflower harvest, indicated a strong interaction between the first crop in the sequence and Paraplow treatments. This interaction may have resulted from the different nature of root systems of corn and sunflower. The higher soil moisture content in the

150 mm of topsoil after sunflower than after corn in Nov. 1993 would have been due to improved water infiltration capacity into the soil by large pores left by taproots, that would have already decomposed 19 months after harvest. In the case of corn, a deeper fibrous root system would have left a system of channels after decomposition, through which water would have percolated deeper into the soil by preferential flow. The largest difference in soil moisture at 0-150 mm depth was observed in treatment A, which was the treatment that would have promoted extensive root growth in both sunflower and corn. Treatment B also showed a large effect, while treatments O and ABC showed no difference at all. The effect observed in treatment B was in spite of the Paraplow having been passed after corn and sunflower were grown. Paraplowing at that time would not have destroyed the root systems, and very likely promoted their decomposition afterwards. In the case of treatment ABC, paraplowing in the third season would have eliminated any effects of corn and sunflower roots.

3.5. CONCLUSIONS

The Paraplow was effective in reducing soil compaction status resulting in lower mechanical impedance to root growth, improved water infiltration capacity and higher aeration in times with a high probability of waterlogging. These effects lasted for more than 20 months, particularly at the positions where soil disturbance was highest.

Soil loosening by Paraplow was achieved in virtually the entire soil volume up to the working depth of 450 mm. The effect was maximal at 200 to 300 mm depth, and minimal at 100 mm. There was no evidence of differences in the effectiveness of subsoiling due to variations in soil moisture.

Crop sequences affected soil physical properties mainly by the differences in water consumption patterns among crops, although there were apparent effects on soil structure other than those related to water use by the crops. Even by the third growing season, some combinations of Paraplow treatment and crop sequences had better water infiltration capacity than others. Paraplowing prior to the third crop resulted in the highest infiltration. Treatments involving Paraplow earlier in the rotation (A and B) had good infiltration capacity only when corn was the first crop. It can be speculated that the benefits of paraplowing were more lasting when they were combined with growing a crop with a fibrous root system.

4. GRAIN CROP RESPONSE TO PARAPLOW AND CROP SEQUENCE IN DIRECT-SEEDING SYSTEMS

ABSTRACT

Crops grown with no-tillage in Uruguay may be affected by high soil compaction caused by livestock and machinery traffic in wet conditions. The Paraplow, a subsoiler that does not invert the soil, was tested at La Estanzuela Experimental Station during 1991-1994. Excess compaction negatively affected crop performance in direct-seeding systems under Uruguayan conditions. Paraplow treatments increased crop productivity in 11 out of 14 experiments, by an average of 102, 36, 29 and 14 % in corn, sunflower, barley and wheat, respectively. This effect was associated with: a) higher plant populations in corn (56 % increase), barley (22 %) and wheat (14 %), mainly due to avoidance of waterlogging and increased soil temperature; b) higher root proliferation in all crops; c) better weed control in two experiments with corn; and d) higher number of grains per unit area in wheat and barley, due to higher tiller survival and reduced floret abortion. A single Paraplow pass caused a 25 to 53 % increase in the overall grain production of two-year crop rotations. Subsoiling before each crop gave only a marginal yield advantage over single Paraplow treatments. Wheat and barley seeded after corn yielded 4 % more than after sunflower, independently of Paraplow treatment. This effect was due to increased kernel weight, and was partly attributed to differences in soil structure aparent up to 18 months after corn and sunflower harvest. Wheat was superior to barley in the ability to withstand adverse soil condition. This was associated to preferential allocation of biomass to the shoot in the vegetative phase, and to higher nodal root formation in more advanced crop stages.

4.1. INTRODUCTION

Grain crops in Uruguay are grown in rotation with grazed pastures. Conventional tillage practised after the pastures is effective in relieving soil compaction and surface unevenness caused by grazing animals. During the transition from conventional to direct-seeding systems, crop performance may be affected by a combination of poor soil structure, water excess in the winter growing season, and soils with high clay content which limit water infiltration and root growth in dry conditions.

In the long term, if soils are left unplowed, the action of biological agents is expected to develop an improved soil structure (Dexter 1991). This process may take a very long time, particularly if the initial soil condition is deficient. Subsoiling with Paraplow (Braim *et al.* 1984), which improves the soil structure while producing little disturbance of the soil surface (section 3), would be suitable for avoiding productivity cutbacks during that transition phase.

Paraplowing increases the soil porosity (Ehlers and Baeumer 1988), especially the volume of macropores (Pikul *et al.* 1991), while preserving the connectivity of the pore system (Hipps and Hodgson 1988a). As a consequence of this, water infiltration capacity is greatly improved (Mukhtar *et al.* 1985, Pikul *et al.* 1990), and unlike other subsoilers which disrupt soil aggregates, paraplowing benefits typically persist for at least two years (Clark *et al.* 1993). Due to increased soil surface roughness and some mixing of residues with soil (Erbach *et al.* 1984), evaporation from the soil surface is higher in paraplowed than in undisturbed soil (Ehlers and Baeumer 1988). Because of the simultaneous effects on water infiltration and evaporation, the incidence of waterlogging in humid regions is greatly reduced by paraplowing (Hipps and Hodgson 1988a).

Even though crop productivity has usually been increased by paraplowing, the magnitude of the response has not been in accordance with the effects on soil structure. Reported yield increases due to Paraplow range from nil (Radford *et al.* 1992, McConkey *et al.* 1997) to 14 % in corn (Erbach *et al.* 1992), 18 % in forage oat (Sojka *et al.* 1997) and 19 % in spring barley (Braim *et al.* 1984). There is even one report of a 6 % yield decrease of winter wheat when Paraplow was used in a soil that had been under no tillage for more than 3 years (Hodgson *et al.* 1989).

Benefits of Paraplow on crops include improved plant emergence in waterlogged conditions (Hipps and Hodgson 1988b) and cold soil (Erbach *et al.* 1992); increased speed of root development (Braim *et al.* 1984) and root density (Hipps and Hodgson 1988a); and higher tiller survival and reduced floret abortion (Braim *et al.* 1984).

The objectives of this paper were to evaluate the effects of Paraplow and crop sequence on development and productivity of directly seeded crops, with emphasis on wheat and barley, and to assess the persistence of those effects.

4.2. MATERIALS AND METHODS

Four experiments (named as *RTN*, *C13*, *C14* and *C15*) were conducted during the period 1991-94 on a silty-clay loam (fine, mixed, superactive, thermic Oxyaquic Argiudoll, or 'Brunosol éutrico típico' in the Uruguayan classification) in SW Uruguay (INIA La Estanzuela Experimental Station, 34°20' S, 57°41' W), to study effects of soil compaction on crop productivity under zero tillage. The experiments were physically near one another on the same soil type (Table A1).

The experiments were described in Chapter 3. Crop sequences for all experiments are shown in Table 3.2.

4.2.1. Field Operations

The *RTN* site was in fallow for one year prior to starting the experiment. Spring-paraplowing was performed on 7 Oct. 1991 (details given in Chapter 3). Pre-emergence herbicides were applied on 15 Oct. 1992: atrazine (3 kg ha^{-1}) on corn (*Zea mays* L.) plots, and prometryn (0.4 kg ha^{-1}) on sunflower (*Helianthus annus* L.) plots. Both were applied in tank mix with glyphosate (0.7 kg ha^{-1}). Seeding was performed one day later by using a Semeato PS-8 triple-disc seeder across Paraplow passes. Corn cv. "*Estanzuela Bagual*" and sunflower cv. "*Estanzuela Yatay*" were seeded at 7 and 4 seeds m^{-2}, respectively. Rows were 0.6 m apart. Mono-ammonium phosphate was banded with the seed at 180 kg ha^{-1}. 2,4-D amine (0.7 kg ha^{-1}) and urea (150 kg ha^{-1}) were applied on corn plots on 21 Nov. 1991. Due to serious damage caused by pigeons, sunflower had to be reseeded on 20 Nov. 1991, after spraying again with glyphosate (0.7 kg ha^{-1}). Haloxyfop-methyl (0.2 kg ha^{-1}) was used as post emergence herbicide on sunflower plots. Urea (150 kg ha^{-1}) was simultaneously broadcast on corn only. Corn and sunflower were harvested on 21 Mar. 1992. Only the central three rows of each plot were collected. Residues were chopped and spread on the soil surface. On 28 Apr. 1992, glyphosate (1.1 kg ha^{-1}) was applied on the whole experiment.

Fall Paraplow treatments were applied on 22 May 1992. Glyphosate (0.7 kg ha^{-1}) was sprayed again on 8 July 1992, just before seeding wheat (*Triticum aestivum* L.) cv. "*Estanzuela Benteveo*" and barley (*Hordeum vulgare* L.) cv. "*Estanzuela Quebracho*". Both crops were seeded at a rate of 300 viable seeds m^{-2} in rows spaced 0.16 m. Mono-ammonium phosphate (150 kg ha^{-1}) was banded with the seeds. On 28 Aug. 1992, urea (150 kg ha^{-1}) and chlorsulfuron (0.02 kg ha^{-1}) were applied to the crops. Harvest was on 13 Dec. 1992. Residues were chopped and spread on the surface, and the soil was left fallow. Glyphosate (1.4 kg ha^{-1}) was sprayed on 10 Mar. 1993, and surface residues were burned on 21 Apr. 1993 to avoid interference with the seeding operation. Paraplowing was done on 7 June, and after an application of glyphosate (0.7 kg ha^{-1}) crops were seeded on 11 July in the same way as in the previous year. On 17 Aug. urea (200 kg ha^{-1}) was broadcast and chlorsulfuron (0.02 kg ha^{-1}) was sprayed on all plots. Crops were harvested on Dec. 1993.

Experiment *C14* was established on a site that had been in grass/legume pasture for three years. Field operations were the same as in the previously described *RTN* experiment, but performed one year later.

In experiment *C13*, 2,4-D amine (0.7 kg ha^{-1}) was sprayed on 8 Sep. 1992 to kill the red clover (*Trifolium pratense* L.) pasture. Glyphosate (1.4 kg ha^{-1}) and atrazine (4 kg ha^{-1}) were sprayed separately one month later. Paraplowing was performed on 22 Oct. 1992, and corn cv. "*Estanzuela Bagual*" was seeded one day later. Mono-ammonium phosphate (200 kg ha^{-1}) was banded with the seed. Urea (180 kg ha^{-1}) and 2,4-D amine (0.7 kg ha^{-1}) were applied by mid-November. The crop was harvested on 24 Mar. 1993. Glyphosate (1.1 kg ha^{-1}) was applied right after harvest and on 23 June 1993 in tank mix with 2,4-D amine (0.5 kg ha^{-1}). Wheat cv. "*Estanzuela Cardenal*" was direct-seeded on 30 June 1993 with 200 kg ha^{-1} of mono-ammonium phosphate banded with the seed. Urea (150 kg ha^{-1}) and chlorsulfuron (0.02 kg ha^{-1}) were applied by mid tillering. The crop was harvested on 6 Dec. 1993. After spraying glyphosate (0.7 kg ha^{-1}). Sunflower cv "*Estanzuela Yatay*" was seeded. The crop failed to emerge due to dry conditions, and was reseeded on 10 Jan. 1994. Sunflower plants did not reach maturity and were chopped on 25 May 1994. Canola (*Brassica napus* L.) cv. "*Topas*" was seeded on 1 June 1994 after spraying with glyphosate (0.7 kg ha^{-1}). Urea (150 kg ha^{-1}) and picloram (0.04 kg ha^{-1}) were applied on 19 Sep. 1994. The crop was straight combined on 5 Dec. 1994.

In experiment *C15* only one crop was grown on a site that had been on grass/legume pasture for three years. The Paraplow treatments were applied on 7 Oct. 1993. Three days later, glyphosate (1.4 kg ha^{-1}) and atrazine (4 kg ha^{-1}) were sprayed, and corn cv. "*Estanzuela Bagual*" was seeded on 13 Nov. 1993. Because of waterlogging after seeding, the crop failed and had to be reseeded 12 days later after spraying with glyphosate (0.5 kg ha^{-1}) again. The corn was harvested on 13 May 1994.

4.2.2. Plant Population Density Measurements

In all four experiments, plant population densities were measured immediately after full emergence. In wheat and barley crops, eight (experiments *RTN* and *C14*) or twenty (experiment *C13*) 0.15-m^2 areas per plot were sampled. In sunflower and corn (*RTN* and *C14*) plant stands were measured in one 6-m^2 area per plot. Corn and sunflower plant densities in experiments *C13* and *C15* were determined in ten 3-m^2 areas per plot. Canola plants were counted in eight 1-m^2 areas per plot.

In experiment *C14* (1994), soil oxygen diffusion rate at 5-cm depth was monitored during plant emergence (13, 16 and 19 July) on some of the spots where plant stands were measured, in plots corresponding to the crop sequence sunflower-barley-wheat (Table 3.9). A linear regression analysis of final plant stand density on ODR (mean of three dates) was performed.

4.2.3. Plant Root Measurements

In experiments *RTN* and *C14*, wheat and barley root samples were taken from selected treatments in three replicates per experiment. Corn and sunflower roots were not measured. Treatments sampled were: O (all subplots), B (all subplots in the first year, and plots including sunflower in the crop rotation in the second year), A (only sequences including sunflower) and ABC (sequences including sunflower in the first year, and all subplots in the second). Sampling dates were: 15 Sep. (tillering), 30 Sep. (end of tillering), 14 Oct. (anthesis), 4 Nov. (grain filling), and 1 Dec. (grain filling) 1992, and 4 Nov. 1993 (grain filling) (*RTN*); and 1 Dec. 1993 (grain filling) and 28 Oct. 1994 (anthesis) (*C14*). In experiment *C13* wheat roots were measured on 7 Dec. 1993 (grain filling) in all plots.

The sampling procedure for wheat and barley root assessments was as follows: blocks of soil 35-cm deep, 40-cm long and 20-to-25-cm wide, containing a segment of crop row in the centre, were dug out with spades, and deposited onto trays with a mesh bottom. Trays were soaked in water overnight and then, soil was washed out with pressurized water. The number of samples per plot was one (experiment *RTN* in 1992), two (*RTN* in 1993 and *C14*), and ten (*C13*).

Plants were preserved intact (above and below ground portions). Eight plants (or less if there were not enough) per sample were randomly selected to perform the following measurements: number of tillers and spikes, number of visible nodes in the main tiller, plant height (above-ground), number of spikelets per spike, number of seminal-root primary axes, number of adventitious-root primary axes, and maximum rooting depth (length of the longest root). All were measured on a per-plant basis.

In the samples taken on 14 and 30 Sep. 1992, all the roots from four plants were stained with methyl violet, stored in plastic bags, and frozen. Seminal and adventitious roots were kept separate. Adventitious and seminal root length and width were then determined by using an image scanner device (Delta T Mark I meter).

Corn roots were measured in experiment *C15* on 28 Jan. 1994 by the core-break method (Böhm 1979). Five 41-mm diameter soil cores were taken per plot from the mid-point between two plants within the rows. Cores were 1.15 m long. The cores were broken at 50–mm intervals, and the roots visible on the exposed faces were counted. Roots that were visibly dead were not considered.

4.2.4 Determinations of Grain Yield and Yield Components

In 1992 and 1994, at wheat and barley maturity, the number of spikes per unit area was determined in four 0.15-m^2 areas in every sub-plot. The number of spikelets per spike was determined on 20 randomly selected spikes within those areas. Total aboveground biomass was determined by cutting two 1-m^2 areas per plot. Plots were then harvested with a plot combine (1.4-m by 10-m areas) and grain yield determined after discounting the areas used for aerial biomass sampling.

In 1993, wheat and barley crops were heterogeneous due to poor fertilizer distribution. In this case, crops were harvested by hand in two or three 1-m^2 areas per plot selected by their homogeneity. Grain yield and yield components were determined from these samples. The total number of spikes in each sample was recorded. The number of spikelets per spike was determined in 20 randomly selected spikes. All spikes were then processed using a stationary thresher.

In all cases, four samples containing approximately 200 seeds were taken from each plot, and seeds were counted and weighed to determine thousand-kernel weight.

Sunflower and corn were harvested by hand and processed using a stationary thresher. In experiments *RTN* and *C14* the three central rows of each plot were harvested. In experiments *C13* and *C15* yields were determined in ten 3-m^2 area per plot. Samples were air-dried before threshing. Grain yields were expressed on 11 % moisture basis. In experiment *C13*, sunflower grain yield was not determined. Instead, the head diameter of each plant in sub-plots was recorded. The total head area per ha was used as an estimator of grain yield.

Canola in experiment *C13* was also manually harvested. Ten 1-m^2 samples per plot were cut at 10 cm height and placed into cloth bags to avoid grain loss by pod shattering. Care was taken to avoid loss of pods during sampling due to tangling with plants from outside the sampling areas. Samples were air-dried and threshed manually. Grain was processed by a seed-cleaning machine, and grain yields were expressed on a 10 % moisture basis.

4.2.5. Bird Damage

The barley crop in experiment *RTN* in 1992 was affected by birds, which caused loss of grain. The damage was higher on some plots than on others, since birds were selective, eating near the edges and those plots in more advanced phenological stages. The percent of grains lost was assessed visually on every plot by four different people, and an average per plot was recorded. There was very little variability among the four observers. The percent loss did not have a normal distribution. It was converted to a normal variable by calculating its square root. The latter variable was used as a linear covariable in the analysis of variance of grain yield, which was the only variable affected by bird damage. This analysis was done by using the LSMEAN procedure in SAS program (SAS Institute 1985).

4.3. RESULTS AND DISCUSSION

Analyses of variance of the crop parameters evaluated in all experiments are presented in Appendix C (Tables C1 to C16).

4.3.1. Plant Population Density

Paraplowing improved crop emergence to a variable extent, depending on the crop and year (Tables 4.1 to 4.4). The overall increase in corn, barley and wheat plant stands was 56, 22 and 14 %, respectively, whereas no effect was detected in sunflower. This effect was significant in three out of four experiments in corn and barley, and two out of four in wheat.

The response of plant emergence to paraplowing was correlated with improved soil aeration. It was already shown that one of the consequences of paraplowing on soil physical properties was an increase in oxygen diffusion rate (ODR) both in *RTN* 1992 (Table 3.8) and *C14* 1994 (Table 3.9). In these two experiments, emerging plants were exposed to excess water as can be derived from the amount of rainfall (51 and 40 mm, respectively) during the seeding-emergence periods (Tables 4.3 and 4.4). It was in these two experiments where both wheat and barley plant population densities were most responsive to paraplowing. Plant emergence of wheat was correlated with oxygen diffusion rate in *C14* 1994 (Fig. 4.1). Regression analysis showed that plant density increased linearly with increasing ODR, at least up to 0.12 $\mu g\ O_2\ cm^{-2}\ min^{-1}$.

The lack of effect of paraplowing on wheat plant density in 1993, and also the higher plant stands achieved in this year compared to 1992 and 1994, were associated with low rainfall (8 mm) during crop establishment (Table 4.3). In this case, oxygen supply to seeds

Table 4.1. Effect of Paraplow on corn plant population density at crop emergence, and rainfall during the seeding-emergence period in four experiments.

	Plant population density (plants/m²)				
Treatment	***RTN***	***C14***	***C13***	***C15***	**Mean**
Paraplow	6.6 *a* †	5.5 *a*	6.5 *a*	3.6 *a*	5.6
Control	4.5 *b*	4.2 *b*	3.0 *b*	2.8 *a*	3.6
Rainfall (mm)	84	30	30	162	

† Means followed by the same letter within columns were not different ($p<0.05$)

Table 4.2. Effect of Paraplow on sunflower plant population density at crop emergence, and rainfall during the seeding-emergence period in two experiments.

	Plant population density (plants/m²)		
Treatment	***RTN***	***C14***	**Mean**
Paraplow	2.5 *a* †	4.7 *a*	3.6
Control	2.3 *a*	4.6 *a*	3.5
Rainfall (mm)	34	30	

† Means followed by the same letter within columns were not different ($p<0.05$)

Table 4.3. Effect of Paraplow (ABC= prior to every crop; B=prior to second crop; A=prior to first crop) and previous crop on wheat plant population density, and rainfall during the seeding-emergence period, in three experiments.

		Plant Population Density (plants/m^2)				
Paraplow Treatment	**Previous Crop**	***RTN* 1992**	***C14* 1993**	***C13* 1993**	***RTN* 1993**	***C14* 1994**
ABC	Corn	166	299	—	281	214
ABC	Sunflower	173	265	—	307	205
B	Corn	160	247	—	283	249
B	Sunflower	172	256	—	256	246
A	Corn	100	258	314	286	214
A	Sunflower	123	255	—	269	197
O (control)	Corn	117	234	292	280	191
O (control)	Sunflower	130	248	—	321	200
ABC	—	170 *a* †	282 *a*	—	294 *a*	248 *a*
B	—	166 *b*	252 *a*	—	270 *a*	206 *ab*
A	—	112 *b*	256 *a*	314 *a*	278 *a*	210 *ab*
O (control)	—	124 *b*	241 *a*	292 *a*	301 *a*	196 *b*
—	Corn	136 *a*	260 *a*	303	283 *a*	217 *a*
—	Sunflower	150 *a*	256 *a*	—	288 *a*	212 *a*
Rainfall(mm)		51	8	15	8	40

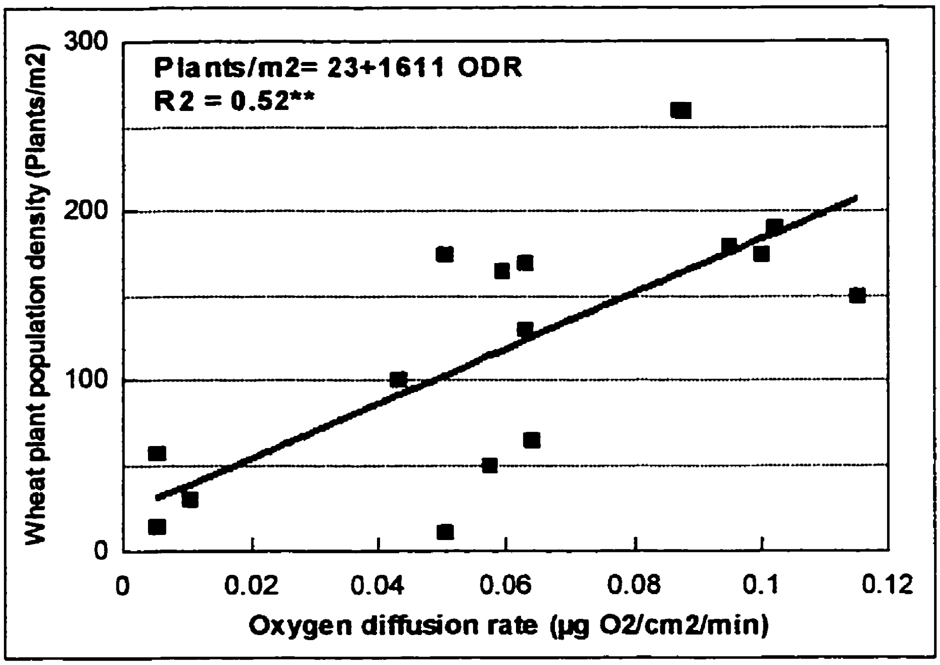
† Means followed by the same letter within columns were not different ($p<0.05$)

Table 4.4. Effect of Paraplow (ABC= prior to every crop; B=prior to second crop; A=prior to first crop) and previous crop on barley plant population density, and rainfall during the seeding-emergence period, in two experiments.

		Plant Population Density (plants/m²)			
Paraplow Treatment	**Previous Crop**	***RTN* 1992**	***C14* 1993**	***RTN* 1933**	***C14* 1994**
ABC	Corn	247	327	239	259
ABC	Sunflower	249	280	234	271
B	Corn	222	258	236	217
B	Sunflower	248	243	238	237
A	Corn	213	199	262	238
A	Sunflower	231	217	239	230
O (control)	Corn	157	206	240	230
O (control)	Sunflower	229	186	248	197
ABC	—	248 *a* †	304 *a*	237 *a*	265 *a*
B	—	235 *a*	251 *ab*	237 *a*	227 *ab*
A	—	222 *ab*	208 *b*	251 *a*	234 *ab*
O (control)	—	193 *b*	196 *b*	244 *a*	214 *b*
—	Corn	210 *b*	248 *a*	244 *a*	236 *a*
—	Sunflower	239 *a*	232 *a*	240 *a*	234 *a*
Rainfall (mm)		51	8	15	40

† Means followed by the same letter within columns were not different ($p<0.05$)

Figure 4.1. Relationship between oxygen diffusion rate measured at 50-mm depth and final wheat plant population in experiment *C14*, 1994.



would have been adequate. In spite of this, barley responded to Paraplow treatment in *C14* 1993 (Table 4.4), suggesting that some other factor besides ODR would have been involved.

Increased soil temperature (Table 3.9) may have been one factor explaining the response of plant emergence to paraplowing. Soil temperature may have decreased the time from seeding to emergence thus minimizing exposure to disease and insects.

Barley establishment was more influenced by paraplowing than wheat. Considering only the situations where subsoiling was performed just prior to seeding the crop, plant densities of barley (256 plants m^{-2}) and wheat (245 plants m^{-2}) were 14 and 22 % higher than the control, respectively (Tables 4.3 and 4.4). The higher response of barley to paraplowing may be attributed to increased soil temperature (Table 3.9), since it has been shown that the base temperature for seedling growth is higher for barley than wheat (López-Castañeda *et al.* 1996). Due to its higher seed size as compared to wheat, barley germination may have required more water, which was a limiting factor in 1993, and oxygen, the limiting factor in 1992 and 1994.

The seed to soil contact may have been an additional factor related to plant emergence and regulated by paraplowing. Subsoiling caused some degree of soil surface disturbance, and consequently reduced the amount of residue on the soil surface. This was not measured in the present study, but Erbach *et al.* (1992) had shown that paraplowing reduced the proportion of soil covered by residues from 82 to 67 %, as compared to no-till. The lower amount of residue cover would have diminished the incidence of "hair-pinning" (straw in the seeding slot), which has been demonstrated to cause crop establishment failures, particularly where disc coulters, such as those used in the present work, have been utilized (Baker *et al.* 1996).

An increase in oxygen supply may have also been the reason why paraplowing improved corn emergence in experiment *RTN*, considering the large amount of rainfall (84 mm) fallen during crop establishment (Table 4.1). The excess moisture in experiment *C15* (162 mm in the four days following seeding) would have equally affected both Paraplow and control treatments. There are apparently no reasons for the response of corn to paraplowing observed in experiments *C13* and *C14*. Since the amount of rainfall after seeding these experiments was not very large (30 mm), ODR was not likely involved in these cases.

Sunflower crop establishment was not affected by paraplowing. This crop was not subjected to water excess in any of the experiments (Table 4.2). The factors that enhanced corn emergence in experiment *C14* would not have applied to sunflower crops.

The improvement in corn emergence from paraplowing may also have been due to higher soil temperatures. Soil temperature after seeding corn and sunflower in *C14* was up to 5 °C higher in subsoiled plots than control plots, which had midday soil temperatures around 16 °C (data not shown). Optimum temperature for germination of corn has been found to be around 30 °C, with a minimum of 9 °C, below which the process does not occur (Blacklow 1972, Warrington and Kanemasu 1983). Sunflower has an optimal temperature for germination of around 25 °C (Gay *et al.* 1991) and a base temperature as low as 1 °C (Mwale *et al.* 1994). Therefore, it follows that corn was more responsive to enhanced soil temperature than sunflower.

In experiment *RTN* 1992, barley had significantly more plants after sunflower than after corn, particularly where Paraplow was not used (Table 4.4). Wheat had the same trends, although the effects of previous crop on plant stands were not significant. Averaged over all experiments, wheat plant stands after corn were 9 % lower than after sunflower where Paraplow was not passed, whereas no difference was observed in the other Paraplow treatments (Table 4.3). Despite these differences between treatments with and without Paraplow in the effect of previous crop, the interaction between Paraplow treatment and previous crop was not large enough as to be statistically significant in any of the experiments. The results in experiment *RTN* 1992 were observedalthough ODR was higher after corn than after sunflower (Table 3.8), and therefore, some factor other than oxygen was involved. Corn produced more residue than sunflower and this could have caused more interference with operation of seeding machine and reduced soil temperature.

4.3.2. Root Development

4.3.2.1. *Rooting Depth*

Rooting depth at the end of tillering in *RTN* 1992 was less than 20 cm for both wheat and barley and was not affected by previous crop. Paraplowing significantly increased rooting depth. Maximum rooting depth of wheat at this time was 19.3, 18.8, 17.5 and 16.8 cm for treatments ABC, B, A and the control, respectively. Barley roots were shallower than those of wheat, and maximum rooting depths were 17.0, 16.3, 15.5 and 14.8 cm, respectively.

Below 20 cm depth soil moisture content was around 30 and 27 % by weight in mid-August and mid-September, respectively (Table 3.6). These moisture contents were well above the 20 % level, below which restrictive mechanical impedance would have developed in both Paraplow and control treatments in this soil (Table 5.6). Therefore, soil PR would not have been an impediment for deeper growth of wheat and barley roots.

During tillering, air-filled porosity below 150 mm depth was always above 15 % by volume (assuming that bulk density in 1992 was similar to values reported in Table 3.4 for 1993), which was higher than the commonly accepted threshold level for root growth of 10 % (Cannell and Jackson 1981). Considering this, lack of oxygen would not have impeded root growth either. However, oxygen diffusion rate, which is the fundamental property defining the aeration status of roots (Grant 1993), may have been limited by the permanently high water content in the upper 150 mm of soil (Table 3.6); by the presence of roots consuming oxygen in this upper horizon (Asady and Smucker 1989); and by the low air permeability expected for a soil layer with more than 50 % clay (Table A1, Appendix). At the end of tillering in experiment *RTN* 1992, both wheat and barley had a 2-cm increase in the maximum rooting depth due to paraplowing, and this may have been related with higher ODR.

After tillering, rooting depth in experiment *RTN* 1992 increased very rapidly, as evidenced by the sharp decrease in soil moisture content (Table 3.6, 14 Oct.) and the concomitant increase in soil PR (Fig 3.5.d). According to these data, treatments with fall-Paraplow would have induced more root growth at depth than the control.

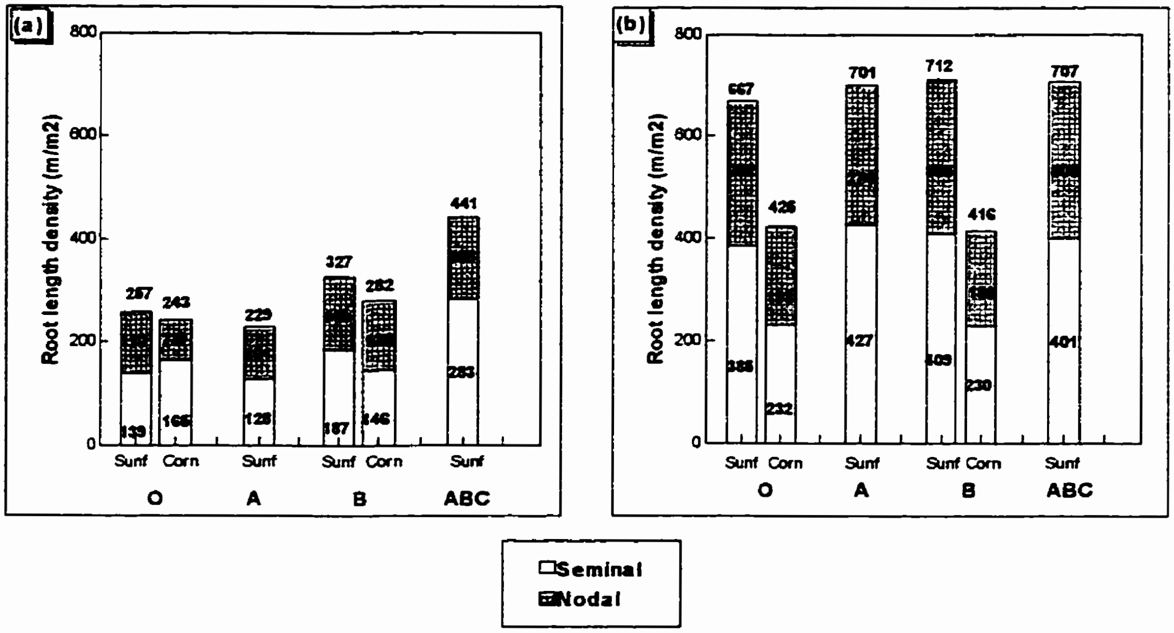
4.3.2.2. *Root Density*

Paraplow treatment also significantly affected wheat root length density of both the seminal and nodal root components at the end of the vegetative phase in *RTN* 1992 (Table C7 Appendix, Fig. 4.2a). The seminal root component accounted for 59 % of total root length density. Seminal root length density for treatment O was approximately one half that for treatment ABC, and did not differ from treatment A. The effects of Paraplow on nodal root length density were similar, although the differences due to treatments were less dramatic than for seminal roots. Total root length density tended to be lower after corn than after sunflower, although the difference was not significant.

A major effect of Paraplow on root growth would have been through reduction of soil penetration resistance. Soil mechanical impedance is known to inhibit root elongation (Atwell 1993), and penetration resistance (PR) values above 2 MPa are thought to prevent the growth of roots that occurs by soil matrix deformation (Taylor *et al.* 1966, Martino and Shaykewich 1994). In experiment *RTN* 1992, the moisture content at which PR equals 2 MPa in the upper 150-mm of this soil was 17 and 21 % by weight for Paraplow and control treatments, respectively (Table 5.6). This implies that upon drying, undisturbed soil developed restricting mechanical resistance more rapidly than paraplowed soil. Soil PR profiles for experiment *RTN* (Fig. 3.5) show that the control treatment had reached PR values of 2 MPa within the top 100 mm of soil very early in the season, whereas treatments with fall-Paraplow maintained PR levels well below this limit throughout the vegetative phase. Therefore, the doubling of root length density of wheat at the end of tillering by paraplowing in this experiment (Fig. 4.2) was attributed to reduced mechanical resistance.

In contrast to wheat, barley root length density at the end of tillering in *RTN* 1992 was not affected by Paraplow treatment (Fig 4.2b). This observation may be attributed to the dissimilar strategies followed by these two crop species in response to mechanical impedance or oxygen deficiency stresses. Masle (1992) found that a number of barley cultivars were able to overcome a depression in initial root growth caused by high-compaction conditions, and actually produced more root biomass by the 5-leaf stage than plants grown in loose soil, whereas most wheat cultivars experiencing high-strength soil favoured shoot growth at the expense of roots. This author did not report data on the effects of penetration resistance on

Figure 4.2. Root length density as affected by paraplowing (ABC= prior to every crop; B=prior to second crop; A=prior to first crop; O=control) and cropping sequence in experiment *RTN* (average of 14 and 30 September 1992). a) Wheat; b) Barley.



root length. Bourget *et al.* (1966) had found that when subjected to transient flooding conditions five days after emergence, the shoot-to-root biomass ratio was decreased by 14 and 43 % for spring wheat and barley, respectively.

Near anthesis, soil moisture content in the 150-300 mm soil layer was 18 and 16 % for wheat and barley, respectively, and this difference was significant at $p<0.10$ (Table 3.6). This indicates that root development in advanced crop stages would have continued to be less affected by high soil strength in barley than wheat.

Barley, unlike wheat, had its root length density strongly affected by previous crop in *RTN* 1992 (Fig. 4.2). When seeded after corn, barley roots had a length 39 % lower than after sunflower ($p<0.05$, Table C12 Appendix). Since barley plant population in this experiment was only 21 % lower after corn than sunflower (Table 4.4), this is an indication that root growth was even more affected by corn residues than was crop emergence. Soil borne pathogens could have caused this effect, but there is no experimental evidence to support it. Later in the growing season, barley plants seeded after corn compensated for the initial low root density by producing more nodal roots per plant than those seeded after sunflower (Table 4.6). This also occurred in the other experiments, even where barley plant stands were not affected by previous crops, suggesting than in these cases, the detrimental action of corn on initial root development would have also occurred.

Corn root density at the end of the vegetative phase in experiment *C15* was higher in Paraplow treatment than in undisturbed soil. This effect was significant ($p<0.05$) between 45 and 65 cm depth (Fig. 4.3). The large response of corn roots to reduced soil strength has been reported for Paraplow (Reeder *et al.* 1993) and other subsoilers (Chaudhary *et al.* 1985). The

Table 4.5. Effect of Paraplow and previous crop on wheat nodal root production in three experiments †

		Nodal root axes/plant					Nodal root axes/tiller					Nodal root axes/m² (x10⁻³)				
Paraplow Treatment	Previous Crop	RTN 1992	C14 1993	C13 1993	RTN 1993	C14 1994	RTN 1992	C14 1993	C13 1993	RTN 1993	C13 1994	RTN 1992	C14 1993	C13 1993	RTN 1993	C14 1994
ABC§	Corn	----	----	----	28.3	----	----	----	----	14.1	----	----	----	----	8.0	----
ABC	Sunflower	16.7	24.7	----	26.0	22.0	5.7	21.3	----	20.2	11.5	3.5	8.4	----	7.6	6.5
B	Corn	20.4	26.9	----	----	----	5.1	20.6	----	----	----	3.5	8.5	----	----	----
B	Sunflower	18.6	25.7	----	32.4	26.6	5.3	24.5	----	14.1	10.2	3.5	8.8	----	8.3	5.8
A	Corn	----	----	21.7	----	----	----	----	12.6	----	----	----	----	6.7	----	----
A	Sunflower	20.6	22.3	----	26.3	28.0	4.6	19.3	----	15.9	10.7	3.4	7.6	----	7.0	6.2
O (control)	Corn	21.6	19.0	23.8	24.6	----	5.2	16.8	12.5	14.5	----	3.2	5.9	6.9	6.9	----
O (control)	Sunflower	22.6	18.7	----	24.7	24.2	5.7	23.6	----	22.0	12.2	2.9	6.1	----	7.3	5.8
ABC	Sunflower	16.7 *b*‡	24.7 *ab*	----	26.0 *ab*	22.0 *a*	5.7 *a*	21.3 *a*	----	20.2 *a*	11.5 *a*	3.5 *a*	8.4 *ab*	----	7.6 *a*	6.5 *a*
B	Sunflower	19.5 *ab*	25.7 *a*	----	32.4 *a*	26.6 *a*	5.2 *a*	24.5 *a*	----	14.1 *b*	10.2 *a*	3.5 *a*	8.8 *a*	----	8.3 *a*	5.8 *a*
A	Sunflower	20.6 *a*	22.3 *ab*	21.7 *a*	26.3 *ab*	28.0 *a*	4.6 *a*	19.3 *a*	12.6 *a*	15.9 *b*	10.7 *a*	3.4 *a*	7.6 *ab*	6.7 *a*	7.0 *a*	6.2 *a*
O (control)	Sunflower	22.1 *a*	18.7 *b*	23.8 *a*	24.7 *b*	24.2 *a*	5.4 *a*	23.6 *a*	12.5 *a*	22.0 *a*	12.2 *a*	3.1 *a*	6.1 *b*	6.9 *a*	7.3 *a*	5.8 *a*
----	Corn	21.0 *a*	22.9 *a*	----	26.5 *a*	----	5.1 *a*	18.7 *b*	----	14.3 *b*	----	3.4	7.2 *a*	----	7.4 *a*	----
----	Sunflower	20.6 *a*	22.2 *a*	----	25.3 *a*	----	5.5 *a*	24.1 *a*	----	21.1 *a*	----	3.2	7.5 *a*	----	7.5 *a*	----

† Only measurements taken during the reproductive phase of the crops were included in this table.

‡ Means followed by the same letter within columns were not different ($p<0.05$)

§ ABC=prior to every crop; B=prior to second crop; A=prior to first crop.

Table 4.6. Effect of Paraplow and previous crop on barley nodal root production in two experiments †.

		Nodal root axes/plant				Nodal root axes/tiller				Nodal root axes/m² (x10 ³)			
Paraplow	**Previous Crop**	**RTN 1992**	***C14* 1993**	**RTN 1993**	***C14* 1994**	**RTN 1992**	***C14* 1993**	**RTN 1993**	***C14* 1994**	**RTN 1992**	***C14* 1993**	**RTN 1993**	***C14* 1994**
ABC§	Corn	----	----	21.1	----	----	----	10.2	----	----	----	6.8	----
ABC	Sunflower	18.4	23.0	19.2	23.4	4.9	8.9	8.1	7.3	4.2	7.8	5.6	6.8
B	Corn	18.1	24.9	----	----	5.5	9.0	----	----	5.2	7.7	----	----
B	Sunflower	15.8	22.2	19.3	23.8	5.3	8.0	10.6	9.5	4.1	6.7	5.9	6.1
A	Corn	----	----	----	----	----	----	----	----	----	----	----	----
A	Sunflower	24.5	20.9	18.1	23.8	4.3	8.9	8.0	12.8	6.4	6.2	5.4	6.2
O (control)	Corn	22.5	20.1	20.5	----	4.6	11.9	9.4	----	3.5	5.4	6.1	----
O (control)	Sunflower	16.2	19.4	17.4	30.0	3.7	9.8	7.5	11.4	4.4	5.0	5.3	5.5
ABC	----	18.4 *b* ‡	23.0 *a*	19.2 *a*	23.4 *b*	4.9 *ab*	8.9 *ab*	8.1 *b*	7.3 *b*	4.2 *a*	7.8 *a*	5.6 *a*	6.8 *a*
B	----	17.0 *b*	22.2 *a*	19.3 *a*	23.8 *b*	5.4 *a*	8.0 *b*	10.6 *a*	9.5 *ab*	4.7 *a*	6.7 *ab*	5.9 *a*	6.1 *ab*
A	----	24.5 *a*	20.9 *a*	18.1 *a*	23.8 *b*	4.3 *ab*	8.9 *ab*	8.0 *b*	12.8 *a*	6.4 *a*	6.2 *ab*	5.4 *a*	6.2 *ab*
O (control)	----	19.3 *ab*	19.4 *a*	17.4 *a*	30.0 *a*	4.1 *b*	9.8 *a*	7.5 *b*	11.4 *a*	4.0 *a*	5.0 *b*	5.3 *a*	5.5 *b*
----	Corn	20.3 *a*	22.5 *a*	20.8 *a*	----	5.0 *a*	10.4 *a*	9.8 *a*	----	4.4 *a*	6.6 *a*	6.5 *a*	----
----	Sunflower	16.0 *b*	20.8 *a*	18.3 *b*	----	4.5 *a*	8.9 *b*	7.8 *b*	----	4.3 *a*	5.9 *a*	5.5 *a*	----

† Only measurements taken during the reproductive phase of the crops were included in this table.
‡ Means followed by the same letter within columns were not different ($p<0.05$)
§ ABC=prior to every crop; B=prior to second crop; A=prior to first crop.

extremely high value of root axes recorded for treatment without subsoiling at 5-cm depth may have been partly due to the presence of bermudagrass (*Cynodon dactylon* L. Pers.) in this treatment (see section 4.4.3). The roots of this weed may have been mistakenly measured as corn roots.

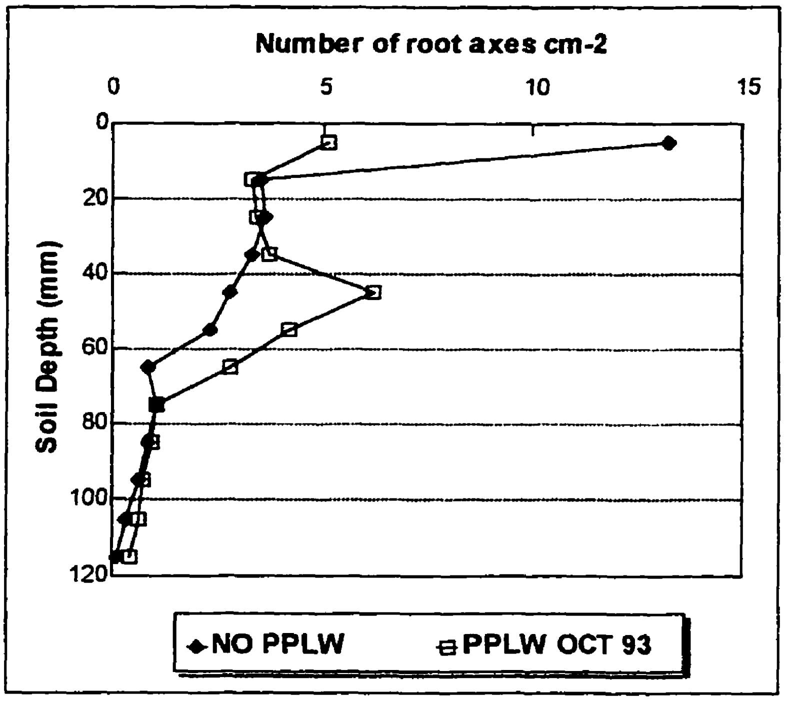
4.3.2.3. *Nodal Root Production in Wheat and Barley*

Given the fact that most of the rain events in SW Uruguay are of very low magnitude (Table A2, Appendix), the presence of nodal or adventitious roots is essential for capturing this water during advanced wheat and barley crop stages, when soil moisture contents normally become very low. The number of adventitious roots per unit area would be a measure of this capacity. Paraplowing affected the production of nodal roots of wheat (Table 4.5) and barley (Table 4.6).

Considering individual wheat plants, the effects of Paraplow treatment were not apparently consistent. Treatment O produced the most nodal root axes per plant in *RTN* 1992, the least in 1993 experiments, and did not differ from the others in *CH* 1994 (Table 4.5). Treatments involving Paraplow tended to produce more nodal root axes per unit area than the undisturbed control. On average, wheat produced 6.0, 6.2, 5.5 and 4.6 x 10^3 nodal roots m^{-2} in year 1, and 7.1, 7.1, 6.6 and 6.6 x 10^3 nodal roots m^{-2} in year 2 in treatments ABC, B, A and O, respectively.

The formation of adventitious roots per barley plant was highest for treatments without Paraplow (A and O) in 1992 and 1994, and not affected by Paraplow in 1993 (Table 4.6). Regarding nodal roots per unit area, barley had similar behaviour to wheat. On average, barley produced 6.0, 5.7, 6.3 and 4.5 x 10^3 nodal roots m^{-2} in year 1, and 6.2, 6.0, 5.8 and 5.4

Figure 4.3. Root density of corn at different depths at the end of the vegetative phase, as affected by paraplow (PPLW) in experiment *C15*, 28 Jan. 1994.



x 10^3 nodal roots m^{-2} in year 2 for treatments ABC, B, A, and O, respectively.

The evolution of nodal root axes during the growing season was monitored in *RTN* 1992. During the vegetative phase, the production of root axes per wheat plant was higher ($p<0.10$) with paraplowing than in the control (Fig. 4.4), whereas in barley it was unaffected by previous subsoiling (Fig. 4.5). The number of adventitious roots per plant increased with time until mid-October, near anthesis of the crops. This increase was larger for the control treatment than for Paraplow treatments, both in wheat (Fig. 4.4) and barley (Fig. 4.5). At anthesis, the number of nodal roots per plant was significantly higher ($p<0.05$) for the control than for treatment B in wheat (Table C7, Appendix) and barley (Table C12, Appendix).

The sharp increase in adventitious root initiation observed in treatment O at mid-October for both crops would have been in response to stress imposed by drying soil. Removal of part of the seminal roots induced an increase in the number of nodal root axes in barley (Crossett *et al.* 1975), and wheat (Wiedenroth and Erdmann 1985). The stress imposed by high mechanical impedance in the control treatment may have caused a similar response.

The further decay of nodal roots recorded in this experiment (4 Nov.) was likely caused by soil surface drying. Crossett *et al.* (1975) found that desiccation of the upper fraction of the root system of barley caused a marked decrease in nodal root numbers, which was compensated for by proliferation of deeper roots. The decline in nodal root axes was more abrupt in the control treatment O than in subsoiled plots, presumably because roots in the former were weaker and shorter.

The number of adventitious roots per tiller had the same trends with time as the number of roots per plant, but in the case of barley, was not affected by paraplowing in the

Figure 4.4. Nodal root primary axes production during the wheat growing season in experiment *RTN* (1992), as affected by Paraplow and previous crop. Asterisks indicate significant (**, p<0.05) or nearly significant (*,p<0.10).

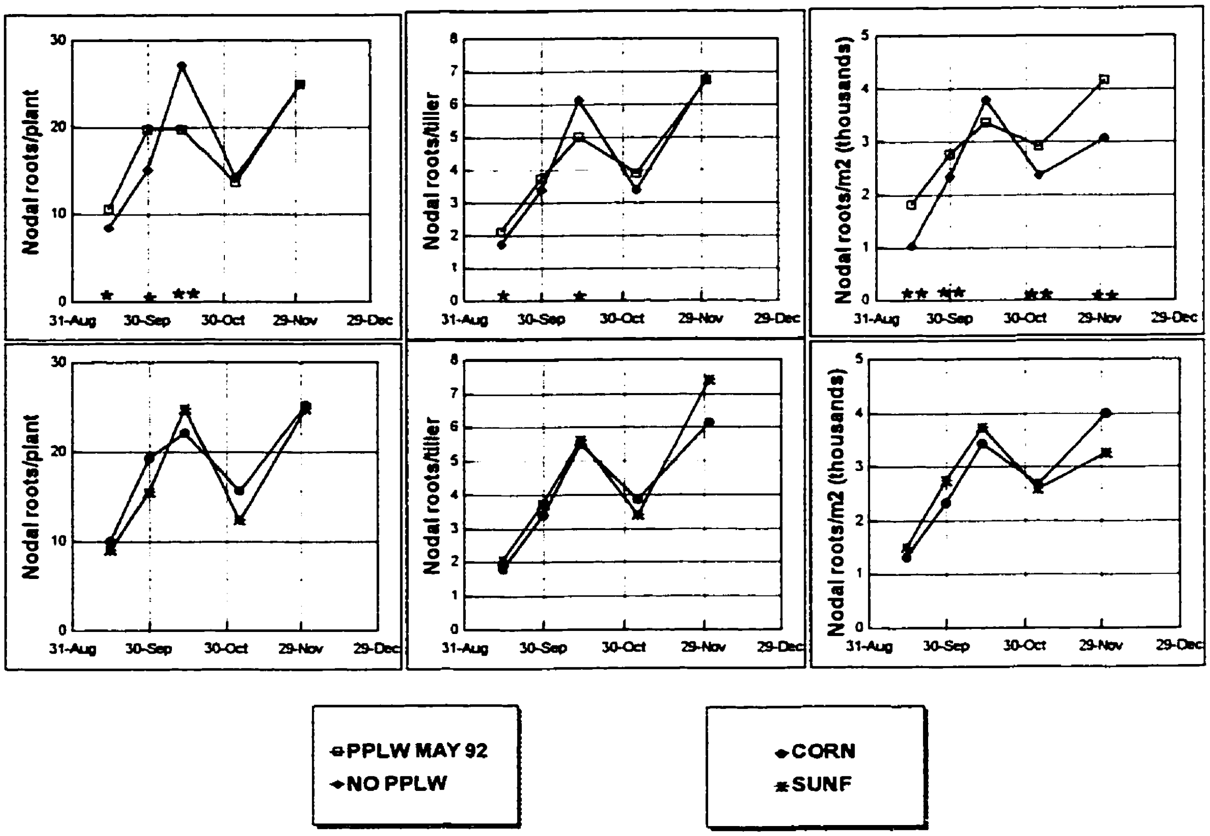
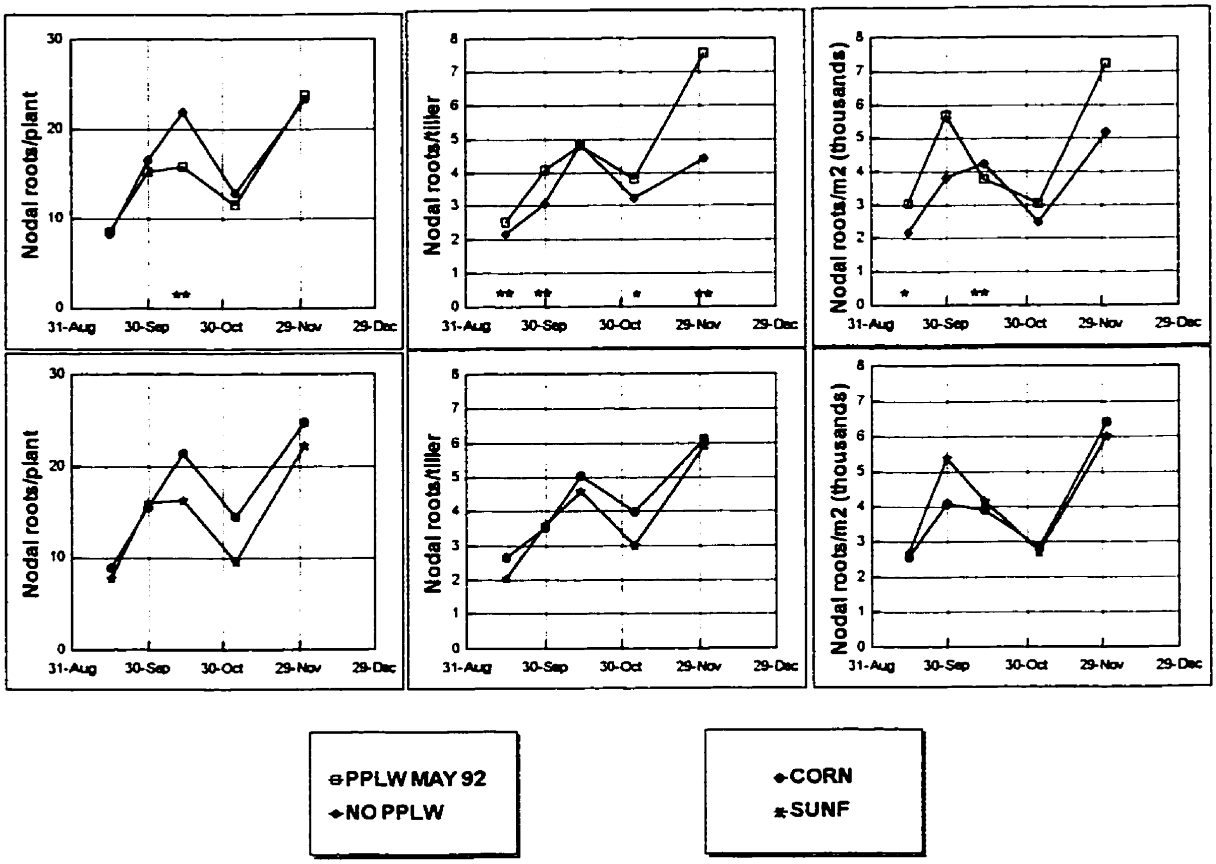


Figure 4.5. Nodal root primary axes production during the barley growing season in experiment *RTN* (1992), as affected by Paraplow and previous crop. Asterisks indicate significant differences (** at p<0.05, * at p<0.10).



same way. In barley, undisturbed soil produced less roots per tiller at all dates except 14 Oct., than Paraplow treatments (Fig. 4.5). The production of roots per unit area was higher for treatment B than the control both before anthesis and at crop maturity in wheat (Fig. 4.4) and only before anthesis in barley (Fig. 4.5).

The number of nodal roots per tiller was also markedly affected by the cropping season. Wheat plants had 5.3, 20.1 and 11.1 nodal root axes per tiller during the grain-filling period in 1992, 1993 and 1994, respectively. Barley had 4.7, 8.7 and 10.3, respectively. Apparently, high moisture conditions, such as in 1993, would have caused the plants to produce a large amount of nodal roots. Waterlogging promotes adventitious root formation in a number of species (Jackson 1985), including wheat (Wiedenroth and Erdmann 1985), as a mechanism for replacing roots suffering from oxygen deficiency. Crops in 1992, the driest season in this study (Fig. A1, Appendix), had the lowest nodal root axes per plant, as well as per unit area.

The formation of nodal roots was also affected by previous crop, particularly in barley. The number of axes per barley plant was 21.4 after corn and 18.4 after sunflower ($p<0.05$) in year 1, and 20.8 and 18.3 ($p<0.05$), respectively, in year 2 (Table 4.6). Corresponding values for the number of nodal root axes per tiller were 7.7 and 6.7 ($p<0.05$) in year 1, and 9.8 and 7.8 ($p<0.05$) in year 2. These results suggest the operation of some physiological mechanism that compensated for the observed lower barley root density after corn than sunflower (Fig. 4.2) by adventitious root production.

In wheat, the number of nodal roots per plant was not affected by previous crop, and the number per tiller was higher after sunflower than after corn in 1993 experiments only.

Both wheat and barley produced the same amount of nodal root primary axes per unit area regardless of preceding crop (Tables 4.5 and 4.6).

4.3.3. Grain Production

4.3.3.1. *Grain Yield*

Paraplowing was effective in improving grain yield in direct-seeding conditions. The effect of Paraplow treatment on grain yield was significant for all crops in all experiments and years with the only exception of wheat in *RTN* 1992 (Appendix C). Considering only the situations where paraplowing was performed immediately prior to seeding, the positive effect on yields was significant ($p<0.05$) in 11 out of 14 crops (Tables 4.7 to 4.10).

The major effect of paraplowing was to improve the soil physical environment (Chapter 3). Therefore, it can be concluded that the structure of the soil used in this study was restrictive for adequate crop development with no tillage. However, paraplowing might have also had other secondary effects which influenced final grain yields.

Corn was the crop with the highest yield response to the Paraplow (Fig. 4.6). Several factors would have contributed to this effect. Firstly, since this crop has a limited tillering capacity, initial plant stand is a strong determinant of the final number of spikes per unit area. Therefore, the observed 56 % increase in plant density due to subsoiling (Table 4.1) was likely responsible for an important part of the effect on yield. Secondly, the increased root proliferation recorded in plots with Paraplow (Fig. 4.3) would have allowed a more thorough and deeper exploration of the soil profile, thus making more water available for the crop. Finally, the improved water infiltration capacity of the soil due to paraplowing, already discussed in Chapter 3, would have also increased the amount of water available for the crop,

Table 4.7. Effect of Paraplow on grain yield of corn in four experiments.

	Grain yield (ton/ha)				
Treatment	***RTN***	***C14***	***C13***	***C15***	**Mean**
Paraplow	3.4 *a* †	6.3 *a*	7.5 *a*	1.6 *a*	4.7
Control	1.8 *b*	4.3 *b*	2.8 *b*	0.3 *b*	2.3

† Means followed by the same letter within columns were not different ($p<0.05$)

Table 4.8. Effect of Paraplow on grain yield of sunflower in two experiments.

	Grain yield (ton/ha)		
Treatment	***RTN***	***C14***	**Mean**
Paraplow	1.5 *a* †	2.3 *a*	1.9
Control	0.9 *b*	1.8 *b*	1.4

† Means followed by the same letter within columns were not different ($p<0.05$)

Table 4.9. Effect of Paraplow and previous crop on wheat yield and plant height at harvest in three experiments.

		Plant height at harvest (cm)					**Grain yield (Kg/ha)**				
Paraplow Treatment	**Previous Crop**	***RTN* 1992**	***C14* 1993**	***C13* 1993**	***RTN* 1993**	***C14* 1994**	***RTN* 1992**	***C14* 1993**	***C13* 1993**	***RTN* 1993**	***C14* 1994**
ABC‡	Corn	80	91	----	91	73	4672	2115	----	2778	5413
ABC	Sunflower	80	92	----	85	74	4554	2457	----	2738	4947
B	Corn	77	92	----	89	77	4740	2813	----	2716	5040
B	Sunflower	76	88	----	86	76	4525	2781	----	2669	4861
A	Corn	75	85	----	87	77	4387	3141	----	2660	4348
A	Sunflower	76	85	85	88	74	4142	3098	2867	2815	4029
O (control)	Corn	76	81	----	84	70	4525	2569	----	2354	3933
O	Sunflower	75	82	85	83	69	4296	2347	2480	2313	3857
ABC	----	80 *a*†	92 *a*	----	88 *a*	73 *ab*	4613 *a*	2286 *b*	----	2758 *a*	5180 *a*
B	----	77 *ab*	88 *ab*	----	88 *a*	77 *a*	4633 *a*	2797 *ab*	----	2692 *a*	4950 *a*
A	----	76 b	85 *ab*	85 *a*	88 *a*	75 *ab*	4264 *a*	3120 *a*	2867 *a*	2738 *a*	4189 *b*
O (control)	----	76 *b*	82 *b*	85 *a*	84 *b*	70 *b*	4411 *a*	2458 *ab*	2480 *b*	2333 *b*	3895 *b*
----	Corn	77 *a*	87 *a*	----	88 *a*	74 *a*	4581 *a*	2659 *a*	----	2627 *a*	4683 *a*
----	Sunflower	77 *a*	87 *a*	----	86 *a*	73 *a*	4379 *a*	2670 *a*	----	2634 *a*	4423 *a*

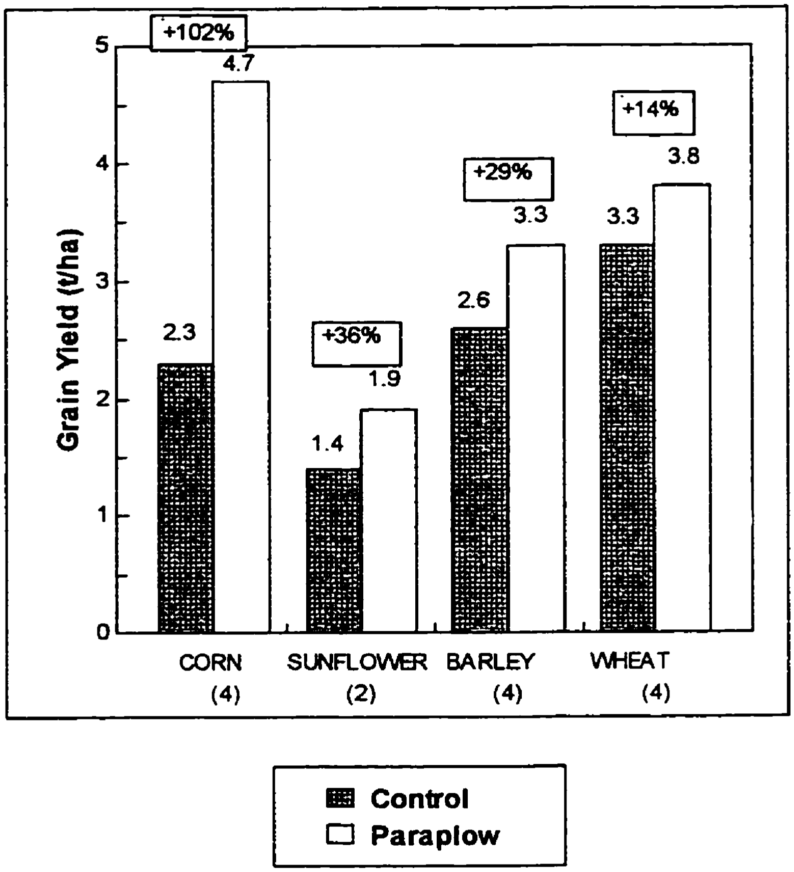
† Means followed by the same letter within columns were not different ($p<0.05$)
‡ ABC=prior to every crop; B=prior to second crop; A=prior to first crop

Table 4.10. Effect of Paraplow and previous crop on barley yield and plant height at harvest in two experiments.

		Plant height at harvest (cm)				Grain yield (Kg/ha)			
Paraplow Treatment	**Previous Crop**	***RTN* 1992**	***C14* 1993**	***RTN* 1993**	***C14* 1994**	***RTN* 1992 ‡**	***C14* 1993**	***RTN* 1993**	***C14* 1994**
ABC§	Corn	62	77	70	66	4292	4358	1443	3845
ABC	Sunflower	64	77	67	64	3731	3884	1335	4199
B	Corn	58	77	68	62	3987	3623	1408	4228
B	Sunflower	58	79	68	62	4127	3824	1395	4063
A	Corn	59	68	69	62	3391	3233	1695	3640
A	Sunflower	56	71	70	59	3552	2749	1732	3308
O (control)	Corn	58	62	70	54	3034	2601	1663	3379
O (control)	Sunflower	56	68	68	52	3630	1919	1594	2736
ABC	—	63 *a*†	77 *a*	69 *a*	65 *a*	4012 *a*	4121 *a*	1389 *b*	4022 *a*
B	—	58 *b*	78 *a*	68 *a*	62 *a*	4057 *a*	3724 *a*	1402 *b*	4145 *a*
A	—	57 *b*	70 *ab*	70 *a*	60 *ab*	3471 *b*	2991 *b*	1714 *a*	3626 *ab*
O (control)	—	57 *b*	65 *b*	69 *a*	53 *b*	3332 *b*	2260 *b*	1629 *ab*	3058 *b*
—	Corn	59 *a*	71 *a*	69 *a*	61 *a*	3676 *a*	3454 *a*	1557 *a*	3773 *a*
—	Sunflower	59 *a*	74 *a*	69 *a*	59 *a*	3760 *a*	3094 *a*	1514 *a*	3576 *a*

† Means followed by the same letter within columns were not different ($p<0.05$).
‡ Data corrected for covariable bird damage.
§ABC=prior to every crop; B=prior to second crop; A=prior to first crop

Figure 4.6. Effect of Paraplow on grain yields of corn, sunflower, barley and wheat. Only cases where Paraplow was used just before the crop were included. Numbers in parentheses indicate number of experiments considered.



particularly after high-rainfall events, which were quite frequent during the vegetative phase of the crop (six rains between 24 and 90 mm day^{-1}).

There are at least two factors, other than those related to the soil physical condition, that may have played a role in the effect of paraplowing on corn yield. Plots with Paraplow generally had lower infestation of bermudagrass, which was a weed present in all experiments, but most notably in *C13* and *C15*, where yield increases were the largest. Improved soil aeration and changes in soil temperature and moisture content caused by paraplowing could have triggered an increase in soil microbial activity leading to higher availability of nutrients, mainly nitrogen, as shown by Braim *et al.* (1984). This was not assessed in the present study. The relatively high fertilizer rates used would have minimized this effect.

Sunflower had in average a 36 % increase in yield due to Paraplow treatment (Table 4.8, Fig 4.6). Considering that sunflower, as corn, grows during the driest time of the year in Uruguay, the factors discussed above related to root proliferation (which was not measured) and water infiltration into soils, would have also operated for this crop. The lack of effects on plant population density of sunflower and on weed infestation (bermudagrass was controlled by post-emergence herbicide) may have been reasons for the lower impact of paraplowing on sunflower than corn. Sojka *et al.* (1990) also showed an 18 % yield increase in sunflower due to in-row subsoiling in a water-limiting environment.

In most cases, subsoiling also increased yields of wheat and barley (Tables 4.9 and 4.10). However, there were situations where the yields of wheat (*RTN* 1992 and *C14* 1993) and barley (*RTN* 1993) with paraplowing did not differ from those without paraplowing.

Averaging experiments *RTN* and *C14*, wheat yields were 3.5, 3.7, 3.7 and 3.4 ton/ha for treatments ABC, B, A, and O, respectively, in year 1; and 4.0, 3.8, 3.5 and 3.1 ton/ha respectively, in year 2. Yields of barley for treatments ABC, B, A, and O were, respectively, 4.1, 3.9, 3.2 and 2.8 ton/ha in year 1, and 2.7, 2.8, 2.7 and 2.3 ton/ha in year 2.

The higher yield increase observed in barley with respect to wheat (Fig. 4.6) is in line with the results obtained by Masle (1992) discussed in section 4.3.2.2. When subjected to adverse soil physical conditions, barley, as compared to wheat, would to a larger extent favour root growth at the expense of grain production. When the stress is relieved, such as occurred in the present work with paraplowing, barley would have higher yield increases than wheat.

The effect of previous crop on grain yields was nearly significant ($p<0.10$) only in wheat in *RTN* 1992 (Table C7) and barley in *C14* 1993 (Table *C13*). In both cases, yield after corn was higher than after sunflower. Even though the effect of previous crop on wheat and barley yield was generally not significant, these crops tended to yield more after corn than after sunflower. On average, wheat yields were 3 and 4 % higher after corn than sunflower in year 1 and 2, respectively. The effect on barley yields was 4 and 5 %, respectively. Higher yields after corn than sunflower were attributed to improved water infiltration capacity (Section 3.3.3.1).

Given the high energy cost of subsoiling, it is desirable to maximize the time residuality of one paraplowing operation. Three of the four experiments reported here have focussed on this problem. In experiments *RTN* and *C14*, treatments ABC, B and A had a total grain output of the crop sequence that was 32, 14 and 25 % higher than the control treatment. The difference between treatments A and B was largely due to the fact that summer crops (corn, sunflower) were more benefited by paraplowing than winter crops (wheat, barley). The relatively small difference between triple paraplowing (treatment ABC) and single spring-paraplowing (treatment A), suggests that the effect of one subsoiling operation would last for at least two years. This conclusion is also supported by results obtained in experiment *C13*. In this case, total grain production of four crops grown in two years was increased by a single paraplowing by 53 % with respect to direct drilling without subsoiling (Table 4.11).

4.3.3.2. *Yield Components of Wheat and Barley*

The effects of paraplowing on yield components of wheat and barley are shown in Tables 4.12 and 4.13. The change in the various wheat yield components caused by paraplowing was, on average of all experiments, +9 % (spike density), +3 % (spikelets per spike), and +1 % (kernel weight). Corresponding values for barley were +16, +6 and -2 %, respectively. In both crops the increase in spike density was the most important single factor explaining the impact of alleviating soil physical compaction. This is in agreement with results obtained by Braim *et al.* (1984) for spring barley, and Hipps and Hodgson (1987) for winter wheat. Higher spike density was likely associated with denser plant stands (16 and 29 % more plants for wheat and barley, respectively) and improved tiller survival.

In the only case where paraplowing did not have any effects on grain yield (wheat in *RTN* 1992), spike density (Table 4.12) was 14 % higher and plant height (Table 4.9) 3 cm taller ($p<0.05$) with than without subsoiling. This suggests that there was an effect of paraplowing which was not reflected in grain yield, very likely because of compensation of lower spike number by higher number of grains per spike in the control treatment.

Table 4.11. Plant population densities and grain yields of sunflower and canola in experiment *C13* (1993/94).

	Plant population density (pl m^{-2})		Head area (m^2 ha^{-1}) †	Grain yield (ton/ha)
Treatment	Sunflower	Canola	Sunflower	Canola
Paraplow Oct. 92	2.5 *a* ‡	64 *a*	577 *a*	2.8 *a*
Control	2.1 *a*	60 *a*	408 b	3.1 *a*

† Since grain yield was not measured, this variable was used as an estimator.

‡ Means followed by the same letter within columns were not different ($p<0.05$)

Table 4.12. Effect of Paraplow and previous crop on wheat yield components in three experiments.

		Spike density (spikes/m²)					Spike size (spikelets/spike)					Thousand-kernel weight (g)				
Paraplow Treatment	**Previous Crop**	**RTN 1992**	**C14 1993**	**C13 1993**	**RTN 1993**	**C14 1994**	**RTN 1992**	**C14 1993**	**C13 1993**	**RTN 1993**	**C14 1994**	**RTN 1992**	**C14 1993**	**C13 1993**	**RTN 1993**	**C14 1994**
ABC§	Corn	441	376	---	474	435	19.8	15.6	----	18.1	18.3	38.2	26.1	---	26.1	37.4
ABC	Sunflower	459	438	---	494	448	19.7	15.4	----	15.8	17.9	39.4	23.5	---	27.3	37.1
B	Corn	486	404	---	486	407	20.3	16.0	----	19.0	18.6	38.7	25.9	---	26.8	36.6
B	Sunflower	422	395	----	550	444	20.3	16.1	----	19.6	17.7	38.2	26.1	---	27.7	36.3
A	Corn	421	434	433	418	432	19.6	15.2	15.4	17.9	18.1	37.5	26.6	n/a	26.2	35.3
A	Sunflower	436	444	----	454	457	20.1	15.3	----	18.1	18.2	38.2	25.7	----	26.7	36.2
O (control)	Corn	436	377	400	489	387	19.7	14.1	15.3	16.5	16.9	39.2	26.5	n/a	25.5	36.2
O (control)	Sunflower	360	358	----	479	372	20.5	14.1	----	16.1	17.6	38.5	25.3	----	26.3	36.2
ABC	----	450 *a*†	407 *a*	---	484 *a*	442 *a*	19.7 *a*	15.5 *a*	----	16.0 *a*	18.1 *a*	38.8 *a*	24.8 *b*	----	26.7 *a*	37.3 *a*
B	----	454 *a*	400 *a*	---	518 *a*	426 *ab*	20.3 *a*	16.1 *a*	----	19.3 *a*	18.1 *a*	38.6 *a*	26.0 *a*	---	27.3 *a*	36.5 *ab*
A	----	429 *ab*	439 *a*	433 *a*	436 *a*	445 *a*	19.9 *a*	15.3 *a*	15.4 *a*	18.0 *a*	18.1 *a*	37.8 *a*	26.1 *a*	---	26.5 *a*	35.7 *b*
O (control)	----	398 *b*	368 *a*	400 *a*	484 *a*	380 *b*	20.1 *a*	14.1 *b*	15.3 *a*	16.3 *a*	17.3 *b*	38.9 *a*	25.9 *a*	----	25.9 *a*	36.2 *ab*
---	Corn	446 *a*	398 *a*	---	467 *a*	415 *a*	19.9 *a*	15.2 *a*	--	17.9 *a*	17.9 *a*	38.4 *a*	26.3 *a*	----	26.1 *a*	36.4 *a*
---	Sunflower	419 *a*	409 *a*	----	494 *a*	430 *a*	20.2 *a*	15.2 *a*	----	17.4 *a*	17.9 *a*	38.6 *a*	25.1 *b*	---	27.0 *a*	36.5 *a*

† Means followed by the same letter within columns were not different ($p<0.05$)
§ABC=prior to every crop; B=prior to second crop; A=prior to first crop

Table 4.13 Effect of Paraplow and previous crop on barley yield components in two experiments.

		Spike density (spikes/m²)				Spike size (spikelets/spike)				Thousand-kernel weight (g)			
Paraplow Treatment	**Previous Crop**	***RTN* 1992**	***C14* 1993**	***RTN* 1993**	***C14* 1994**	***RTN* 1992**	***C14* 1993**	***RTN* 1993**	***C14* 1994**	***RTN* 1992**	***C14* 1993**	***RTN* 1993**	***C14* 1994**
ABC§	Corn	496	608	316	421	22.2	20.0	19.2	20.8	49.6	42.3	42.4	51.8
ABC	Sunflower	523	539	420	394	20.8	19.4	19.9	21.0	49.7	42.7	42.9	51.4
B	Corn	503	480	367	403	20.6	20.2	19.9	19.9	50.2	41.7	41.5	52.1
B	Sunflower	499	514	382	440	21.4	19.0	20.4	20.3	48.2	42.8	41.0	52.2
A	Corn	430	457	385	404	22.1	18.9	18.8	18.0	52.5	44.1	43.5	52.5
A	Sunflower	475	431	390	394	22.1	18.8	18.7	17.6	51.0	42.9	42.4	48.1
O (control)	Corn	441	380	380	414	22.2	16.7	19.0	18.1	51.5	43.4	43.0	54.2
O (control)	Sunflower	476	306	389	353	21.6	18.2	19.1	19.3	51.8	42.2	40.6	52.0
ABC	----	510 *a*†	574 *a*	368 *a*	407 *a*	21.5 *a*	19.7 *a*	19.6 *a*	20.9 *a*	49.7 *b*	42.5 *a*	42.7 *a*	51.6 *ab*
B	----	501 *ab*	497 *b*	375 *a*	422 *a*	21.0 *a*	19.6 *a*	20.2 *a*	20.1 *a*	49.2 *b*	42.2 *a*	41.3 *a*	52.1 *ab*
A	----	453 *b*	444 *b*	387 *a*	399 *a*	22.1 *a*	18.9*ab*	18.8 *a*	17.8 *b*	51.7 *a*	43.5 *a*	43.0 *a*	50.3 *b*
O (control)	----	459 *b*	343 *c*	385 *a*	384 *a*	21.9 *a*	17.5 *b*	19.1 *a*	18.7 *b*	51.7 *a*	42.8 *a*	41.8 *a*	53.1 *a*
----	Corn	468 *a*	481 *a*	362 *a*	411 *a*	21.8 *a*	19.0 *a*	19.2 *a*	19.2 *a*	51.0 *a*	42.9 *a*	42.6 *a*	52.7 *a*
----	Sunflower	493 *a*	447 *a*	395 *a*	395 *a*	21.5 *a*	18.9 *a*	19.5 *a*	19.6 *a*	50.2 *a*	42.6 *a*	41.7 *a*	50.9 *b*

† Means followed by the same letter within columns were not different ($p<0.05$)
§ABC=prior to every crop; B=prior to second crop; A=prior to first crop

Paraplowing usually induced increased spike densities of wheat and barley, although the effect was often not significant (Tables 4.12 and 4.13). On average, wheat had 12 and 7 % more spikes with paraplowing than the check in year 1 and 2, respectively. Paraplowing increased the spike density of barley in year 1 only. The magnitude of the increase was 30 % (Table 4.13).

The size of the spikes, measured as the number of spikelets per spike, was increased by Paraplow in experiment *C14*, but not in *RTN* . In *C14*, wheat spikes were 10 and 5 % bigger in Paraplow treatment than in the control in year 1 and 2, respectively (Table 4.12), whereas in barley the increase was 12 % in both years (Table 4.13).

The weight of kernels was negatively correlated with the other components, and tended to be higher where Paraplow was not used. However, this effect was of low magnitude, and was significant only in *C14* 1993 for wheat (Table 4.12), and *RTN* 1992 for barley (Table 4.13).

The only yield component that was somewhat affected by previous crop was kernel weight, which tended to be higher after corn than after sunflower. The difference between preceding crops was significant ($p<0.05$) in *C14* 1993 for wheat (Table 4.12) and *C14* 1994 for barley (Table 4.13). In these cases, kernel weight after corn was 5 and 4 % higher than after sunflower, respectively. These results suggest that the mechanism involved in the response to previous crop acted during the later stages of the crop cycle. In this study it was found that soil water infiltration capacity was lower after sunflower than after corn (section 3.3.3.1). Water availability would have been a limiting factor during the grain-filling period, and crops seeded after corn would have received a better supply than after sunflower.

4.4. CONCLUSIONS

Paraplowing induced yield increases in all crops tested and in most of the experiments conducted, indicating that crop productivity in direct-seeding systems was affected by soil physical constraints. The response to subsoiling depended mainly on the crop being grown, on timing of subsoiling, and on the climatic conditions, chiefly the amount of rainfall, during the growing seasons. Weed infestation was also a factor influencing the response to Paraplow in two experiments.

Paraplowing increased crop yields by improving plant establishment, root proliferation, tiller survival, and by reducing floret abortion. Thethese factors varied with crop, crop sequence and year. Plant populations increased due to avoidance of waterlogging, increased soil temperatures, and closer seed to soil contact. Root growth was enhanced due to reduced soil strength, especially at low moisture contents, improved aeration of the subsoil, and higher water infiltration capacity. Finally, superior tiller survival and reduced spikelet abortion resulted from higher number of nodal roots per unit area.

Crops seeded after corn tended to produce slightly higher yields than those after sunflower. This was partly due to the nature of residues left by these crops, but there is some evidence that factors related to soil structure would have been important as well. More research is needed to assess the effects of crops with contrasting root systems on soil physical properties.

Wheat and barley had contrasting responses to adverse soil physical condition. The former, when subjected to high soil strength decreased root length density in the vegetative phase to a larger extent than the latter. During the reproductive stages, both crops suffered root growth cutbacks, but as evidenced from soil moisture data, barley was still less affected than wheat. Wheat was superior to barley in the ability to produce nodal roots in response to a soil stress (such as excess moisture in 1993) and this was probably related with the lower impact of detrimental soil conditions on grain yield observed in this crop. Assuming that the cultivars used in this study are representative of the species, it can be speculated that wheat would be more adapted than barley to grow in adverse soil structure.

One Paraplow treatment improved the yields of crops seeded up to two years later, and its effects were no different from paraplowing before every crop in the rotation. Considering the high energy costs of subsoiling, maximum benefit would be obtained by paraplowing on alternate years.

5. USING SOIL PENETRATION RESISTANCE TO ESTIMATE SHORT-TIME VARIATIONS IN SOIL MOISTURE CONTENT

ABSTRACT

Soil penetration resistance (PR) variations in the short term are directly related to changes in soil moisture content. PR is much easier to measure than soil moisture, and if the relationship between the variables for a given soil and structural condition were known, soil moisture could be conveniently measured by means of a cone penetrometer. Several thousand pairs of soil penetration resistance and gravimetric soil moisture measurements taken at three depths and after different tillage treatments, in three experiments on a silty-clay loam Mollisol of SW Uruguay, were used to study the relationship between both variables. Data were organized in 14 data sets, each corresponding to a combination of experiment, soil depth and tillage treatment, and fitted to an exponential model.

In all cases, soil moisture, as well the rate of change in PR with soil moisture, increased as PR decreased. When all the data sets were pooled, PR means varied between 0.2 and 3.1 MPa, as soil moisture varied from 38 to 15 % by weight. The data was represented well by an exponential model, although there was a great deal of random variability around the regression curves, due to factors discussed in the text. This random variability tended to be lower for dry than for wet soil, and for deep than for shallow soil layers. Validation of models indicated that, due to large spatial variability in other soil properties, treatment means, rather than individual PR measurements, should be used to predict soil moisture. Linear regression analyses of predicted on measured soil moisture contents for all experiments yielded intercepts not significantly different from zero, and slopes not significantly different

from 1.0, with r^2>0.69. It was concluded that PR data should always be reported along with a reference soil moisture content. The potential of the PR-soil moisture relationship as an indicator of soil quality is discussed.

5.1 INTRODUCTION

Measuring soil moisture in the field with standard methods (gravimetric, resistance blocks, neutron probes, TDR) can be time-consuming and tedious, requires disturbing soil by digging or installing special tube-settings, and often does not permit measurements of thin depth increments nor sufficient replication to account for spatial variability. On the other hand, soil penetration resistance (PR) measurements do not disturb soil to a large extent, can be made relatively easily, therefore making adequate replication in space feasible; and provide information for narrowly spaced depth increments (as small as 0.01 m).

Soil PR depends mainly on soil texture (Ayers and Perumpral 1982), soil particle surface roughness (Cruse *et al.* 1981), bulk density (Mirreh and Ketcheson 1972) and soil moisture content (Taylor and Gardner 1963). The resistance sensed by a cone probe penetrating into a soil is the sum of the pressure at the tip of the cone and a frictional component, which includes soil-metal friction and adhesion. Tip pressure is a function of soil shearing strength -determined by cohesion and angle of internal friction- and compressibility (Farrell and Greacen 1966). Soil-metal friction can be of high magnitude (Armbruster *et al.* 1990) and is often not reported as a separate component of PR.

Soil moisture content affects most factors determining PR. Cohesion is at its minimum in saturated soil due to the presence of free water in soil pores. As soil moisture decreases, negative water potentials develop, and water held by soil particles acts as a bonding agent, thus increasing cohesion. The contribution of matric potential to soil cohesion reaches a maximum at some intermediate soil moisture content, at which the degree of soil saturation is still relatively high. Decreasing degree of saturation by decreasing soil moisture content beyond this maximum value decreases soil cohesion (Williams and Shaykewich 1970). In soils containing expansive clay minerals, the increase in bulk density with soil drying increases cohesion (Camp and Gill 1969) due to a higher number of contacts between particles per unit volume of soil. This counterbalances the decrease in soil cohesion expected at lowest moisture contents. Soil compressibility is also highly related to water content (Larson *et al.* 1980). As soil moisture increases, the maximum bulk density achieved by a compaction force increases up to some water content below saturation. Above this point pore water pressure starts to rise, acting against compressive forces, thus reducing compressibility (Akram and Kemper 1979).

The overall effect of soil moisture on PR depends upon whether the soil shrinks on drying. If soil shrinkage and expansion are not involved, the strength parameters and compressibility would be the main determinant of resistance, and the relationship would show an initial increase in PR with soil moisture, and an exponential decrease after a maximum is achieved (Ayers and Perumpral 1982). On the other hand, if shrinkage is involved, both cohesion and friction would increase upon drying (Camp and Gill 1969) and as a result, PR would always decrease with increasing soil moisture.

For a given soil, short-term variations in soil PR are mostly associated with soil moisture changes, since bulk density normally does not undergo large changes over relatively short time periods. If the relationship between soil PR and soil moisture content were known, then PR data could be used to estimate soil moisture contents. This information might be used in assessing soil water status and also, as a measure of root activity, assuming that short-term changes in soil moisture content reflect localized water uptake by roots.

Mielke *et al.* (1994) developed empirical models to estimate gravimetric soil moisture content from PR measurements over a wide range of soils in laboratory conditions. The power function they selected accurately described the relationship at high soil densities, but showed considerable scatter of data when densities from a cultivated field were used. On the other hand, Jayawardane and Blackwell (1990) fitted a model estimating soil strength as a linear function of volumetric soil moisture content in field conditions. Their model overestimated moisture content in dry soil.

Several thousand pairs of soil PR and soil moisture measurements were taken at three depths and after different tillage treatments on a silty-clay loam Mollisol of SW Uruguay. The information was used to study the relationship between the variables and to assess the possibility of predicting soil moisture content from PR determinations.

5.2 MATERIALS AND METHODS

Several experiments were conducted during the period 1991-93 on a silty-clay loam (fine, mixed, superactive, thermic Oxyaquic Argiudoll, or 'Brunosol éutrico típico' in the Uruguayan clasification) in SW Uruguay (INIA La Estanzuela Experimental Station), to study soil compaction effects on crop productivity under zero tillage. Three of these experiments (named as *RTN*, *C15* and CxT) were selected for the present study. The experiments were physically near one another on the same soil type. Selected soil properties for these sites are shown in Table A.1.

5.2.1 Experiment Description

Experiments *RTN* and *C15* were already described in Chapter 3. The third experiment (CxT) was set up to study the interactions between wheat and barley cultivars and two tillage systems (mouldboard plow and zero tillage) on a soil that had been heavily compacted by grazing cattle. The experimental design was in complete randomized blocks, with split-split plots. The two tillage treatments described above constituted main plots, crops (wheat and barley) became subplots, and cultivars (four of each crop) were sub-subplots. Cultivar plots were 4 m x 15 m. The experiment was seeded in July 1992.

5.2.2 Field Operations

In the *RTN* experiment a three-shank Paraplow was passed to 0.45 m depth on October 1991 (treatment A), May 1992 (treatment B), on both dates (treatment ABC), or not used (treatment O). Shanks were separated by 0.5 m. Corn cv. 'Estanzuela Bagual' or sunflower cv. 'Estanzuela Yatay' were seeded after subsoiling in October. A Semeato PS-8 direct-drilling, triple-disc seeder was used to plant the crops. Wheat cv. 'Estanzuela Benteveo' and barley cv. 'Estanzuela Quebracho' were seeded in July 1992 by using a Semeato TD-220 direct-drilling, triple-disc seeder.

The same Paraplow was used in experiment *C15*. Subsoiling was performed on 7 Oct. 1993. Corn cv. 'Estanzuela Bagual' was seeded on 25 Nov. by using the Semeato PS-8 drill mentioned above.

In experiment CxT a mouldboard plow was passed on March 1992 to a depth of 20 cm. The seedbed was prepared by two passes of disc implements. Both conventional and zero tillage treatments were seeded in July 1992.

5.2.3 Penetration Resistance Determinations

PR was measured by using a Rimik CP10 hand-held recording cone penetrometer. The cone used had an included semiangle of 15° and a base diameter of 12.8 mm. PR was recorded up to the 450 mm depth in 15-mm increments. Rate of penetration was about 10 mm s^{-1}. The number of replicates varied among sampling dates, but was usually between two and four per plot. In both Paraplow experiments, half the measurements were taken on the hilltops, and half on the depressions associated with Paraplow passes. In the CxT experiment, determinations were randomly distributed within main plots. Four sets of PR data from experiment *RTN*, four from experiment *C15*, and two from experiment CxT were used in the present study, each from one of the following sampling dates: 27 July, 17 Aug., 17 Sep., and 14 Oct., 1992 (*RTN* experiment); 6 Oct. and 23 Nov. 1993, and 20 Jan. and 13 May 1994 (*C15* experiment); and 17 July, and 7 Oct. 1992 (CxT experiment).

PR values were tested for autocorrelation with depth. When autocorrelation was detected, data were corrected according to the procedure described in Chapter 6. Corrected PR values were used to study their relation with soil moisture.

5.2.4 Soil Moisture and Bulk Density Determinations

At the same time as PR, soil moisture was measured by the gravimetric method. Soil cores were taken from a distance within 0.1 m from the PR measurement points. A truck-mounted Concorde mechanical corer harnessed with 45-mm-internal-diameter tubes was used. On two occasions (7 and 14 Oct. 1992 samplings), soil cores were extracted from the same spots where PR was measured. Sampling depths were from 0 to 150; 150 to 300; and 300 to 450 mm. On both 7 and 14 Oct. samples from the 300-450 mm depth could not be taken because the soil was too dry to introduce the probe. Soil samples were hermetically stored in aluminum containers, taken to the laboratory, weighed, dried at 105 °C for 48 hours, and weighed again. Soil moisture content was calculated on a weight basis. In the *C15* experiment, soil bulk density was estimated in the same samples by dividing the dry soil weight by sample volume (239 cm^3).

5.2.5 Model Used to Describe the Relationship between Soil Moisture and PR

Three soil layers were considered in each sampling point, with centres at the following depths: 75, 225 and 375 mm. Each PR value was estimated as the average of three most immediate depths (60, 75 and 90 mm were used to estimate PR at 75 mm; 210, 225 and 240 mm were used to estimate PR at 225 mm; and 360, 375 and 390 mm were used to estimate PR at 375 mm). Each of these PR averages was paired with the corresponding soil moisture values. Data were fitted to the following empirical model:

$$P = a.e^{b(w-w_{min})^c}$$

where P is the soil PR (in MPa), w is the soil moisture content (in percent by weight), w_{min} is an arbitrary soil moisture content slightly lower than the minimum observed value (in percent by weight), and a, b, and c are empirical constants.

The coefficient a is the maximum possible value of P, or P corresponding to $w=w_{min}$. Since w_{min} is somewhat arbitrary, a can not be thought of as a constant for a given soil, unless a fixed, reference w_{min} is used.

Both b and c ($b<0$, $c>0$) are the parameters affecting the rate of change in PR with soil moisture as well as the shape of the curve. As b increases (gets closer to 0), the rate of change of PR with soil moisture (the slope of the curve) decreases. When b=0, P becomes independent of w. Therefore, very low b values indicate high sensitivity of P to changes in soil moisture. High c values also determine a steep change of P with soil moisture, and low P in wet soil. When c tends to 0 (the function does not exist at c=0), then P becomes independent of w, taking the value $a.e^b$. In the particular case where c=1, the function can be made linear by the transformation: $\ln P = \ln a + bw$.

Because b is a linear coefficient, it has the same influence on the relationship between w and P at any w level. The influence of c on the other hand, becomes more important as w increases. At low moisture contents the effect of c is almost negligible, and b is the main factor governing the rate of change in P with w. In wet soil the effect of c becomes dominant, and soils with high c values will have low PR levels when wet, regardless of b.

5.2.6 Procedure for Model Fitting and Validation

A different model was estimated for different combinations of soil layers and tillage treatments in each experiment. In the *RTN* experiment soil moisture content values at 375-mm depth showed little variability and were pooled with the 225-mm soil depth data to estimate the model. In the CxT experiment, data at 375-mm depth were not considered because very few points were available and they did not seem to fit the same relationship as in the 225-mm soil depth.

The following 14 data sets were used to estimate the models: 1) *RTN* experiment: a) Treatments B and ABC pooled, 75-mm depth; b) Treatments B and ABC pooled, 225- and 375-mm depths pooled; c) Treatments A and O pooled, 75-mm depth; and d) Treatments A and O pooled, 225- and 375-mm depths pooled. 2) *C15* experiment: a) Paraplow, 75 mm; b)

Paraplow, 225 mm; c) Paraplow, 375 mm; d) Control, 75 mm; e) Control, 225 mm; and f) Control, 375 mm. 3) CxT experiment: a) Mouldboard plow, 75 mm; b) plow, 225 mm; c) Zero tillage, 75 mm; and d) Zero tillage, 225 mm.

The coefficients were estimated by the non-linear least squares, Gauss-Newton method, using the SAS NLIN Procedure (Sas Institute 1985). The boundary conditions were $b<0$ and $c>0$.

Once the coefficients were estimated, the equation above was transformed to estimate w from P:

$$w=\left(\frac{\ln a-\ln P}{b}\right)^{\frac{1}{c}}+w_{\min}$$

The derivative of the equation was used to estimate the rate of change in P with w at any given w level:

$$\frac{dP}{dw}=abc(w-w_{\min})^{c-1}e^{b(w-w_{\min})^{c}}$$

Predicted soil moisture contents were derived from PR, and compared with the corresponding measured values by means of a linear regression analysis. This operation was performed in two ways: a) by using individual PR values; and b) by using PR treatment means for each depth and sampling date.

5.3 RESULTS

The sampling dates selected in the three experiments covered a wide range of soil moisture contents and PR's (Tables 5.1, 5.2 and 5.3). In experiment *RTN*, PR increased with

Table 5.1 Number of pairs (n) and mean and extreme (in parentheses) values of soil moisture and PR for each sampling date and treatment-depth combination in experiment *RTN*.

Treatment	Depth (mm)	Date	n	PR (MPa)	w (%)
O.A	75	27 Jul. 1992	32	1.0 (0.5-1.7)	28 (24-34)
O,A	75	17 Aug. 1992	32	1.4 (0.5-2.3)	25 (20-35)
O.A	75	17 Sep. 1992	48	1.8 (0.9-3.1)	27 (21-33)
O,A	75	14 Oct. 1992	24	3.1 (1.4-4.4)	15 (13-18)
O.A	225/375	27 Jul. 1992	64	1.2 (0.6-1.8)	30 (23-34)
O.A	225/375	17 Aug. 1992	64	1.3 (0.7-1.9)	30 (19-36)
O.A	225/375	17 Sep. 1992	48	1.4 (0.5-2.6)	23 (19-29)
O.A	225/375	14 Oct. 1992	24	2.9 (1.4-4.1)	17 (13-22)
B.ABC	75	27 Jul. 1992	32	0.8 (0.4-1.1)	29 (26-34)
B.ABC	75	17 Aug. 1992	32	1.2 (0.5-2.0)	25 (17-31)
B.ABC	75	17 Sep. 1992	48	1.2 (0.5-2.7)	27 (18-37)
B,ABC	75	14 Oct. 1992	24	2.4 (0.5-4.3)	16 (13-18)
B.ABC	225/375	27 Jul. 1992	64	1.1 (0.5-1.7)	31 (25-35)
B,ABC	225/375	17 Aug. 1992	64	1.0 (0.3-1.7)	30 (19-37)
B.ABC	225/375	17 Sep. 1992	48	1.4 (0.5-2.6)	24 (20-33)
B.ABC	225/375	14 Oct. 1992	24	3.1 (1.4-4.5)	16 (14-20)

Table 5.2. Number of pairs (n) and mean and extreme (in parentheses) values of soil moisture and PR for each sampling date and treatment-depth combination in experiment *C15*.

Treatment	Depth (mm)	Date	n	PR (MPa)	w (%)
Paraplow	75	23 Nov. 1993	12	0.8 (0.2-1.3)	38 (35-43)
Paraplow	75	20 Jan. 1994	4	0.9 (0.3-1.6)	34 (33-34)
Paraplow	75	13 May 1994	12	1.4 (0.7-2.4)	27 (18-33)
Paraplow	225	23 Nov. 1993	12	0.5 (0.2-0.9)	26 (18-32)
Paraplow	225	20 Jan. 1994	4	2.1 (1.8-2.5)	17 (16-18)
Paraplow	225	13 May 1994	12	0.8 (0.5-1.3)	31 (29-34)
Paraplow	375	23 Nov. 1993	12	1.2 (0.8-1.5)	29 (24-37)
Paraplow	375	20 Jan. 1994	4	1.7 (1.4-2.4)	15 (12-18)
Paraplow	375	13 May 1994	12	1.1 (0.6-1.6)	26 (24-29)
Control	75	6 Oct. 1993	38	2.3 (1.2-4.0)	21 (15-32)
Control	75	23 Nov. 1993	12	1.8 (0.9-2.7)	30 (23-42)
Control	75	20 Jan. 1994	2	2.5 (2.4-2.7)	18 (18-19)
Control	75	13 May 1994	12	1.3 (1.1-1.6)	26 (16-42)
Control	225	6 Oct. 1993	45	2.1 (0.5-3.3)	22 (18-28)
Control	225	23 Nov. 1993	12	1.2 (0.8-2.2)	31 (27-37)
Control	225	20 Jan. 1994	3	2.5 (2.2-3.0)	18 (16-21)
Control	225	13 May 1994	12	1.1 (0.7-1.6)	31 (28-33)
Control	375	6 Oct. 1993	45	2.1 (0.5-3.3)	22 (16-27)
Control	375	23 Nov. 1993	12	1.6 (1.0-2.6)	26 (23-30)
Control	375	20 Jan. 1994	3	2.4 (2.0-3.1)	18 (16-20)
Control	375	13 May 1994	12	1.2 (0.6-1.7)	26 (24-29)

Table 5.3. Number of pairs (n) and mean and extreme (in parentheses) values of soil moisture and PR for each sampling date and treatment-depth combination in experiment CxT.

Treatment	Depth (mm)	Date	n	PR (MPa)	w (%)
CT	75	17 Jul. 1992	6	0.2 (0.2-0.3)	35 (34-37)
CT	75	7 Oct. 1992	18	1.0 (0.5-2.0)	28 (23-31)
CT	225	17 Jul. 1992	6	0.6 (0.4-1.0)	33 (32-35)
CT	225	7 Oct. 1992	18	2.0 (0.5-3.3)	26 (21-31)
ZT	75	17 Jul. 1992	6	0.9 (0.8-1.1)	29 (26-33)
ZT	75	7 Oct. 1992	18	2.2 (0.8-4.5)	25 (20-30)
ZT	225	17 Jul. 1992	6	1.3 (1.0-2.0)	30 (26-31)
ZT	225	7 Oct. 1992	18	2.8 (1.3-4.3)	23 (18-28)

time as soil became drier, particularly between 17 Sep. and 14 Oct. samplings. At 75-mm depth, PR means ranged between 1.0 and 3.1 MPa for undisturbed soil, and from 0.8 to 2.4 MPa for paraplowed soil. Soil moisture was very similar for both treatments, ranging from 29 to 15 %. At the deeper soil layers, PR means did not differ between treatments, and ranged from 1.1 to 3.1 MPa, while soil moisture decreased from 31 to16 %.

In the *C15* site, soil moisture fluctuated during the sampling period, showing a minimum on 20 Jan., except for Paraplow treatment at 75-mm depth, which had nearly double the moisture content recorded in any other depth-treatment combination on this date. Differences between tillage treatments either in PR or soil moisture were evident up to the 20 Jan. sampling, tending to disappear thereafter. PR ranges for paraplowed treatments were usually narrower than for control, particularly at the 75-mm depth, where they were 0.8-1.4 and 1.3-2.5 MPa, respectively. Soil moisture ranges at this depth were 27-38 and 18-30 %, respectively. Differences at deeper horizons were generally of lower magnitude.

The third experiment (CxT) showed the least variability in soil moisture content, with means ranging between 23 and 35 %, considering all depths and treatments. In spite of this, PR varied markedly among sampling dates (from 0.2 to 2.8 MPa). A strong treatment effect was also evident.

The relationships between soil moisture content and PR for each soil depth and tillage treatment combination showed that in all cases, as soil moisture increased PR decreased. The rate of change in PR with soil moisture also decreased as soil moisture content increased. Data were well represented by the model selected ($p<0.05$) in all cases, although there was a great deal of random variability around the curves fitted, as revealed by the width of the 95 %

confidence intervals (Figs. 5.1, 5.2 and 5.3). This random variability tended to be lower for dry than for wet soil, and for deep than for shallow soil layers.

The magnitude of these coefficients varied greatly from site to site (Table 5.4). Overall, the *RTN* site had the lowest w_{min}, the highest a values, and the lowest b values. On the other hand, the CxT site presented the highest w_{min}, lowest a, and highest b values. The coefficients were not independent of each other. Considering all 14 models together, high w_{min} values were associated with low a and high b values, and vice versa. There was a close relationship between b and c. The relationships between coefficients depended on whether the soil was disturbed or not (Fig. 5.4). Each depth at each site had a distinct set of model coefficients describing the effect of soil moisture on PR (Fig. 5.5).

The a coefficient tended to be higher in undisturbed than in disturbed soil, with two exceptions (*RTN* experiment at 75 mm, and *C15* experiment at 375 mm) (Table 5.3). It also tended to increase with depth, particularly where the soil was disturbed either by mouldboard plow or by Paraplow. In both cases, the high a values observed in disturbed soil were compensated for by low b values (-0.47 and -1.10, respectively), which resulted in a steep decrease in P with increasing w above w_{min}.

Some notable points in the estimated soil moisture-PR curves are shown in Table 5.5. The water content at which P=2 MPa and the derivative of the equations at this water content were generally higher for undisturbed than for disturbed soil, and showed no clear trend with soil depth. The maximum soil moisture content recorded in deep soil horizons was lower in undisturbed than disturbed soil in *C15* and CxT sites.

Comparisons between measured and estimated soil moisture contents are presented

Figure 5.1. Relationship between PR and soil moisture content for different combinations of soil layers and Paraplow treatments in *RTN* experiment. a) treatments O and A, depth 75 mm; b) treatments O and A, depths 225 and 375 mm; c) treatments B and ABC, depth 75 mm; and d) treatments B and ABC, depths 225 and 375 mm. The curves represent the model fitted and the 95% interval of confidence.

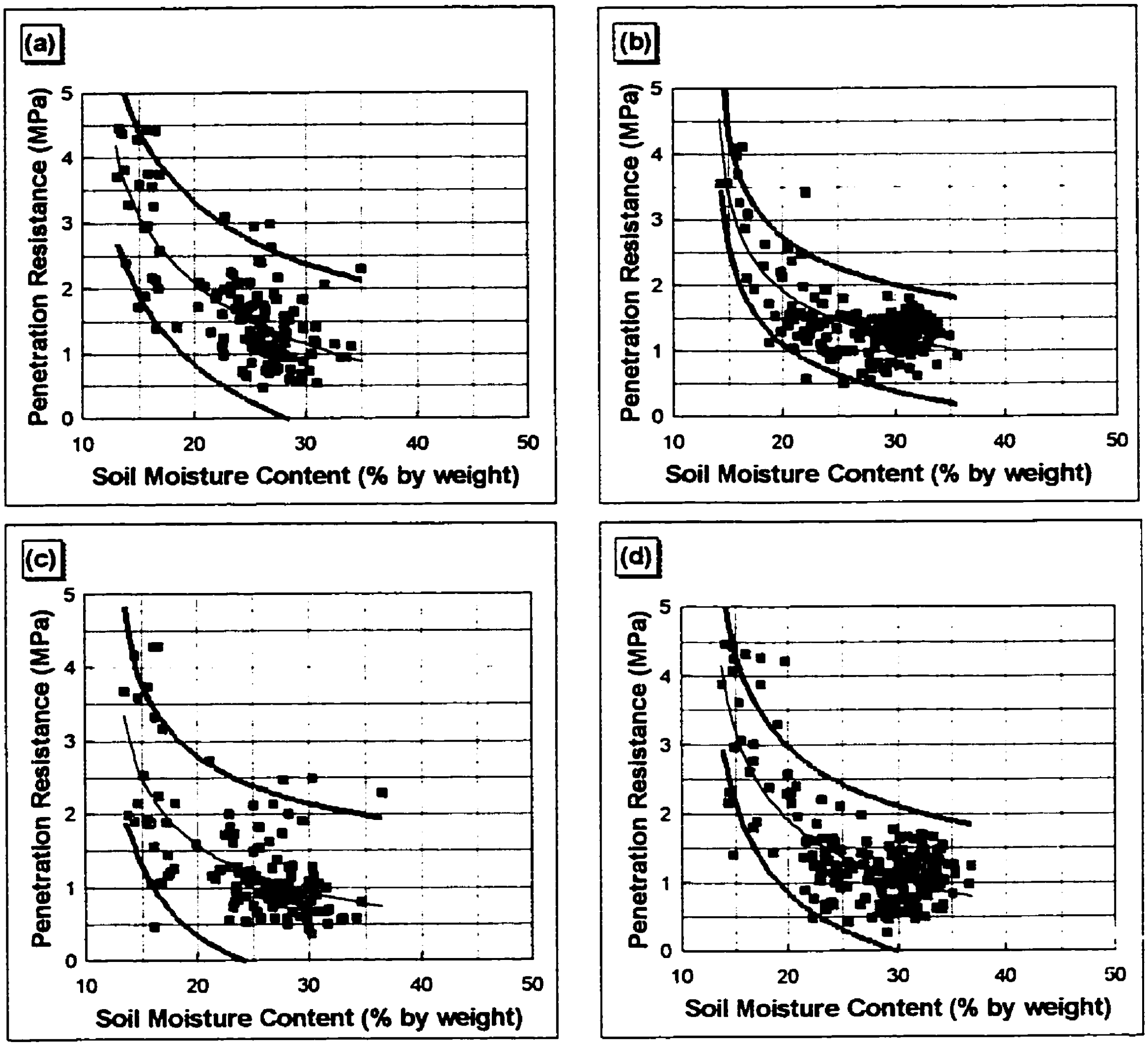


Figure 5.2. Relationship between PR and soil moisture content for different combinations of soil layers and Paraplow treatments in *C15* experiment. a) Paraplow, depth 75 mm; b) Paraplow, depth 225 mm; c) Paraplow, depth 375 mm; d) Control, depth 75 mm; e) Control, depth 225 mm; and f) Control, depth 375 mm. The curves represent the model fitted and the 95 % interval of confidence.

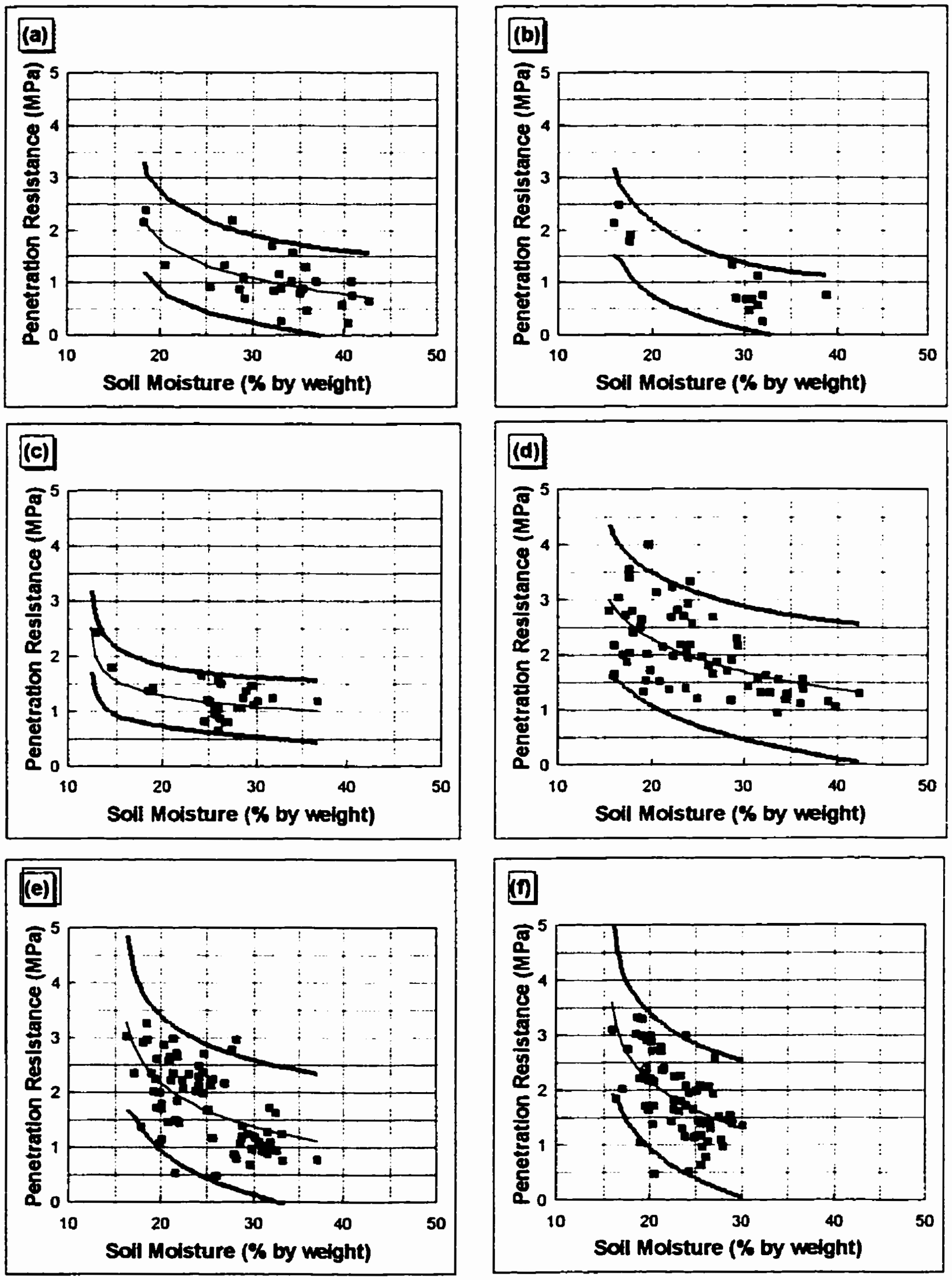


Figure 5.3. Relationship between PR and soil moisture content for different combinations of soil layers and tillage treatments in CxT experiment. a) Conventional tillage, depth 75 mm; b) Conventional tillage, depth 225 mm; c) Zero tillage, 75 mm; and d) Zero tillage, depth 225 mm. The curves represent the model fitted and the 95 % interval of confidence.

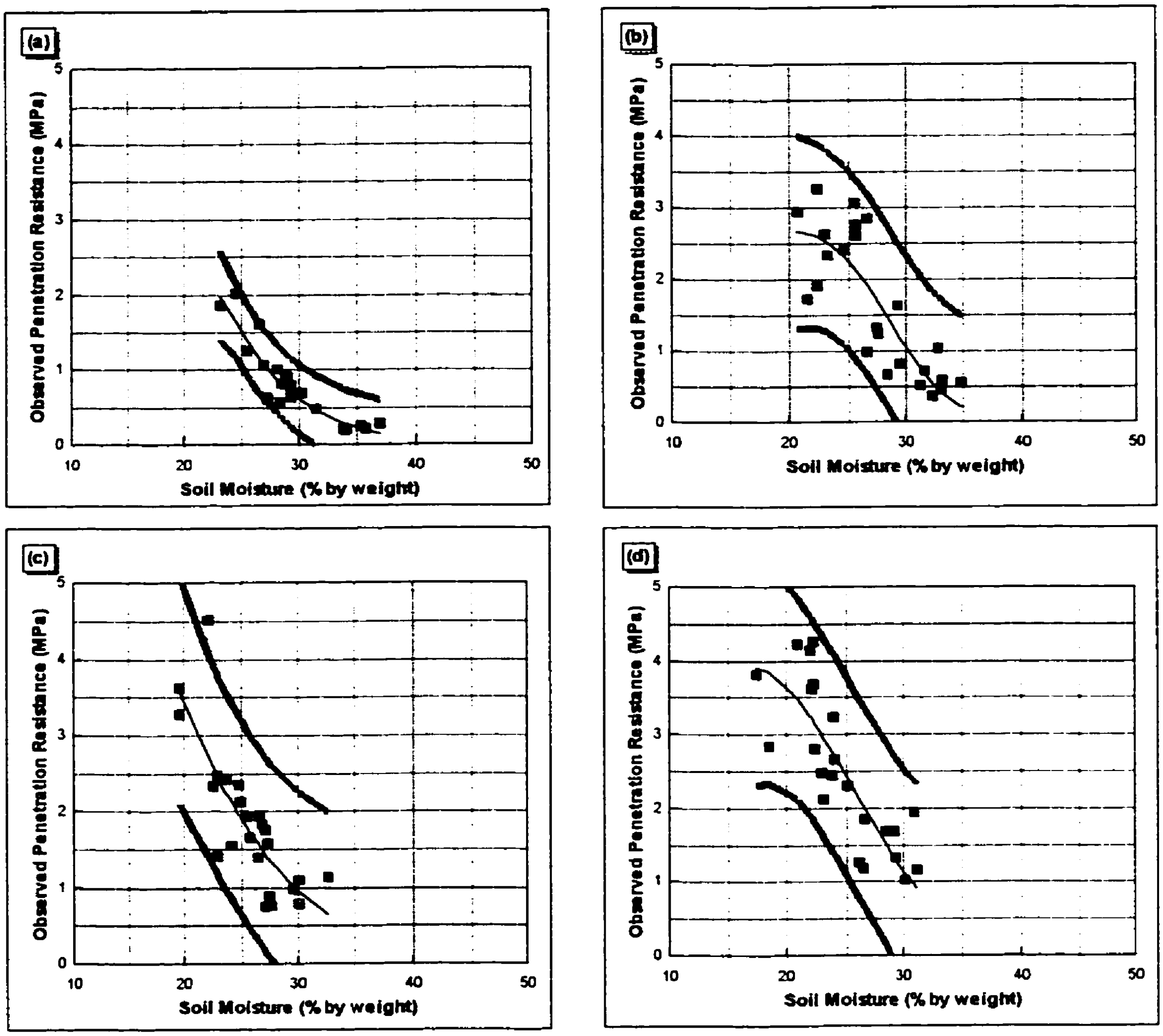


Table 5.4. Coefficients calculated for each of the 14 models.

Experiment	Treatment	Depth (mm)	n	*a* (MPa)	*b*	*c*	w_{min} (%)
RTN	O. A	75	128	4.2	-0.18	0.697	13
RTN	O.A	225/375	187	7.1	-0.74	0.314	14
RTN	B.ABC	75	135	4.7	-0.47	0.439	13
RTN	B.ABC	225/375	199	6.3	-0.49	0.454	13
C15	Paraplow	75	28	2.4	-0.19	0.574	18
C15	Paraplow	225	28	3.0	-0.27	0.604	15
C15	Paraplow	375	28	5.4	-1.10	0.136	12.3
C15	Control	75	72	4.0	-0.25	0.445	14
C15	Control	225	57	3.9	-0.31	0.462	16
C15	Control	375	72	3.8	-0.26	0.523	15.9
CxT	CT	75	24	2.0	-0.13	1.13	23
CxT	CT	225	24	2.7	-0.003	2.52	20
CxT	ZT	75	24	3.8	-0.09	1.14	19
CxT	ZT	225	23	3.9	-0.01	1.88	17.5

Figure 5.4 Relationship between coefficients of the models describing the effect of soil moisture on PR. a) *a* and *wmin*; b) *b* and *a*; c) *c* and *b*. Data were divided into tho groups: disturbed (including CT and Paraplow treatments) and undisturbed (including ZT and Control treatments).

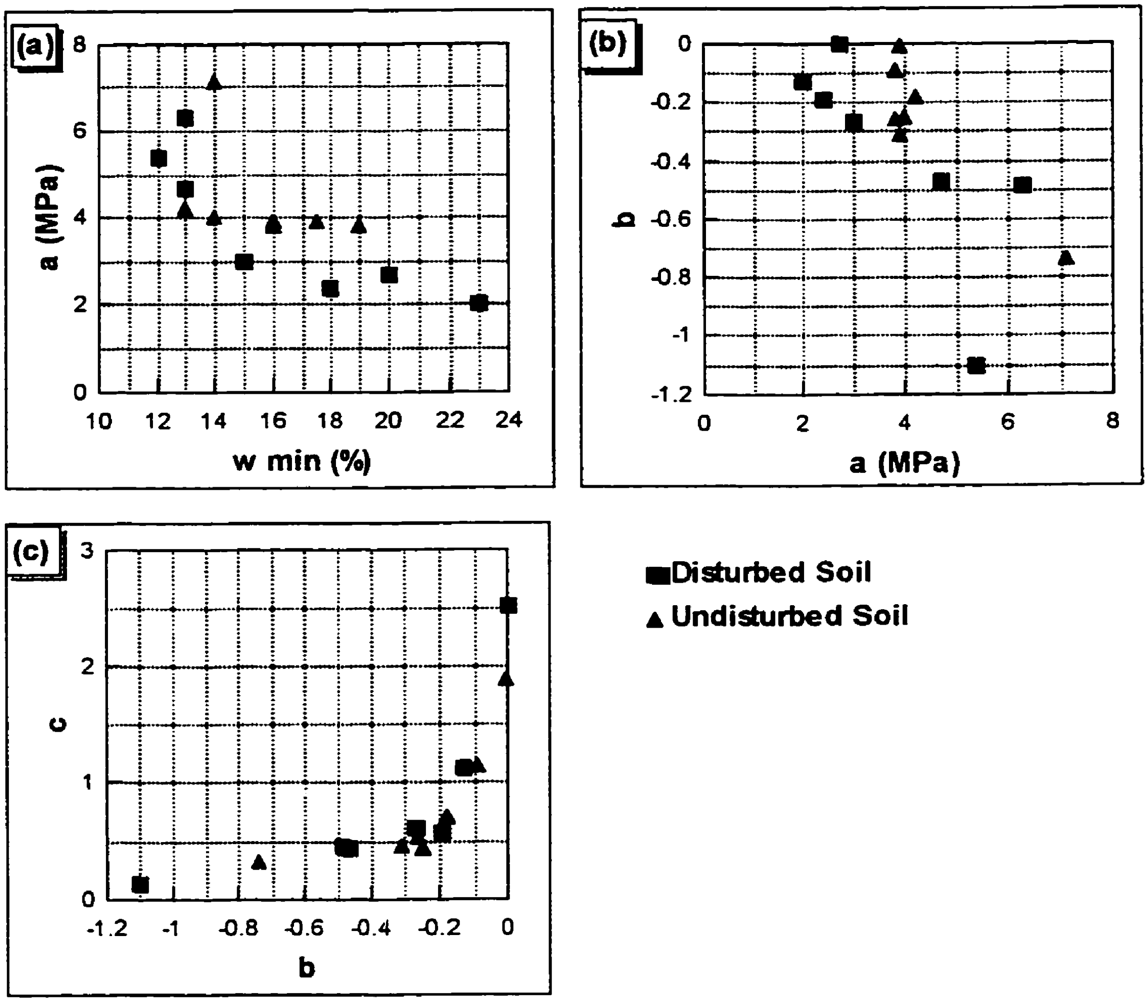


Figure 5.5 Curves describing the relationship between soil moisture and PR in undisturbed soil for different sites. a) 75 mm depth; b) 225 mm depth (225/375 mm in *RTN*).

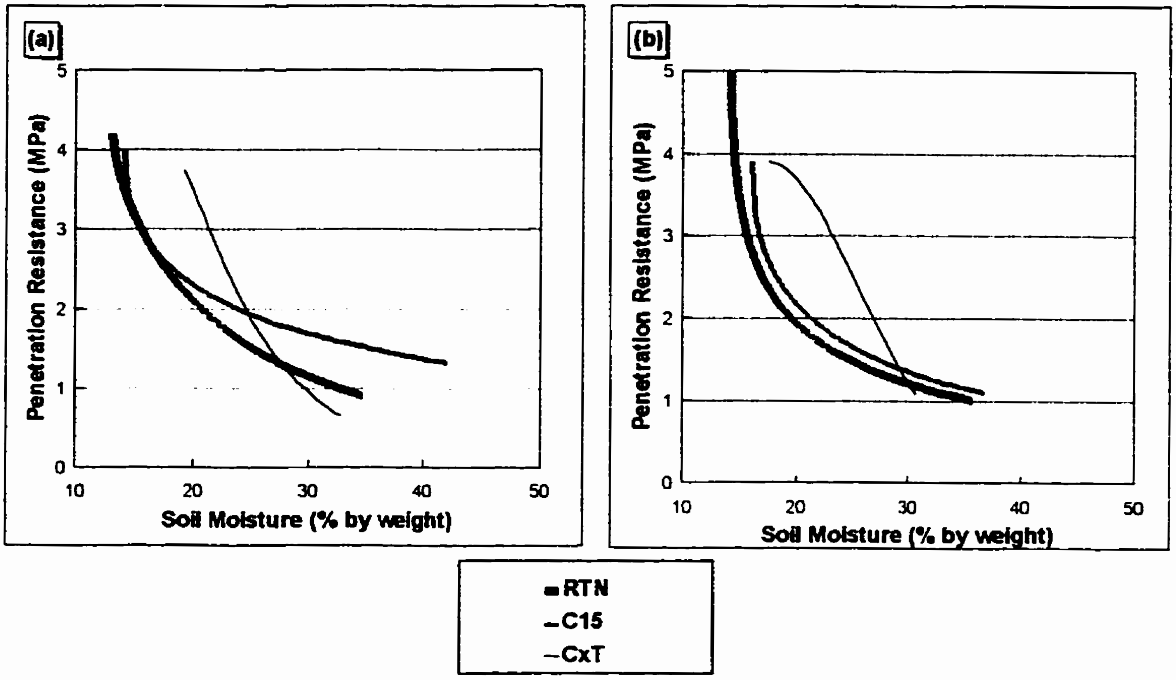


Table 5.5. Selected soil properties derived from the PR-soil moisture curves for each of the 14 models in this study.

Experiment	Treatment	Depth (mm)	w_{min} (%)	w (%) for P=2MPa	w (%) for P=1MPa	w_{max} (%)	dP/dw for w (P=2)
RTN	O. A	75	13	21	33	35	-0.15
RTN	O,A	225/375	14	20	36	36	-0.15
RTN	B,ABC	75	13	17	28	37	-0.19
RTN	B,ABC	225/375	13	20	31	37	-0.16
C15	Paraplow	75	18	19	32	43	-0.23
C15	Paraplow	225	15	17	25	39	-0.25
C15	Paraplow	375	12	13	35	37	-0.54
C15	Control	75	14	24	>42	42	-0.06
C15	Control	225	16	21	>37	37	-0.12
C15	Control	375	16	22	>30	30	-0.12
CxT	CT	75	23	23	27	37	-0.23
CxT	CT	225	20	26	30	35	-0.23
CxT	ZT	75	19	25	30	33	-0.26
CxT	ZT	225	18	26	31	31	-0.28

in Figs. 5.6, 5.7 and 5.8. In all three sites, when treatment means were used, linear regression analyses (Table 5.6) indicated that intercepts and slopes did not significantly differ from 0 and 1, respectively ($p<0.05$) with coefficients of determination higher than 0.69. When pairs of individual PR and soil moisture measurements were used, dispersion of points was generally higher, and in one case (*RTN*) the slope was significantly lower than 1. In both *RTN* and *C15* sites, in the region of wet soil, the models overpredicted at extremely high soil moisture contents (Figs. 5.6a and 5.7a). This problem was corrected by using treatment means instead of individual measurements.

The analysis of the interaction of bulk density on the relationship between soil moisture and PR did not reveal any particular effect. Pairs of data with high and low bulk densities seemed to fit in the same curves for each soil depth and treatment combination. In the 75-mm depth the higher PR's were associated with higher bulk densities, but both groups of data (high and low bulk densities) seemed to belong in the same general curves (Fig 5.9).

5.4. DISCUSSION

The model adequately described the relationship between w and P for the soil used in this study. This conclusion is supported by two pieces of evidence: 1) data fitness to model was always statistically significant, and b) the linear regression analyses of predicted on measured soil moisture content resulted in slope=1 and intercept=0 in the three sites.

Soil strength depends on soil water potential rather than on percent moisture by weight or volume (Williams and Shaykewich 1970). However, gravimetric soil moisture content is easier to measure in the field, and is proportional to water potential for a given soil type - tillage treatment - soil depth combination. Therefore, for developing empirical

Figure 5.6. Comparison between estimated and measured soil moisture content in experiment *RTN*. a) moisture values derived from individual PR measurements (n=649); b) moisture values calculated from treatment means (n=40), each mean being the average of 8 to 32 PR measurements.

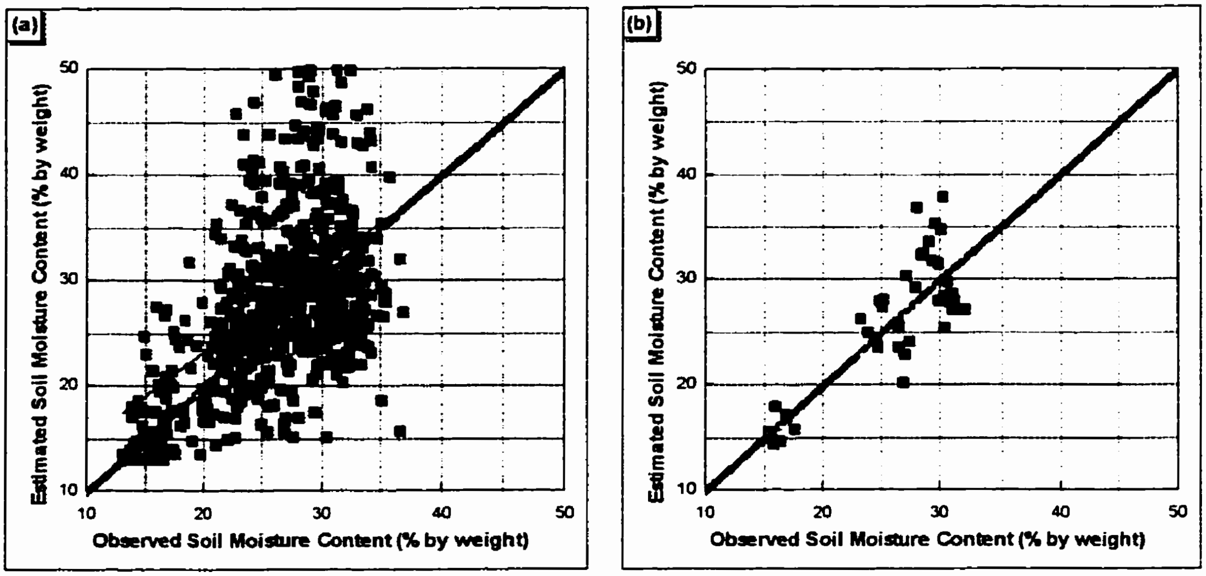


Figure 5.7. Comparison between estimated and measured soil moisture content in experiment *C15*. a) moisture values derived from individual PR measurements (n=300); b) moisture values calculated from treatment means (n=24), each mean being the average of 3 to 21 penetration resistance measurements.

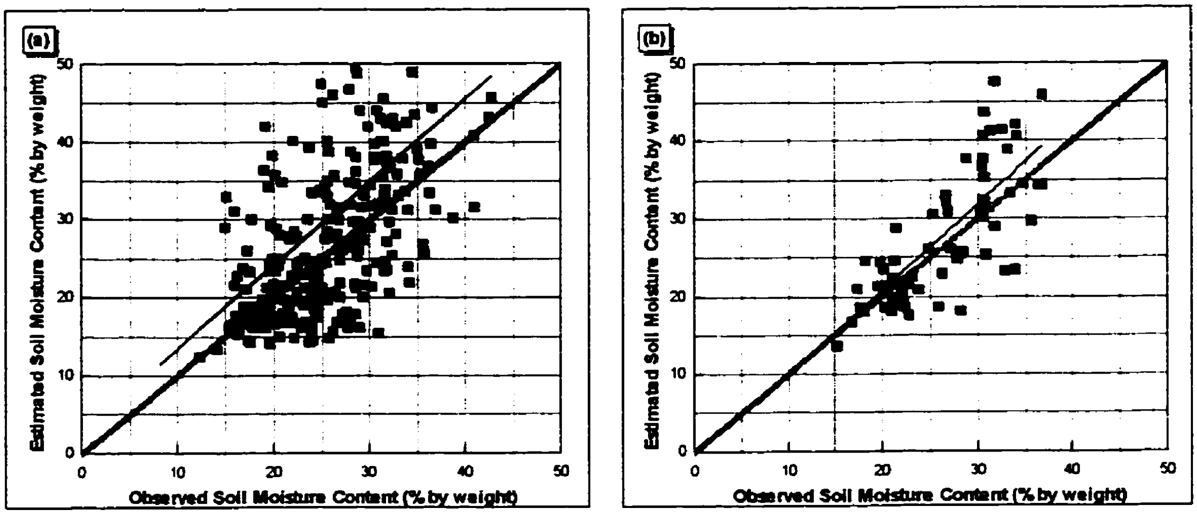


Figure 5.8. Comparison between estimated and measured soil moisture content in experiment CxT. a) moisture values derived from individual PR measurements (n=96); b) moisture values calculated from treatment means (n=24), each mean being the average of 2 to 5 penetration resistance measurements.

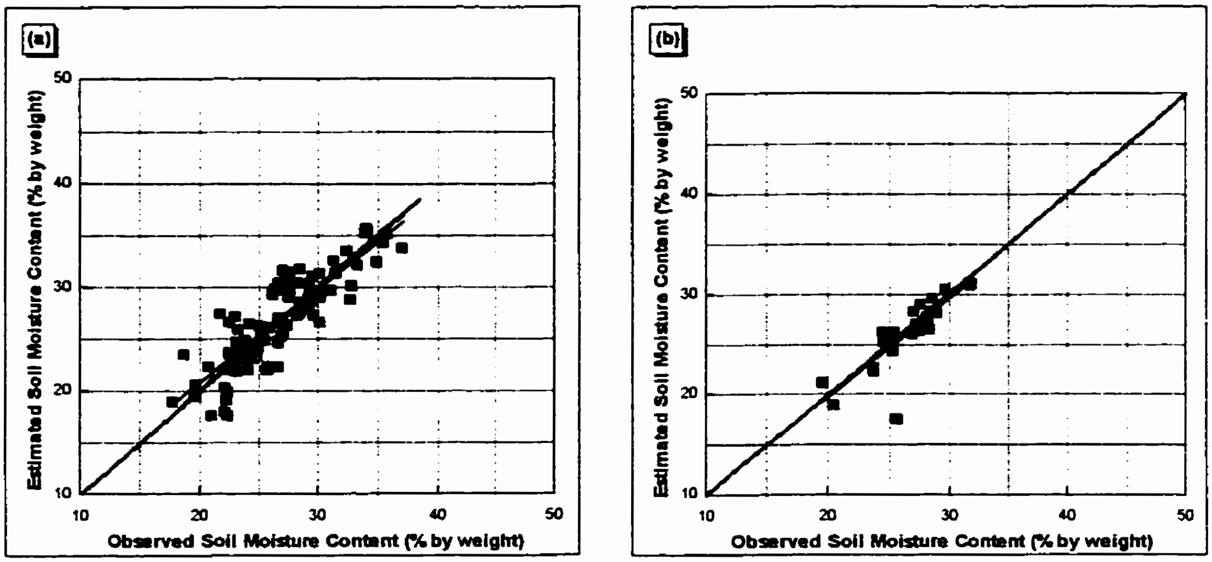
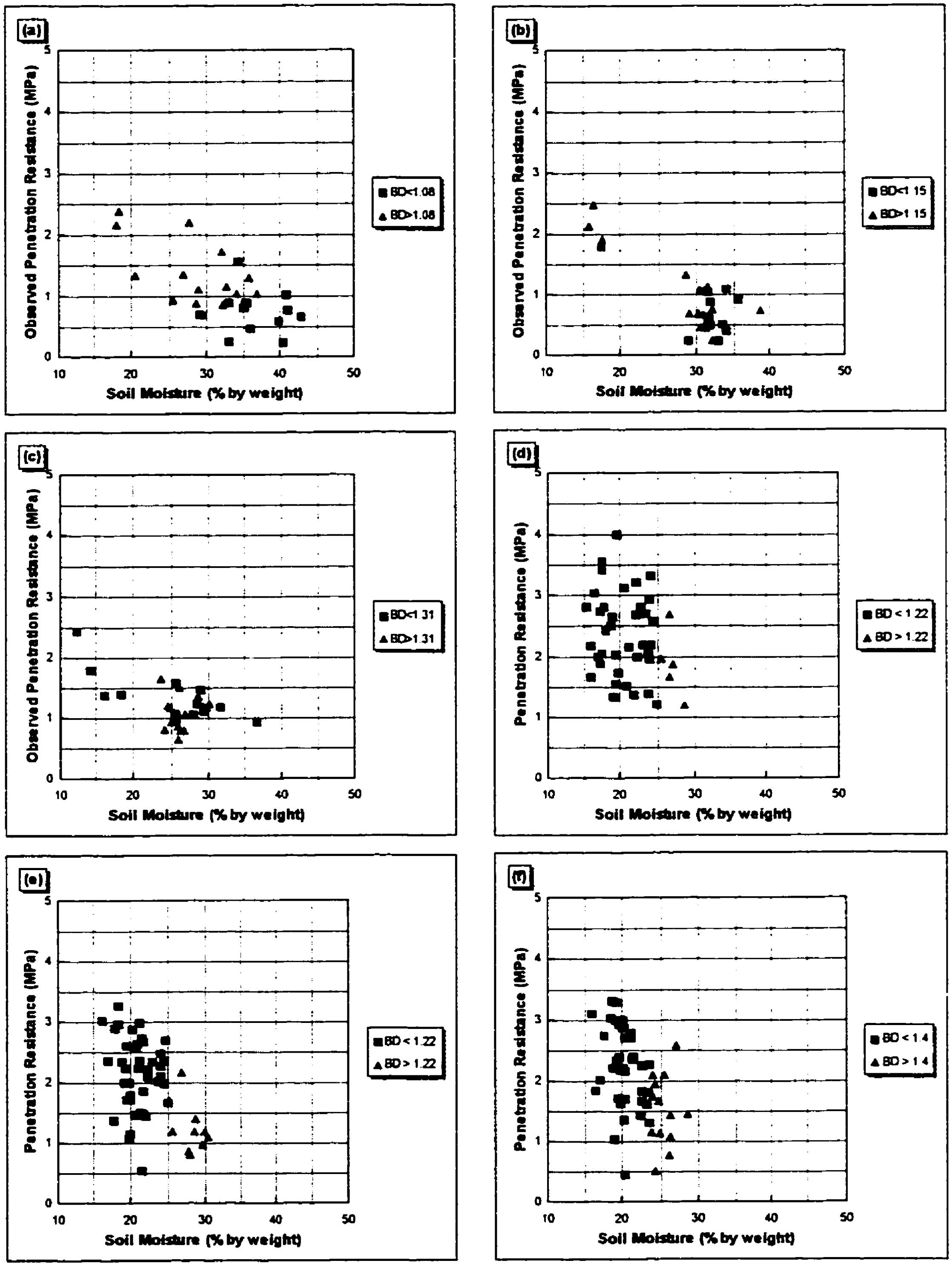


Table 5.6. Linear regression analysis of estimated on measured soil moisture contents for each site. Values in parentheses are standard errors.

Experiment	Data Used	n	Intercept	Slope	Standard Error of Estimate	r^2
RTN	Individual Pairs	649	7 (6)	0.82 (0.06)	8	0.23
RTN	Treatment Means	40	0 (3)	1.0 (0.1)	4	0.70
C15	Individual Pairs	300	3 (3)	1.1 (0.1)	14	0.17
C15	Treatment Means	24	-3 (3)	1.1 (0.1)	3	0.83
CxT	Individual Pairs	96	3 (2)	0.91 (0.06)	2	0.74
CxT	Treatment Means	24	0 (3)	1.0 (0.1)	2	0.69

Figure 5.9. Effect of soil bulk density (above and below median bulk density) on the relationship between PR and gravimetric soil moisture content for each combination of soil depth and subsoiling treatment in experiment *C15*: a) Paraplow, 75 mm; b) Paraplow, 225 mm; c) Paraplow, 375 mm; d) Control, 75 mm; e) Control, 225 mm; and f) Control, 375 mm.



relationships, gravimetric soil moisture can be conveniently used.

The relationship between soil moisture and PR has been described by various types of models, including linear (Gerard *et al.* 1982. Jayawardane and Blackwell 1991), inverse linear (Henderson *et al.* 1988), inverse quadratic (Ayers and Perumpral 1982) second-degree polynomial (Mirreh and Ketcheson 1972), and power (Mielke *et al.* 1994) functions. Most of them, with the exception of the inverse quadratic function, are not adequate to describe the relationship in the whole range of soil moisture contents observed in soils, which shows an increase in PR in the region of dry soil, followed by a sigmoidal decrease with increasing soil moisture.

As stated above, the fundamental property determining soil strength is water potential rather than percent moisture. The latter is usually expressed as a function of the logarithm of water potential (Gupta *et al.* 1989), and for this reason, the exponential function selected in our study would be more appropriate than the inverse quadratic model, which is purely empirical. The exponential function has the additional advantage over the inverse quadratic that the coefficients *a*, *b* and *c* can provide direct information about maximum PR, rate of decrease of PR with soil moisture in the dry-soil range, and magnitude of PR in the wet-soil range, respectively. One advantage of the inverse quadratic model is that, unlike the exponential, it describes the decrease in PR expected when soil moisture decreases below w_{min}. In the experiments reported here, such decrease was not observed.

One major drawback of the approach used here is that sampling dates were scattered in a time span of 10 weeks (*RTN* and CxT) to 7 months (*C15*). If soil consolidation occurred during the time it took to complete all measurements in one site, PR would have tended to increase with time. This may have occurred after soil disturbance either by conventional tillage or Paraplow. To avoid this problem, a shorter sampling period would have been desirable.

In the cases where the first measurements were performed in the wettest and the last in the driest soil condition (*RTN* and CxT), part of the increase in PR with decreasing moisture content could have been due to soil consolidation. The relatively high value of a in experiment *RTN* for Paraplow treatment at 75-mm depth could be evidence of this effect. In the *C15* site, where soil moisture content was variable along the sampling periods, consolidation would have caused increased random variability. The higher variability around the fitted curve for Paraplow treatment with respect to the control observed in Fig. 5.2 seems to support this point.

The relatively large dispersion of points around the fitted curves (Figs. 5.1, 5.2 and 5.3.) could have been due to a number of reasons besides the consolidation effect: a) gravimetric soil moisture contents measured in 15-cm-deep soil cores were paired with PR measured in 3-cm soil layers and this may have been a source or error where soil moisture content varied markedly within the soil core; b) gravimetric moisture content and PR were not taken exactly on the same soil spot, except for 7 and 14 Oct. 1992, and PR is known to be highly variable within short distances in space (Selim *et al.* 1987); c) heterogeneity induced by Paraplow or other factors, which may have caused spatial variability in soil structure; and d) at high moisture contents PR becomes relatively independent of soil moisture content, and therefore, variations of PR in this range may have not been associated with variations in percent water.

Considering all 14 situations represented in Figs. 5.1 to 5.3, dispersion of points around the estimated curves was lowest for tilled soil, which probably represented the most homogeneous soil condition. In general, deeper soil layers had less random variability than surface soil layers, very likely for the same reason (soil is more heterogeneous at depth than near the soil surface). Paraplowed treatments near the soil surface had the greatest variation in PR not explained by soil moisture status. This is in agreement with the fact that Paraplow induces a large degree of variability in soil structure.

The empirical coefficients *a*, *b* and *c* (Table 5.4 and Fig. 5.5) were sensitive to variations in site, tillage treatment, and soil depth. The fact that model coefficients varied markedly among sites, and to a lesser extent within sites, and considering that all three sites were on the same soil type, suggests that the relationship between soil moisture and PR may have been more affected by soil physical condition determined by factors other than tillage (e.g. previous land use). Thus, one could characterize the soil moisture-PR curve for a given site and use it for prediction purposes with certain degree of confidence, even if the soil condition is modified by tillage or any other means. However, the observation that the relationships between these coefficients varied according to soil disturbance (Fig.5.4), indicates that tillage effects, even being only minor, can also be detected by the soil moisture-PR curve.

The silty-clay-loam soil used in this study contains some expanding clay minerals and tends to shrink upon drying. For this reason, this soil is expected to show sharp increases in PR as soil gets drier. Soils with higher clay contents would show higher *a* values because of their high cohesion, and these high *a* values would be likely associated with steep decrease in PR with soil moisture, i.e., low *b* values. On the other hand, coaser textured soils would have lower *a* and high *b* values because of their low cohesiveness.

The models developed in the present study may be used to make inferences about the non-limiting water range (Letey 1985) for different soil layers and tillage treatments. PR levels above 1 MPa would restrict root growth into soil aggregates, and those above 2 MPa would completely stop it (Taylor *et al.* 1966, Martino and Shaykewich 1994). Soil moisture content when PR equals these critical levels can be used as an indicator of soil structural quality. At all three sites, undisturbed soil generally showed higher moisture contents at 1 and 2 MPa than disturbed soil, independent of soil depth (Table 5.5.) The rate of change in PR with soil moisture at PR=2 MPa, which indicates the ease with which the soil overcomes high mechanical impedance by wetting, was higher for Paraplow than control in *RTN* and *C15* sites, and higher for ZT than CT in CxT site. Maximum observed soil moisture content (w_{max}), which was generally higher for disturbed soil, can be taken as an indicator of water infiltration capacity, since rainfall was abundant in all three cases. The difference between w_{max} and soil moisture at PR=2 MPa would be a measure of the usable-water holding capacity.

The same data used for estimating the coefficients in the models were used for validation. Ideally, the models should have been evaluated by using other sets of data, but such data were not available. Validation showed that PR could be used to estimate soil moisture changes in the short term in the soil used in this study. It can be speculated that this conclusion could be extended to soils with large rates of change in PR with soil moisture, i.e., soils with high cohesion.

Further study is required to determine minimum number of replicates required for estimating soil moisture in a given soil; and to assess to what extent goodness of fit of the data could be improved by measuring both variables on the same soil spot, and at smaller depth intervals.

5.5 CONCLUSIONS

PR as a tool for determining soil compaction status or mechanical impedance for root growth, if measured without reference to soil moisture content, is meaningless. Variation in PR due to soil moisture is of much higher magnitude than that due to tillage treatments. The PR-soil moisture curve would be a more useful indicator of soil structure than a single determination of PR.

Cone PR could be used as an estimator of soil moisture content for the silty-clay loam of this study, provided a previous calibration for each soil layer is made, and that soil structure does not change significantly between the time of calibration and the time of measurement. A large number of replicates is necessary to achieve reasonable accuracy, particularly when the soil is in the high moisture content range.

6. OCCURRENCE AND CORRECTION OF AUTOCORRELATION ACROSS SOIL DEPTHS IN PENETRATION RESISTANCE MEASUREMENTS

ABSTRACT

Cone probes of static penetration have become standard instruments for measuring soil mechanical impedance to root growth and for detecting compacted soil layers. Penetrometers usually record resistance values at depth increments as low as 0.01 m. However, such fine resolution may be invalidated if autocorrelation across soil depths occurs. Several penetration resistance (PR) data sets from tillage experiments on a silty-clay loam in SW Uruguay were used to assess the extent of autocorrelation, and to correct measured values. PR data were fitted to linear models including experimental design effects, and a third-degree function of soil depth as covariable. Simple and multiple linear regression analyses of residuals at every soil depth on residuals at soil layers above, spaced every 15 mm, were used to recalculate residuals and estimate corrected PR's.

When considering all depths simultaneously, unidirectional autocorrelograms showed ranges of 90 to 180 mm. The deeper the soil layer considered, the greater was the distance over which the dependence of residuals extended. Multiple regression analyses identified significant effects of up to three lag distances (45 mm). Regression coefficients were highest when PR decreased with depth, independently of PR level. Two hypotheses, based respectively on variable speed of penetration and downward soil displacement, were formulated to account for this observation. The difference between corrected and measured PR's was generally low. It was concluded that PR data should be checked for autocorrelation whenever abrupt decreases in PR with depth are expected.

6.1 INTRODUCTION

Cone probes of static penetration have become standard instruments for measuring soil mechanical impedance to root growth and for detecting compacted soil layers. Available penetrometers are capable of recording resistance values at depth increments as small as 0.01 m, to a maximum depth of 1 m.

As a penetrometer is pushed down into the soil, the volume of the cone is accommodated by compressing the surrounding soil. The volume of soil subjected to deformation can be spherical, with radii up to ten times the probe radius, for blunt (included semiangle of 30°) probes (Farrell and Greacen 1966), or cylindrical for sharp (included semiangle of 5°) probes (Greacen *et al.* 1968). Because more pressure is required to form a compacted sphere than a cylinder, point resistance tends to be higher for blunt than for sharp probes (Bengough and Mullins 1991). The fundamental property one would like to determine is the point resistance. However, measured penetration resistance is the sum of point resistance, and a frictional component, the latter being higher for sharp probes due to a larger contact area between cone and soil.

Blunt cones compact the soil in the path of the probe, creating a body of soil that moves ahead of the probe, thus artificially increasing the frictional resistance offered by the soil at the depths below. To minimize both soil-metal and soil-soil frictional interferences, cones of medium included semi angles are of widespread use. Koolen and Vaandrager (1984) and Voorhees *et al.* (1975) have found that lowest cone resistance occurs at semi angles between 15° and 20°.

The speed at which the cone probe is introduced into the soil is another factor affecting the measured resistance, since soil compression is a time-dependent process. Slowly moving probes would allow the soil particles being stressed to rearrange and transmit the pressure to particles located further away. Thus, one expects a more representative measurement with slow than with fast penetration. Also, the probe causes tensile failure, which relieves stress at 'the tip, and this is also time-dependent. Waldron and Constantin (1970) and Voorhees *et al.* (1975) demonstrated this effect of speed for slowly moving (less than 1 mm/min), fine probes. Bradford *et al.* (1971) concluded that the effect was negligible when fine probes were driven into the soil at speeds higher than 1 mm/min. Freitag (1968) demonstrated that penetration speed increased cone resistance in fine-grained soils.

Cone penetration resistance at a given depth is not independent of that at nearby depths. This autocorrelation effect has been shown to occur by O'Sullivan *et al.* (1987) and Christensen *et al.* (1989), and may be associated with the ways in which penetrometers deform the soil and the effect of varying speed of penetration, as discussed above. The occurrence of autocorrelation may affect the accuracy of measurements taken at short depth increments.

Soil penetration resistance measurements were performed at various times in tillage experiments carried out on a silty-clay-loam Mollisol of SW Uruguay. Several sets of these determinations, taken in a wide range of soil moisture conditions, were used to assess the extent of autocorrelation across depths, and to correct observed PR values. The results of this study are presented in this paper.

6.2 MATERIALS AND METHODS

Several experiments were conducted during the period 1991-93 on a silty-clay loam (fine, mixed, superactive, thermic Oxyaquic Argiudoll, or 'Brunosol éutrico típico' in the Uruguayan classification) in SW Uruguay (INIA La Estanzuela Experimental Station), to study effects of soil compaction on crop productivity under zero tillage. Three of these experiments (named as *RTN*, *C14* and CxT) were selected for the present study. The experiments were physically near one another on the same soil type. Selected soil properties for these sites are shown in Table A1.

6.2.1 Experiment Description and Field Operations

The experiments *RTN* and *C14* and field operations performed on them were described in Chapter 3. Experiment *CxT* was described in Chapter 5.

6.2.2 Penetration Resistance Determinations

Penetration resistance (PR) was measured by using a Rimik CP10 hand-held recording cone penetrometer. The cone used had an included semiangle of 15° and a base diameter of 12.8 mm. PR was recorded up to 450 mm depth in 15-mm increments. Rate of penetration was about 10 mm s^{-1}. The number of replicates varied among sampling dates, but was usually between two and four per plot. In Paraplow experiments, half the measurements were taken on the hilltops, and half on the depressions associated with Paraplow passes. In the CxT experiment, determinations were randomly distributed within main plots. Eleven sets of PR data were used in the present study, from each of the following sampling dates: 27 July, 17 Aug., 17 Sept., and 14 Oct., 1992, and 28 June 1993 (*RTN* experiment); 17, 21, and 24 July, 4 Aug., and 7 Oct. 1992 (CxT experiment); and 24 June 1993 (*C14* experiment).

6.2.3 Autocorrelation Test and Correction of Data

PR data were tested for autocorrelation across depths by using the procedure described by Christensen *et al.* (1989). This procedure was modified in that the effect of the covariable (depth) was assumed to be curvilinear rather than linear. The procedure for data analysis was as follows: 1) An analysis of variance of PR was performed. Sources of variance were: Paraplow treatment, current and preceding crops, and replications (*RTN* and *C14* experiments); tillage treatment, crop, cultivars and replications (*CxT* experiment). A third-degree polynomial equation was included in the models to account for the covariable (depth) effect, instead of the linear term used by the authors mentioned above. This modification was based on the observation that PR was a curvilinear rather than linear function of depth, usually with one or more inflection points. 2) Residuals (i.e., the difference between observed PR values and those estimated by the model used) from the analysis of variance were calculated. 3) Simple and multiple regression analyses of residuals at a reference depth on residuals at depths above separated by different lag distances were performed. Data were fitted to the following four models: a) residuals at reference depth on residuals at a distance of 15 mm (lag 1); b) residuals at reference depth on residuals at distances of 15 and 30 mm (lags 1 and 2, respectively); c) residuals at reference depth on residuals at distances of 15, 30 and 45 mm (lags 1, 2 and 3, respectively); and d) residuals at reference depth on residuals at distances of 15, 30, 45 and 60 mm (lags 1, 2, 3 and 4, respectively). 4) Residuals were recalculated based on the regression equations obtained in step 3), provided they significantly fitted the observed data ($p<0.05$): residuals at the top soil layer (15 mm) remained unchanged; residuals at 30 mm depth were estimated by model a); residuals at 45 mm were calculated by using model b); those at depths 60 mm and below were estimated by model c), since lag 4 never showed any significant effects. 5) PR data were corrected by adding recalculated residuals to each measured PR value.

Two data sets (27 July and 14 Oct. 1992) were used to study the influence of the depth being considered on the extent of autocorrelation. The selection was based on the fact that they represented extreme values in mean PR.

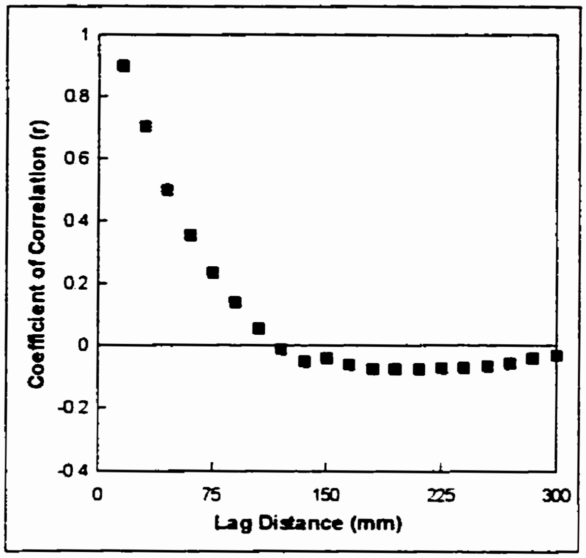
6.3 RESULTS

Autocorrelation was detected in all data sets. When all depths were considered simultaneously, linear correlation coefficients between residuals were positive and significant ($p<0.05$) up to lags 6 to 12 (90 to 180 mm), depending on the sampling date. The autocorrelograms for the 27 July 1992 and 14 Oct. 1992 data sets are shown as examples in Fig. 6.1. In these cases measurements taken at a given point were positively correlated with those within a soil layer 90 and 120 mm thick, respectively, located directly above. Each point in the autocorrelogram in Fig. 6.1 a was estimated from 1,280 to 3,710 pairs of residuals, depending upon the lag distance. The distribution of these individual points is represented in Fig. 6.2 for lags 1 to 4. Results were very similar for all other sampling dates (not shown).

The extent of autocorrelation varied with soil depth. Near the soil surface ranges extended for 60 mm or less, while at the deepest layers, ranges up to 255 mm were recorded. The correlation coefficients increased with depth for all lag distances (Fig.6.3). However, this increase was small for lag 1 (15 mm), which had a very large effect in all soil depths.

Multiple regression analyses showed significant effects of lags 1, 2 and 3 in 10 out of 11 data sets (Table 6.1), and of lags 1 and 2 in the remaining (14 Oct. 1992) data set. Lags 4 and over did not add significant improvements to the three-variable model. With only one

Figure 6.1 Autocorrelograms of PR across soil depths. a) 27 July 1992; values of r higher than 0.06 are significant at the 95% level of probability. b) 14 Oct. 1992; values of r higher than 0.05 (lag 1) or 0.11 (lag 20) are significant at the 95% level of probability.



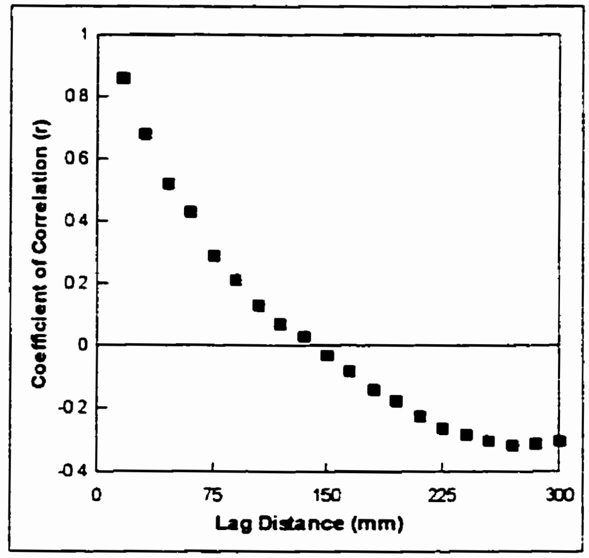


Figure 6.2 Relationship between PR residuals at the depth of reference with residuals at different soil layers above, for the 27 July 1992 data set.

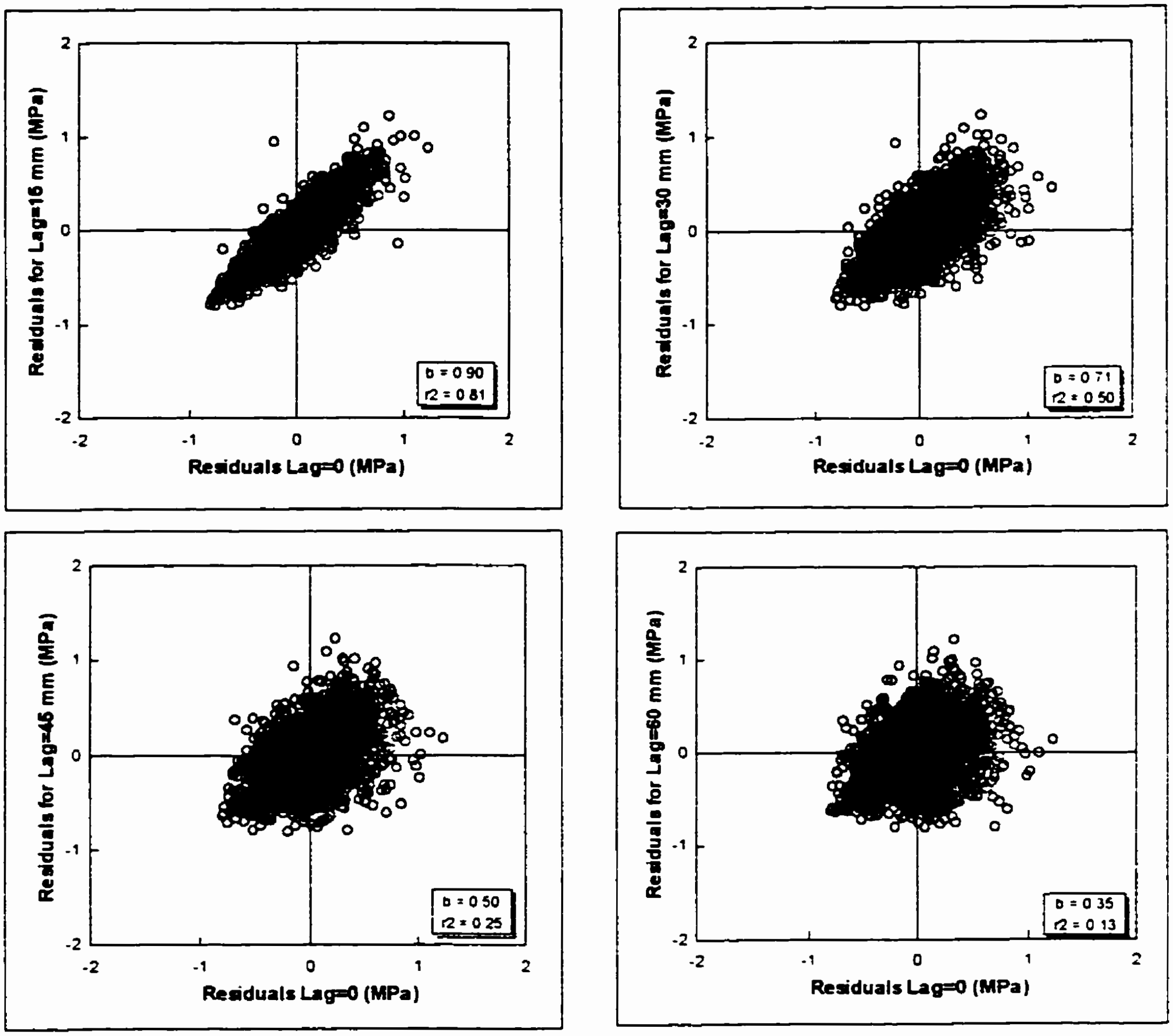


Figure 6.3 Effect of soil depth on the extent of autocorrelation of PR residuals. a) 27 July 1992. b) 14 Oct. 1992. Arrows indicate values of r at the 95% level of probability.

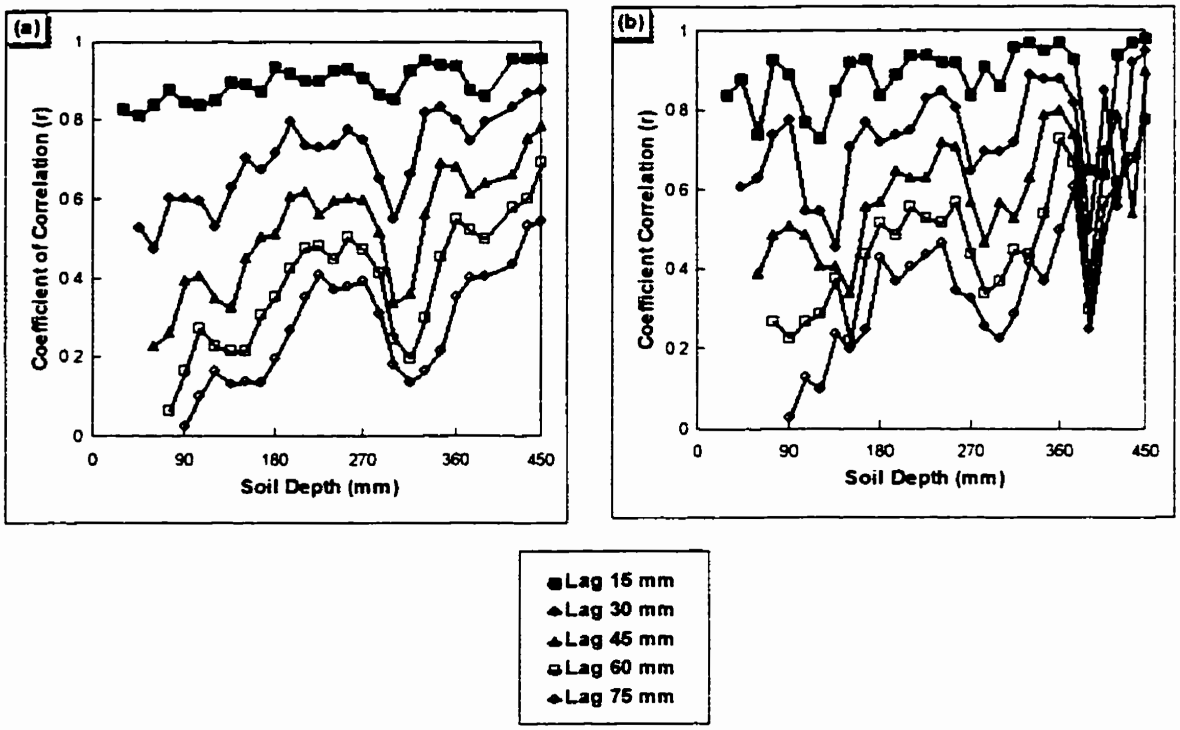


Table 6.1 Multiple regression analyses of PR residuals at a reference depth on residuals at depths above separated by 15, 30, and 45 mm (lags 1, 2 and 3, respectively).

Date	Site	PR mean	n	Regression Coefficients			Intercept	R^2
		MPa		Lag 1	Lag 2	Lag 3	kPa	
27 July 1992	*RTN*	1.05	3456	1.46 (0.02)†	-0.74 (0.03)	0.16 (0.02)	ns‡	0.9
17 Aug. 1992	*RTN*	1.14	3456	1.27 (0.02)	-0.49 (0.02)	0.05 (0.01)	-6	0.9
17 Sept.1992	*RTN*	1.45	2565	1.45 (0.02)	-0.72 (0.03)	0.16 (0.02)	ns	0.9
14 Oct. 1992	*RTN*	2.8	1154	1.04 (0.03)	-0.20 (0.04)	ns	ns	0.8
28 June 1993	*RTN*	1	6048	1.28 (0.01)	-0.52 (0.02)	0.09 (0.01)	ns	0.8
17 July 1992	CxT	0.99	1998	1.16 (0.02)	-0.36 (0.03)	0.05 (0.02)	ns	0.8
21 July 1992	CxT	0.99	1620	1.52 (0.02)	-0.83 (0.04)	0.22 (0.02)	ns	0.9
24 July 1992	CxT	1.11	1296	1.34 (0.03)	-0.57 (0.04)	0.10 (0.02)	ns	0.9
4 Aug. 1992	CxT	1.23	1296	1.49 (0.03)	-0.83 (0.04)	0.20 (0.02)	ns	0.9
7 Oct. 1992	CxT	2.1	972	1.55 (0.03)	-0.52 (0.05)	0.21 (0.02)	ns	0.9
24 June 1993	*C14*	1.01	4320	1.33 (0.01)	-0.59 (0.02)	0.16 (0.01)	ns	0.9

† Values in parentheses are standard errors
‡ Not significant ($p<0.05$)

exception (17 Aug. 1992), the intercepts were not different from zero ($p<0.05$). The number of pairs of residuals involved in each analysis depended on the data set, and ranged from 972 to 6,048. The models obtained explained between 77 and 93% of the variability in residuals at the depth of reference (lag 0), and were all highly significant ($p<0.01$). The 11 data sets represented a wide range of situations, with penetration resistance means varying between 0.99 and 2.80 MPa. The coefficients of regression varied significantly ($p<0.05$) among data sets. This variation was not dependent upon PR level. The negative values of coefficients for lag 2 do not appear to have any physical meaning, but they are only an artifact of the multiple regression calculation.

Analysis of individual soil depths (Fig.6.4) showed that there was a relation between the regression coefficient of residuals for lag 1 and the rate of change of PR with depth. Low regression coefficients for lag 1 (about 0.5) were associated with large increases (>30 $kPa.mm^{-1}$) of PR with depth. Conversely, high regression coefficients were obtained when PR decreased with depth. The lag-1 regression coefficient was very sensitive to rate of change in PR when PR increments were negative. When PR decreased with depth, residuals at the soil layer below tended to be higher than at the depth above (regression coefficient >1). When PR increased with depth, residuals decreased with depth (regression coefficient <1). When PR did not change from one soil layer to the one below, regression coefficient was approximately 0.9.

Analysis of variance of corrected PR showed lower coefficients of variation than that of measured PR for all data sets. The difference between measured and corrected experiment means was not very large (Fig. 6.5). The effect of correction was important for certain treatments and sampling dates, and negligible for others (Fig. 6.6).

Figure 6.4 Effect of rate of change in PR with depth on simple linear regression coefficient for lag 1 (15mm). The graph includes 29 pairs of soil depths in each of the 11 data sets.

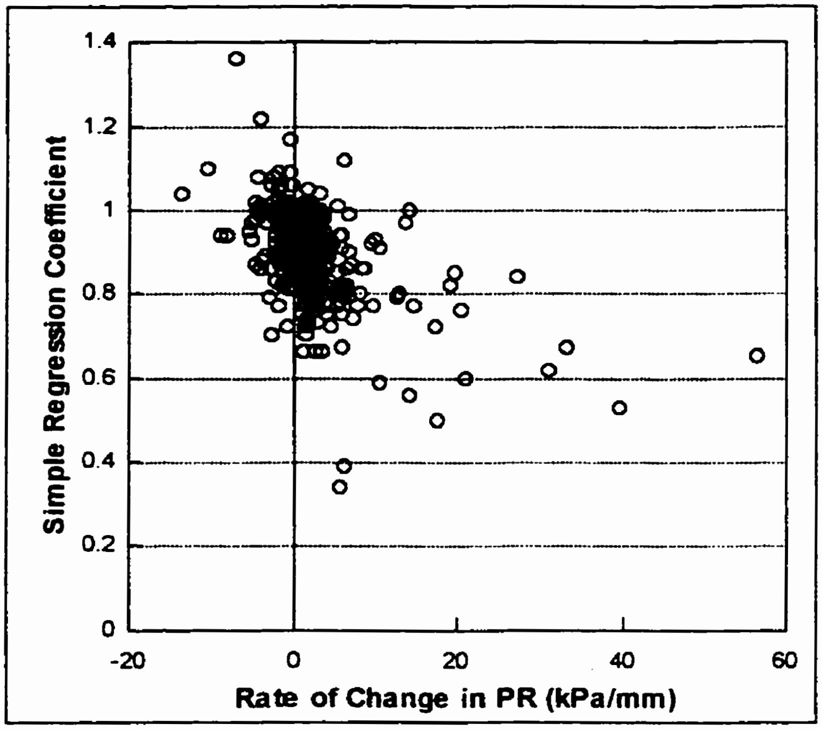


Figure 6.5 Effect of correction for autocorrelation on experimental means of two data sets.

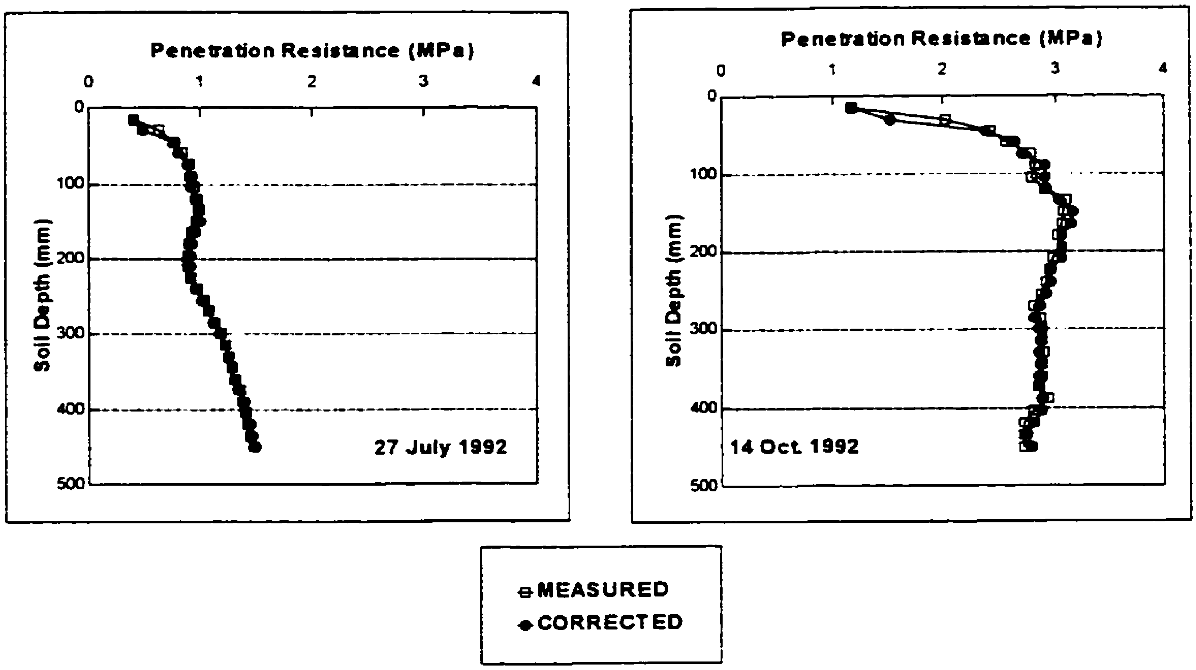
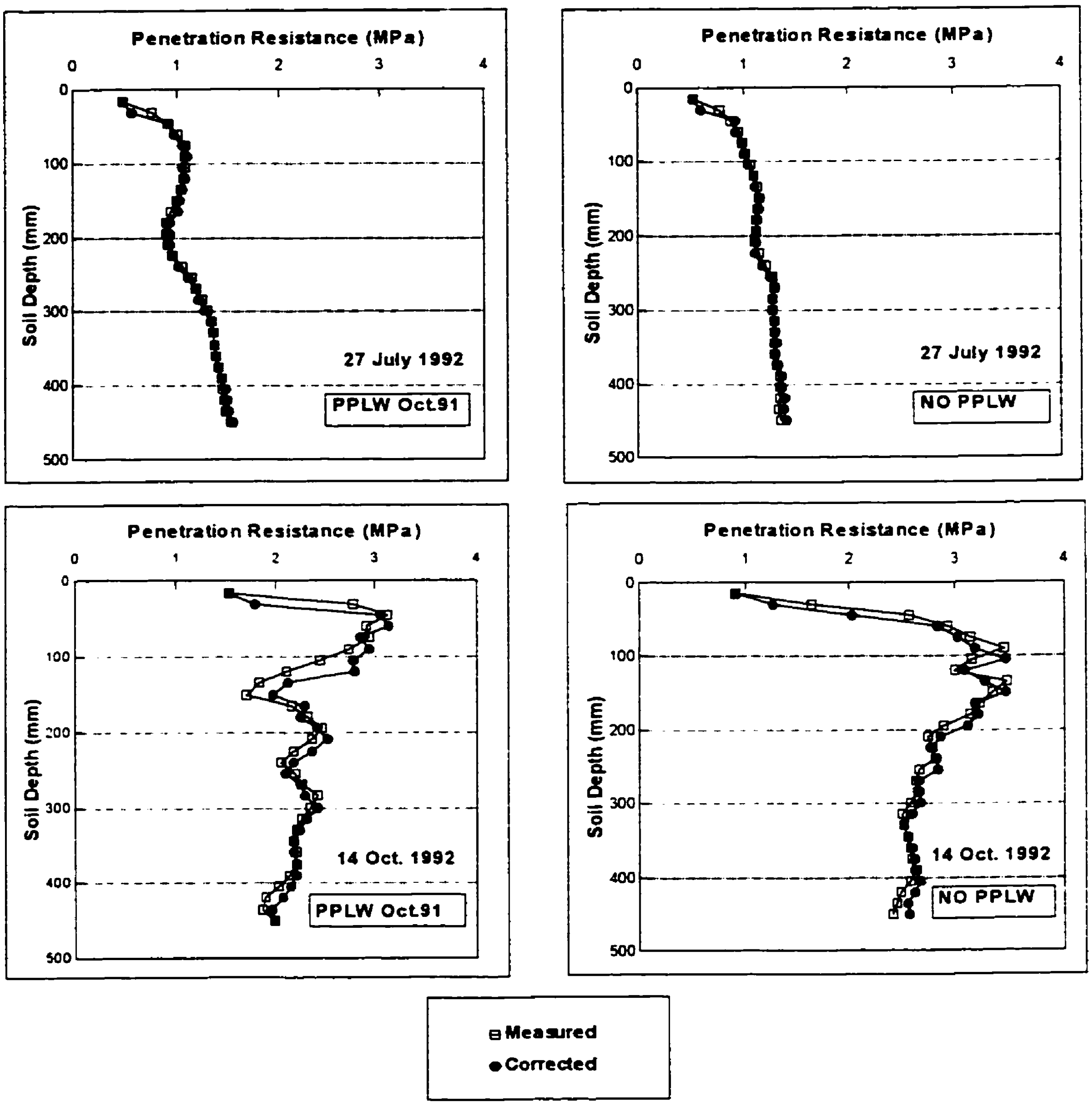


Figure 6.6 Effect of correction for autocorrelation for selected treatments of two data sets



6.4. DISCUSSION

A cubic model was selected to account for the covariable effect, instead of the linear model proposed by Christensen *et al.* (1989). This means that the curve representing the effect of depth on PR has one inflection point. Had the linear model been used, the estimated function would have smoothed out some parts of the PR profile. In that case, residuals would have shown autocorrelation mainly because PR estimated by the model departs from actual PR in entire regions of the soil profile. The use of a cubic model does not ensure complete elimination of this problem, but is undoubtedly a better approximation.

In cases in which there are two or more inflection points, a higher-order polynomial would provide a more accurate correction. A fourth-degree polynomial was tested with the 27 July 1992 data set, and it was found that corrected PR values did not differ from those estimated from the third-degree function (not shown). Therefore, it was concluded that the use of the third-degree polynomial was a reasonable choice.

There are several possible reasons for the observed occurrence of autocorrelation in soil penetration resistance measurements. One would be related to rate of penetration, which can not be maintained constant if the penetrometer is manually operated. If during probe penetration the cone tip finds a hard soil layer, it tends to slow down, and this may cause the device to register PR values lower than at the intended speed (Freitag 1968), and the operator to increase the force applied on the penetrometer. This increased force would cause the penetrometer to speed up, particularly if it encounters a low-resistance spot. The fact that highest autocorrelation coefficients were found where PR decreased with depth (Fig. 6.4) seems to support this explanation.

The second factor involved is associated with downward soil displacement by the penetrometer tip. When a metal cone with an included semi-angle of 15° is pushed down into the soil, it displaces soil mainly by cylindrical expansion, although some spherical soil compression may also be involved (Greacen *et al.* 1968 Farrell and Greacen 1966). If the cone finds a high-resistance soil layer, which would usually be associated with a high soil density, it would displace a large mass of soil, causing the device to overestimate resistance at some distance below, particularly if the soil layer below is highly compressible. The extent of the volume of soil subjected to deformation or plastic failure depends upon the compressibility of the soil layer, which in turn depends upon the basic strength properties, i.e. cohesiveness and angle of internal friction. This effect of downward soil mobilization would have also been accentuated wherever PR decreased with depth, because in these cases, the cone moved to soil layers of higher compressibility, usually the result of higher moisture content.

Besides variable penetration speed and downward soil displacement, another possible cause of autocorrelation is spatial proximity. PR has been reported to be autocorrelated in space, with ranges of up to 1 m (O'Sullivan *et al.* 1987, Perfect *et al.* 1990), owing to the fact that measurements taken at close distances are more likely to be similar than those taken far apart. This component of autocorrelation would not be related with the rate of change in PR with depth and therefore would have not been associated with the effect observed in Fig. 6.4 However, the fact that Fig. 6.4 shows an asymptote of approximately 0.5 reveals that some other factors besides those related with rate of change of PR with depth contributed to autocorrelation, and spatial proximity may well have been one of them.

The analyses by O'Sullivan *et al.* (1987) and Christensen *et al.* (1989) did not determine the spatial extent of autocorrelation nor the effect of soil depth. In the work presented here, PR at a reference depth was found to be dependent on that at soil layers located up to 180 mm above (Fig. 6.1). This dependence was very large at short ranges, with coefficients of determination for lag 1 ranging between 0.75 and 0.90, and decreased very rapidly with distance. For this reason, sequential multiple regression analyses only detected significant contribution to the model up to a distance of 45 mm (Table 6.1). For practical purposes, it can be concluded that measurements separated by more than 50 mm were independent of each other.

Correction of residuals was based on a single model per data set, obtained by pooling all soil depths. Based on results presented in Fig. 6.3, it could have been argued that a different model should have been used for every depth. However, since regression coefficient for lag 1 did not change much with soil depth, and most of the variability of residuals was explained by variation in residuals at this lag distance, it can be concluded that results obtained would not have been much different. Also, the use of a different model for each depth would have been tedious and less accurate, since the number of pairs would have been reduced by a factor of 29.

Corrected PR values were generally very similar to those measured. Effect of correction was significant only in a few cases, particularly where PR was high near the soil surface and decreased markedly with depth (Fig. 6.6).

6.5. CONCLUSIONS

PR measurements taken at a certain soil depth depended on PR values at depths above. The range of dependence extended for up to 180 mm, but the soil layer within 45 mm was responsible for more than 77% of the influence.

Autocorrelation was particularly important wherever measured PR decreased with depth. Two hypotheses, based respectively on variable speed of penetration and downward soil displacement, were formulated to account for this observation.

Correction for autocorrelation was treatment-selective, and in most cases did not modify substantially measured PR values. The latter could safely be used in most cases in the fine-grained soils used in this study with depth increments of 15 mm or more. In cases where high PR values near the soil surface are associated with lower subsurface PR correction for autocorrelation may be required.

7. SUMMARY AND CONCLUSIONS

The particular combination of soil type, climate and system of production under which agriculture is developed in Uruguay impose restrictions for the adequate development of crops with direct seeding. These restrictions occurred at least during the transition from systems based on soil tillage.

Because of their high clay contents, particularly below 20-cm depth, soils in Uruguay are very cohesive when dry, and thus impose high mechanical impedance to the growth of roots. Under high soil moisture conditions, the slow flow of gases into soil causes frequent oxygen deficiency for roots, chiefly during the winter season, when rainfall is higher than potential evapotranspiration. These soils have also a reduced water infiltration capacity, which is a critical property considering that 43 % of the precipitation in Uruguay falls in rain events higher than 30 mm day^{-1}.

All of these problems are aggravated by the soil compaction caused by grazing and machinery traffic, especially on wet soil. Tillage produces a transient alleviation of these constraints, and if soil structure is seriously degraded, it might be the only alternative to achieve acceptable crop yields.

Technologies other than conventional tillage are needed to avoid the problem or speed up the long-term process of soil structure build up under zero tillage. Two of these technologies, soil loosening by Paraplow and sequence of crops, were addressed in this thesis (Chapters 3 and 4).

The adaptation and development of analytical methods for describing soil structure was another objective of this thesis. Two aspects of the use of cone penetrometers of static penetration, the occurrence of autocorrelation across soil depths, and the relationship of PR with soil moisture content, were studied (Chapters 5 and 6).

7.1. ANALYTICAL METHODS FOR SOIL STRUCTURE

Numerous methods and techniques are available for describing different aspects of soil structure. According to Letey (1991) the definition of soil structure should include not only descriptive, but also functional parameters. This author stressed the need for establishing more quantitative relationships between soil physical properties and their functions of supporting roots and storing and transmitting energy, gases and water. These relationships could be based on the concept of 'non-limiting water range' that the same author had proposed before (Letey 1985). This concept has been recently redefined by da Silva and Kay (1996) as the 'least-limiting water range' (LLWR), and shows interesting prospects as a valuable indicator of soil quality for crop growth.

The determination of LLWR for a given soil requires, among other inputs, a measure of the effect of soil moisture on PR. The results presented in Chapter 5 indicated that this relationship between soil moisture and PR was affected by soil management practices, such as conventional tillage or subsoiling, as well as by the soil depth considered. The empirical coefficient *b*, which describes the rate of change of PR with moisture at low moisture contents, varied between -0.003 and -1.10 among the 14 situations analysed (Table 5.4). High *b* values correspond to soils that do not develop high mechanical impedance upon drying, and are desirable. The lower limit of available water, defined as the soil moisture content at which PR equals 2 MPa, was also shown to vary widely with tillage practices (Table 5.5).

A potential use of the soil moisture-PR curve is to estimate short-term variations in soil moisture content with fine depth resolution (10 mm), by means of a penetrometer, which is more convenient to use than most instruments designed for measuring soil water. Short-term variations in PR, such as those observed in Fig. 3.1a, would have reflected variations in soil moisture due to absorption by roots. The data presented in Chapter 5, however, showed that due to large dispersion of points around the fitted curves, particularly in wet soil, this use of PR would be limited. More work is needed on sampling methods to assess more fully the possibilities of this technique.

The cone penetrometer was a central instrument in this study. One uncertainty that arose when analysing PR data was on the independence of measurements taken at close depth intervals (15 mm) in a single penetration. The occurrence of autocorrelation in PR determinations had been reported previously (Christensen *et al.* 1989), but no information was available on the extent of this effect. The analysis presented in Chapter 6 demonstrated that PR measured at a certain soil depth was affected by PR values in soil layers located up to 180 mm above. However, 77 % of this effect was restricted to a distance of 45 mm. A major contribution of this analysis was to demonstrate that the occurrence of autocorrelation was associated with soil layers where PR decreased with depth. This would be the situation where the soil surface is drier than the subsoil, and it was concluded that correction of PR by autocorrelation effect would be necessary only in these conditions.

7.2. PARAPLOW

Paraplowing induced yield increases that were very large compared with reports in the literature. This corroborates the hypothesis that soil physical condition seriously impairs crop productivity under direct drilling in the soils of SW Uruguay, at least during the transition from conventional to zero tillage systems. Grain yields obtained with the use of Paraplow were similar to those normally obtained with conventional tillage.

The benefits of the Paraplow observed in the experiments reported here can be summarized as follows:

A) There was an increase in crop emergence of corn, barley and wheat, and no effect on sunflower. This was mainly due to avoidance of waterlogging and increased soil temperature. In some cases, a closer seed-soil contact may also have been a factor.

B) Roots grew faster and deeper, and explored the soil more fully. This was the consequence of a reduction in soil penetration resistance, particularly at low moisture contents in the soil layer between 20 and 30 cm depth; improved water infiltration that allowed an increased root proliferation; and higher flow of oxygen into the subsoil, which allowed a faster penetration of wheat and barley roots into the soil.

C) Soil surface desiccation right after passing the Paraplow allowed for a better control of weeds such as bermudagrass, which seriously affected corn yields without Paraplow in two experiments.

D) In wheat and barley crops there was higher tiller survival and reduced floret abortion, which resulted in higher numbers of grains per unit area.

The effects of paraplowing on soil physical properties rapidly declined with time after subsoiling, but lasted for up to 25 months. Effects on crop productivity had similar residuality. The additional yield advantage of passing the Paraplow before each crop, compared with one pass in two years was very small compared to the extra energy cost involved. Cumulative crop productivity in two years was increased by 25-53 % by one subsoiling operation. Growers would take maximum advantage by using the Paraplow on alternate years.

7.3. CROP SEQUENCE

The first crop in the rotation had an influence on the behaviour of subsequent crops. This was partly attributed to well-known effects determined by the nature of the residues left by the different crops, which modified the energy balance at the soil surface, and interfered with seeding machinery.

The crop sequences that had sunflower as the first crop somehow resulted in reduced infiltration capacity of the soil in the subsequent cropping seasons, as compared with rotations that started with corn (Chapter 3). This was reflected by a 4 % reduction in wheat and barley grain yields, mainly due to lower kernel weight (Chapter 4). The effects of crop sequence were particularly strong in Paraplow treatments. These results raise the question of what effects contrasting root types have on the structure of unplowed soils. The evidence from this study would support the hypothesis that plants with fibrous roots such as corn, would be more beneficial to soil than species with tap roots.

Wheat tolerated adverse soil physical conditions better than barley. When subjected to high compaction early in the season, wheat plants responded by limiting root development, whereas barley roots were unaffected. In more advanced crop stages, wheat tended to produce more nodal roots than barley in response to a stressful situation, such as low oxygen availability in soil. As a result, grain yields of wheat were less affected by soil compaction than those of barley. It was concluded that wheat is a more suitable crop than barley to grow during the transition from CT to ZT.

8. FUTURE RESEARCH NEEDS

It was demonstrated in this study that wheat would be more tolerant to soil compaction imposed by zero-tillage than barley. More comprehensive studies are needed to determine the intra- and inter-specific variability in this tolerance. Masle (1992) already demonstrated that there is variability both in wheat and barley in their tolerance to soil compaction. This opens up the opportunity for developing plant breeding strategies to obtaining cultivars suitable for conditions where soil compaction is expected to be a problem. In addition, information on the behaviour of different crop species would allow the development of crop sequences that minimize yield losses caused by adverse soil structure in direct-seeding systems.

The ability of certain species to perform biological tillage should also be considered as a potentially useful tool to select the most suitable crops to grow in a rotation. Studies should be conducted to identify species and cultivars capable of creating root channels in compacted soils. In the same sense, more knowledge is needed on the manipulation of soil organisms, such as earthworms, to improve our capacity to use them as agents of soil structure buildup.

The creation of these biopores has been repeatedly mentioned as a mechanism which is very positive for root and crop development in soils that remain unplowed for a long time. However, there are some doubts on their efficacy, in light of recent research findings that showed poor root growth in large biopores (Stirzaker *et al.* 1996) related with poor root-soil contact, and difficulty in penetrating biopore walls.

The use of soil conditioners, that mainly improve the water infiltration capacity of soils, and provide stability to soil structure, is a technique that has been studied for a long time without much success. Recent reports on the use of polymers applied on soil surface suggest that they might be useful in zero-tillage conditions, particularly in improving the water infiltration into soil. Their efficacy in unplowed soils subjected to traffic in wet conditions needs evaluation.

Finally, more research is needed to evaluate the long-term effects of the opposing processes acting on unplowed soil: biological tillage and soil compaction by animals and machinery. The conclusions derived from this thesis are valid for the transition phase from conventional- to zero-tillage systems only. Long-term experiments comparing different crop sequences with varying intensity of pasture grazing, and varying frequency of subsoiling with Paraplow, would provide this valuable information.

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9. APPENDICES

A. Description of Soil and Climate

Table A.1 Selected physical and chemical characteristics of soil.

Horizon	Depth m	Sand %	Silt %	Clay %	pH	Organic C $g.kg^{-1}$	Total N $g.kg^{-1}$	CEC $cmol.kg^{-1}$	FC %W	PWP %W
					***RTN* Site**					
A_p	<0.18	9	56	35	5.8	22.4	1.9	32	30	12
B_{2t}	0.18-0.74	5	44	51	6.4	9.5	1.1	31	31	15
B_3	0.74-0.97	5	46	49	7.2	3.4	0.5	29	30	15
C_{ca}	>0.97	6	50	44	7.4	1.0	0.4	29	28	14
					CxT and *C14* Sites					
A_p	<0.30	8	64	28	5.6	20.8	1.7	29	29	13
B_{21t}	0.30-0.42	6	47	47	6.1	7.8	0.8	26	30	16
B_{22}	0.42-0.72	4	46	50	6.6	9.5	0.7	27	30	16
B_3	0.72-0.97	5	49	46	6.8	1.4	0.4	28	27	15
C_{ca}	>0.97	n/a†	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

† not available

Figure A.1. Precipitation (mm) at INIA La Estanzuela in 10 - day periods.

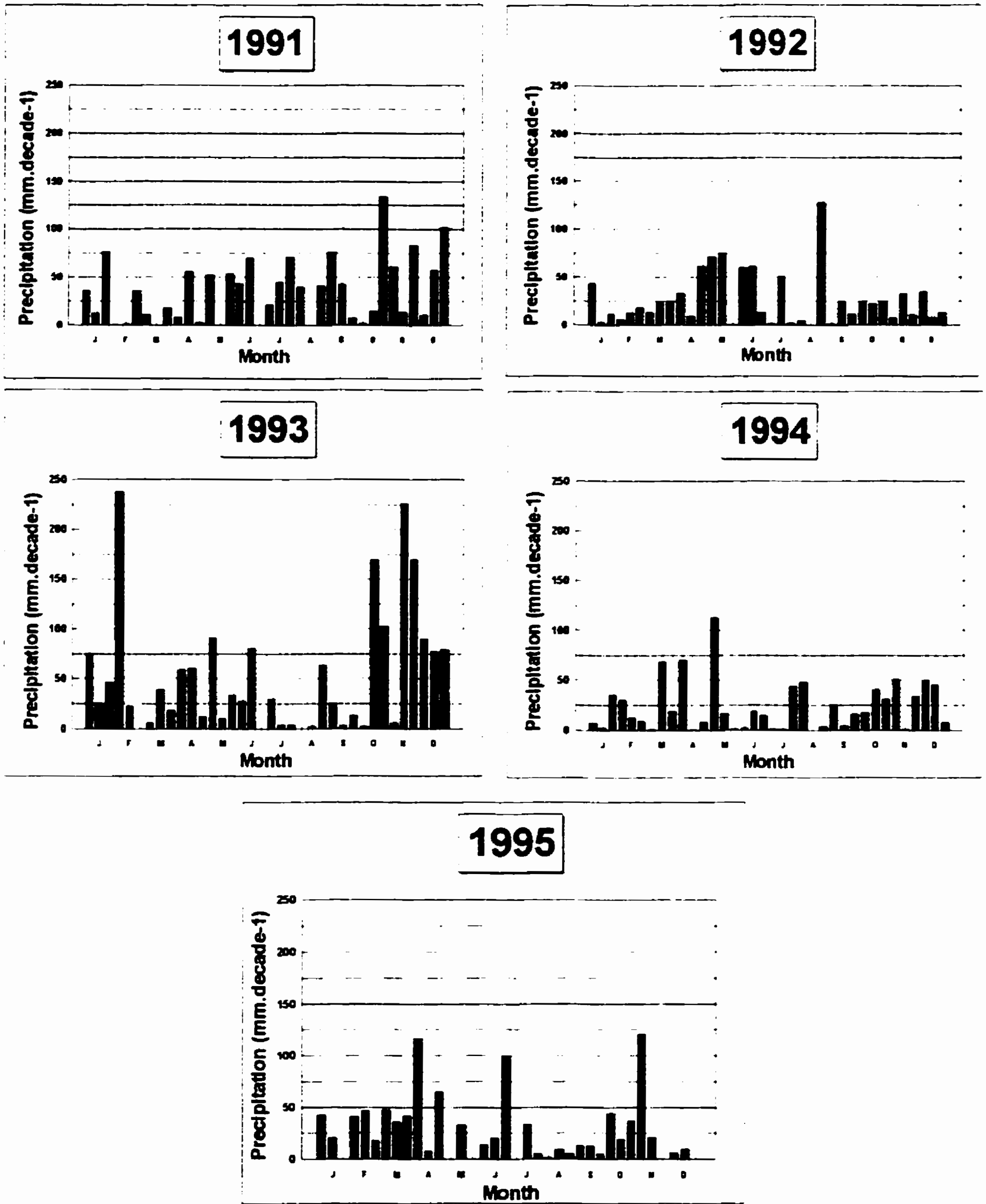


Figure A.2. Distribution of daily precipitation at INIA La Estanzuela in the period 1991-1995

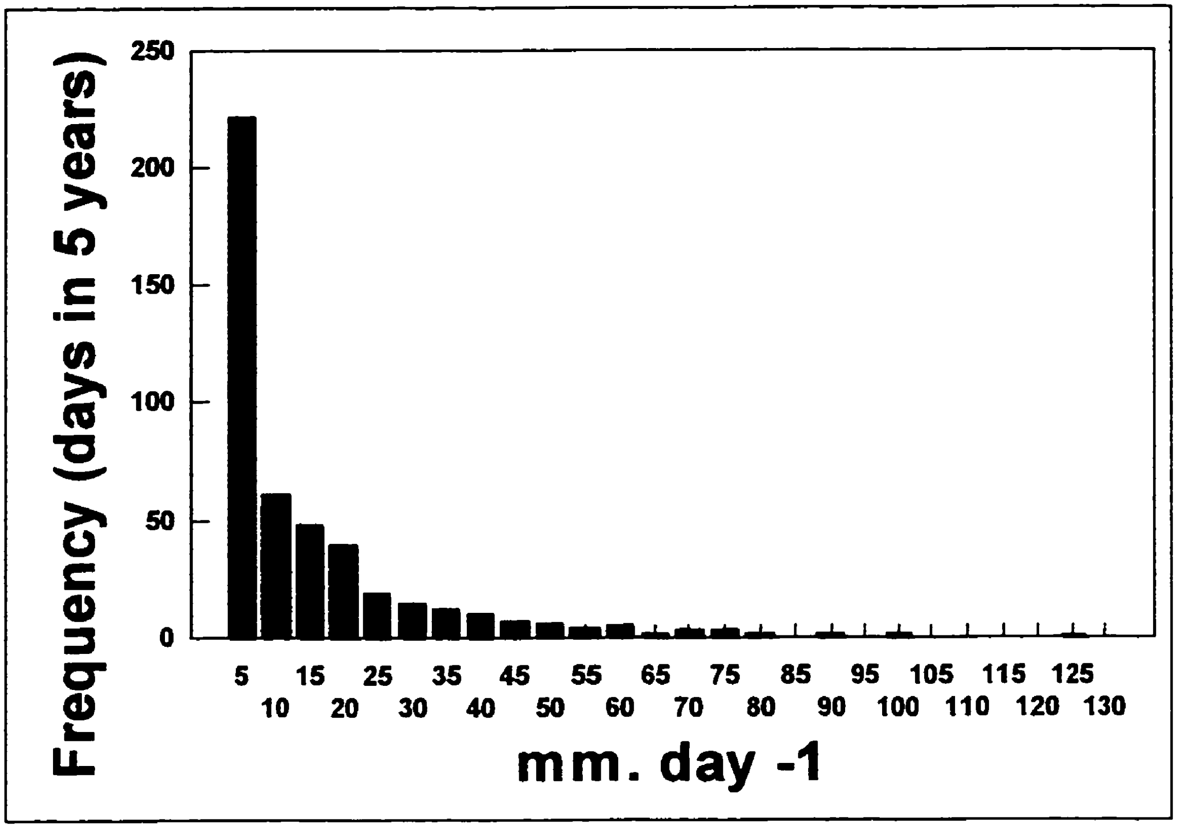


Figure A.3. Rainfall intensity in 10-minute intervals on 26-28 Nov. 1993 at INIA La Estanzuela

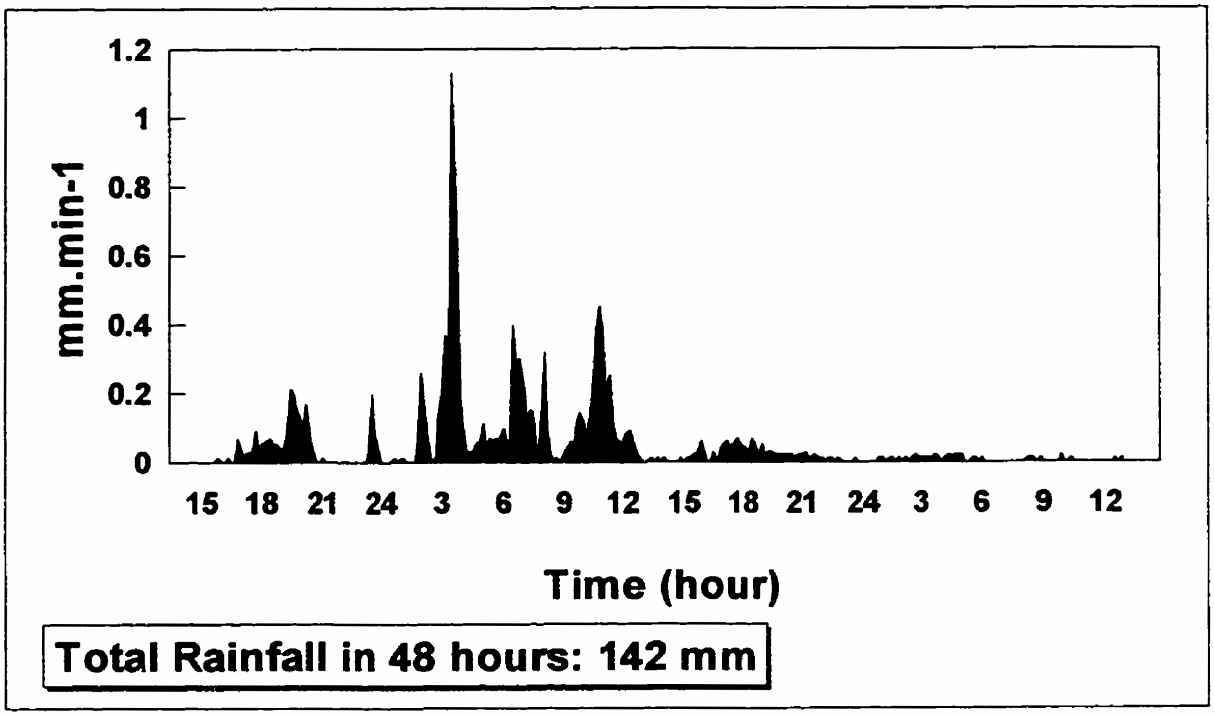


Figure A.4. Air temperature at INIA La Estanzuela in 10-day periods.

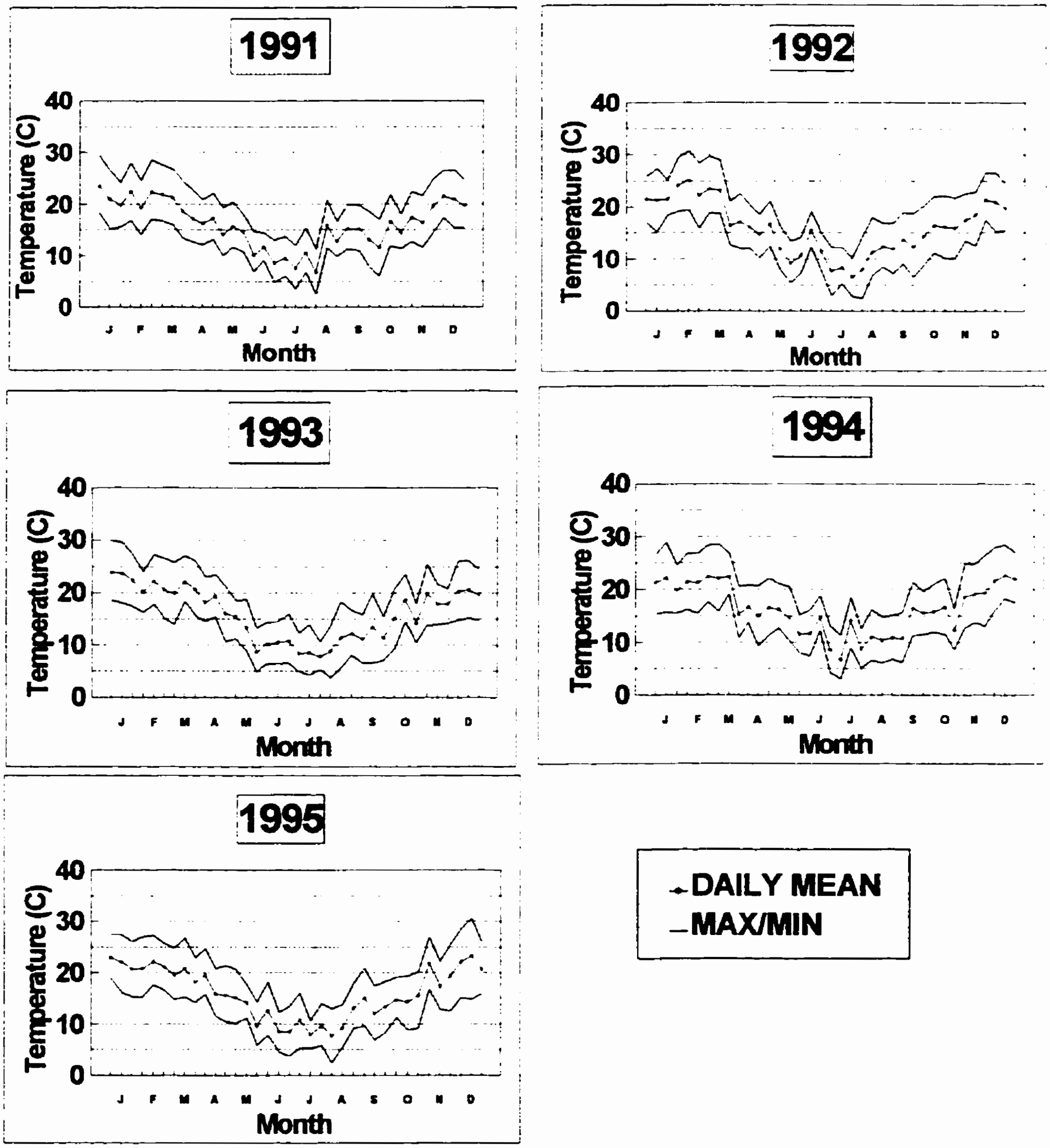


Figure A.5. Relative humidity of air at INIA La Estanzuela in 10-day periods.

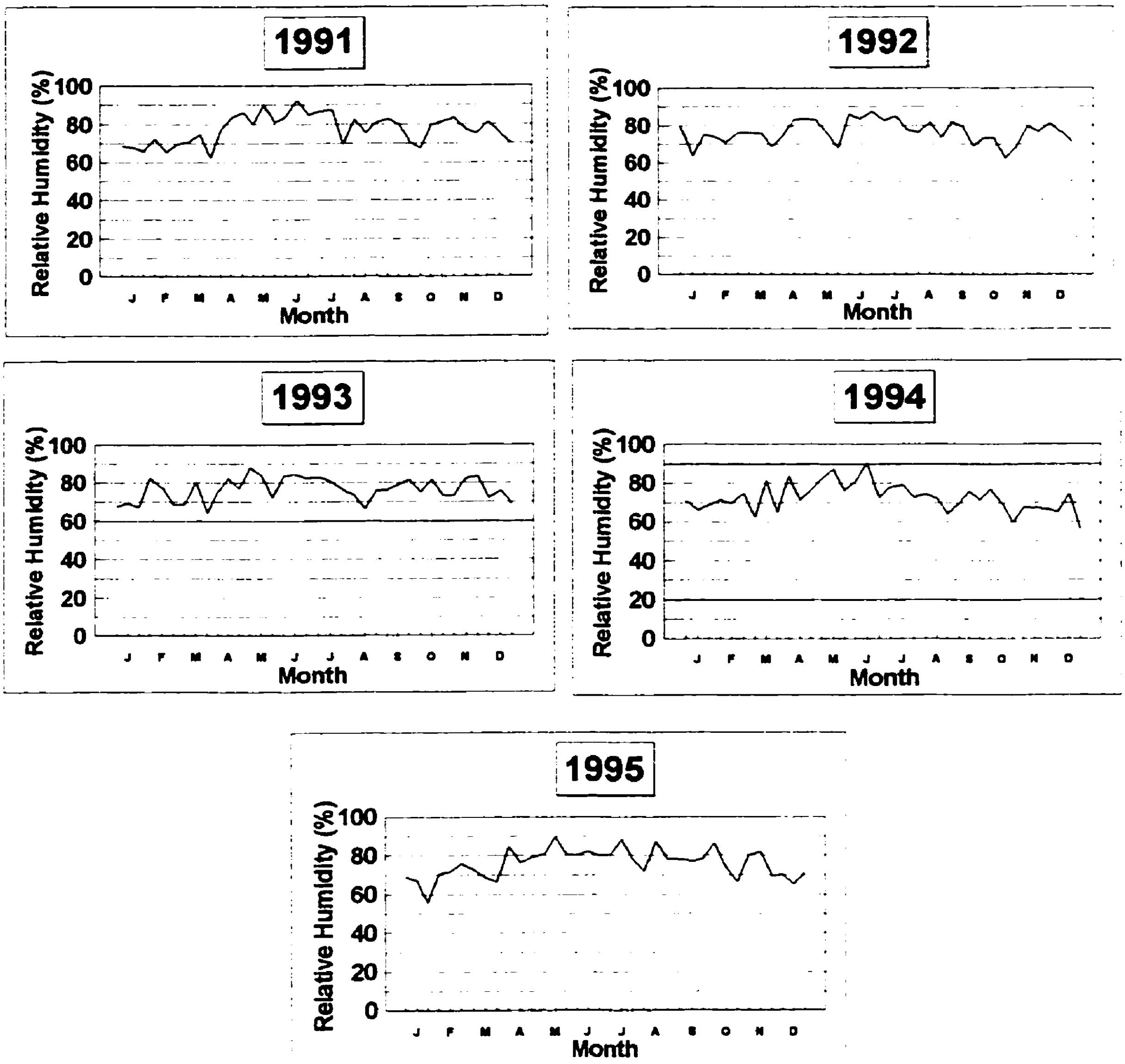


Figure A.6. Solar radiation (cal cm^{-2} day^{-1}) at INIA La Estanzuela. Daily values.

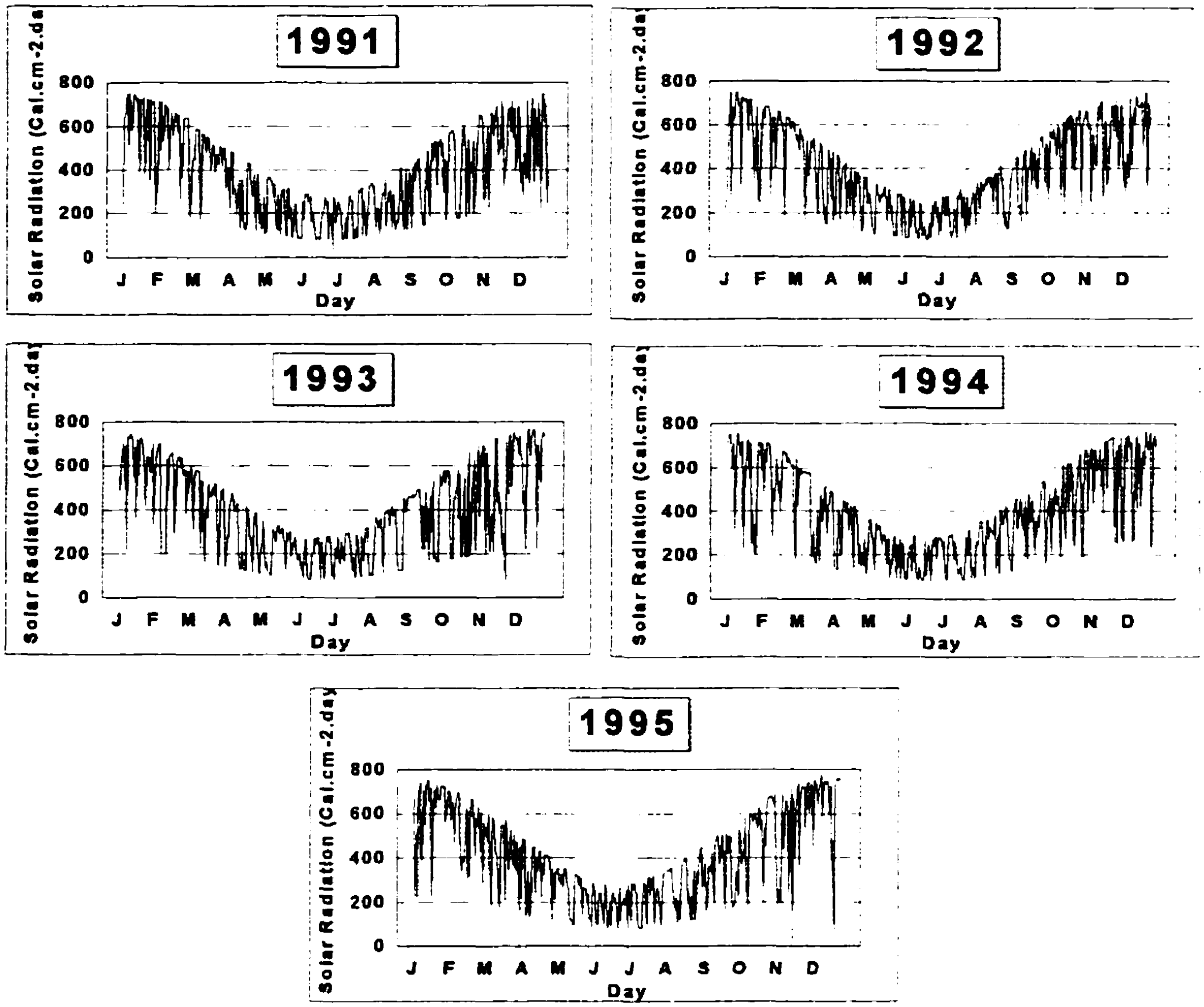
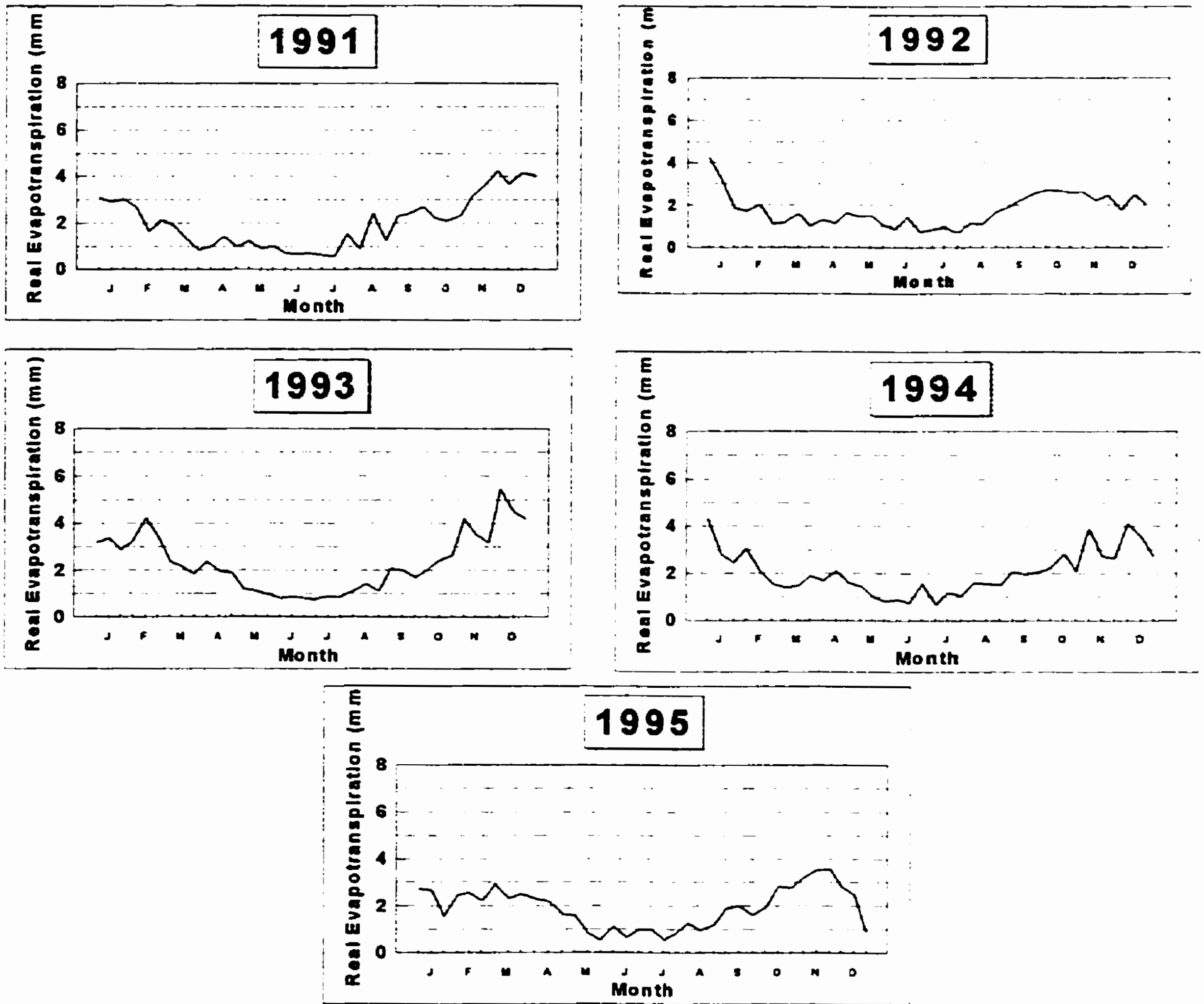


Figure A.7. Real evapotranspiration (mm day^{-1}) at INIA La Estanzuela in 10-day periods.



B. Effects of Paraplow on Soil Properties

Table B.1. Analysis of variance of penetration resistance at different depths. Experiment *RTN*, 27 July 1992.

	DEPTH (mm)									
EFFECT	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
BLOCK	* ¶	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW †	***	***	***	***	***	***	***	**	**	***
PREV ‡	ns	ns	ns	**	**	ns	ns	ns	ns	ns
POS §	*	*	ns	ns	ns	ns	ns	ns	ns	ns
PREV*POS #	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV #	**	**	**	ns	ns	ns	ns	ns	ns	ns
PPLW*POS #	ns	ns	ns	ns	ns	**	ns	ns	ns	ns
PPLW*PREV*POS #	ns	ns	ns	ns	ns	ns	ns	ns	ns	*
MEAN (kPa)	**411**	**630**	**749**	**834**	**891**	**907**	**937**	**967**	**983**	**960**
C.V.(%)	**43**	**31**	**30**	**32**	**30**	**30**	**31**	**33**	**34**	**32**

EFFECT	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**
BLOCK	ns	*	*	ns	ns	ns	ns	*	ns	ns
PPLW	***	***	***	***	***	***	***	***	***	**
PREV	*	*	*	**	**	*	ns	ns	ns	ns
POS	ns	ns	ns	ns	ns	*	*	**	***	**
PREV*POS	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*POS	ns	ns	ns	*	ns	ns	ns	ns	ns	ns
PPLW*PREV*POS	**	**	*	ns	ns	ns	ns	**	***	***
MEAN (kPa)	**924**	**898**	**887**	**886**	**910**	**963**	**1023**	**1068**	**1123**	**1179**
C.V.(%)	**32**	**31**	**31**	**29**	**31**	**30**	**28**	**24**	**20**	**18**

EFFECT	**315**	**330**	**345**	**360**	**375**	**390**	**405**	**420**	**435**	**450**
BLOCK	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW	*	ns	ns	ns	ns	ns	na	ns	ns	ns
PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
POS	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PREV*POS	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*POS	*	*	*	ns	*	ns	ns	ns	ns	ns
PPLW*PREV*POS	ns	**	ns	ns	ns	ns	ns	ns	ns	ns
MEAN (kPa)	**1223**	**1248**	**1273**	**1303**	**1346**	**1371**	**1400**	**1416**	**1434**	**1468**
C.V.(%)	**19**	**20**	**19**	**19**	**19**	**18**	**18**	**18**	**17**	**16**

† Effect of Paraplow treatment
‡ Effect of previous crop
§ Effect of position within plots
¶ ns Effect not significant (p<0.10)
* Effect significant (p<0.10)
** Effect significant (p<0.05)
*** Effect significant (p<0.01)
\# Effects of interactions between variables

Table B.2. Analysis of variance of penetration resistance at different depths. Experiment *RTN*, 17 Aug. 1992.

	DEPTH (mm)									
EFFECT	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
BLOCK	ns¶	ns	ns	*	**	**	**	**	**	*
PPLW †	*	***	***	***	***	**	*	ns	ns	ns
PREV ‡	***	ns	ns	ns	ns	ns	ns	ns	ns	**
POS §	•	ns	ns	ns	ns	ns	ns	ns	ns	ns
PREV*POS #	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV #	ns	ns	ns	ns	*	**	**	**	**	**
PPLW*POS #	ns	ns	ns	ns	*	**	*	*	ns	ns
PPLW*PREV*POS #	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
MEAN (kPa)	**721**	**1151**	**1310**	**1319**	**1279**	**1192**	**1083**	**1019**	**974**	**948**
C.V.(%)	**65**	**54**	**42**	**35**	**31**	**26**	**26**	**25**	**25**	**25**

EFFECT	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**
BLOCK	ns	ns	ns	ns	*	ns	*	ns	ns	ns
PPLW	ns	*	***	***	***	***	***	***	***	***
PREV	**	***	ns	ns	ns	ns	ns	ns	ns	ns
POS	**	**	**	ns	ns	ns	*	***	**	*
PREV*POS	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV	*	*	*	*	ns	ns	ns	ns	ns	ns
PPLW*POS	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV*POS	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
MEAN (kPa)	**940**	**946**	**983**	**1036**	**1094**	**1129**	**1114**	**1120**	**1113**	**1112**
C.V.(%)	**25**	**28**	**27**	**31**	**32**	**32**	**28**	**27**	**27**	**27**

EFFECT	**315**	**330**	**345**	**360**	**375**	**390**	**405**	**420**	**435**	**450**
BLOCK	*	***	***	**	***	**	*	ns	ns	ns
PPLW	***	***	***	**	**	***	***	***	**	**
PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
POS	*	ns	ns	ns	ns	ns	*	*	*	ns
PREV*POS	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*POS	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV*POS	ns	ns	ns	ns	ns	ns	*	ns	ns	ns
MEAN (kPa)	**1119**	**1136**	**1173**	**1211**	**1248**	**1289**	**1317**	**1341**	**1361**	**1376**
C.V.(%)	**25**	**24**	**21**	**19**	**17**	**15**	**14**	**14**	**14**	**15**

Effect of Paraplow treatment
‡ Effect of previous crop
§ Effect of position within plots
¶ ns Effect not significant (p<0.10)

* Effect significant (p<0.10)
** Effect significant (p<0.05)
*** Effect significant (p<0.01)
\# Effects of interactions between variables

Table B.3. Analysis of variance of penetration resistance at different depths. Experiment *RTN*, 17 Sep. 1992.

	DEPTH (mm)									
EFFECT	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
BLOCK	ns¶	ns	ns	ns	ns	ns	ns	ns	***	***
PPLW †	**	***	***	***	**	**	ns	*	***	**
CROP ‡	***	***	***	**	ns	***	***	**	**	***
PREV §	ns	ns	**	*	**	**	ns	ns	ns	ns
PPLW*CROP #	**	**	***	ns	ns	ns	**	ns	ns	**
CROP*PREV #	*	**	ns	ns	ns	ns	*	ns	ns	ns
PPLW*PREV #	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV*CROP #	***	**	**	ns	ns	ns	*	*	ns	*
MEAN (kPa)	**550**	**1016**	**1303**	**1444**	**1529**	**1557**	**1538**	**1524**	**1466**	**1439**
C.V.(%)	**63**	**38**	**31**	**41**	**39**	**36**	**38**	**37**	**33**	**33**

EFFECT	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**
BLOCK	ns	ns	*	*	*	***	**	***	ns	ns
PPLW	ns	ns	ns	ns	ns	***	***	***	**	*
CROP	*	ns	ns	**	*	ns	ns	ns	ns	ns
PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*CROP	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CROP*PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV*CROP	**	ns	**	*	ns	ns	ns	ns	ns	ns
MEAN (kPa)	**1388**	**1390**	**1383**	**1391**	**1392**	**1379**	**1366**	**1366**	**1364**	**1360**
C.V.(%)	**34**	**34**	**34**	**36**	**34**	**32**	**32**	**31**	**27**	**25**

EFFECT	**315**	**330**	**345**	**360**	**375**	**390**	**405**	**420**	**435**	**450**
BLOCK	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CROP	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*CROP	**	ns	ns	ns	ns	ns	ns	ns	ns	ns
CROP*PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV	*	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV*CROP	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
MEAN (kPa)	**1360**	**1380**	**1401**	**1408**	**1411**	**1418**	**1436**	**1453**	**1483**	**1515**
C.V.(%)	**24**	**23**	**23**	**23**	**22**	**21**	**20**	**19**	**18**	**19**

† Effect of Paraplow treatment
‡ Effect of previous crop
§ Effect of position within plots
¶ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)
\# Effects of interactions between variables

Table B.4. Analysis of variance of penetration resistance at different depths. Experiment *RTN*, 14 Oct. 1992.

	DEPTH (mm)									
EFFECT	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
BLOCK	* ¶	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW †	*	ns	ns	***	**	**	ns	ns	ns	ns
CROP ‡	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PREV §	ns	**	ns	ns	ns	ns	ns	ns	*	ns
PPLW*CROP #	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CROP*PREV #	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV #	ns	ns	ns	ns	ns	ns	ns	ns	ns	*
MEAN (kPa)	**1170**	**2018**	**2425**	**2570**	**2774**	**2815**	**2778**	**2888**	**3050**	**3071**
C.V.(%)	**75**	**56**	**56**	**55**	**47**	**44**	**46**	**35**	**31**	**31**

EFFECT	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**
BLOCK	ns	ns	ns	ns	ns	**	*	ns	ns	ns
PPLW	ns	ns	ns	ns	ns	**	ns	ns	ns	ns
CROP	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PREV	ns	ns	ns	ns	ns	ns	*	*	ns	ns
PPLW*CROP	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CROP*PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV	*	ns	ns	ns	ns	ns	ns	ns	ns	ns
MEAN (kPa)	**3117**	**3064**	**3069**	**2981**	**2979**	**2952**	**2919**	**2869**	**2909**	**2937**
C.V.(%)	**34**	**33**	**31**	**36**	**35**	**34**	**30**	**28**	**23**	**19**

EFFECT	**315**	**330**	**345**	**360**	**375**	**390**	**405**	**420**	**435**	**450**
BLOCK	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CROP	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PREV	**	**	**	**	**	**	**	**	*	*
PPLW*CROP	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CROP*PREV	ns	ns	ns	ns	*	*	ns	ns	ns	ns
PPLW*PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
MEAN (kPa)	**2937**	**2944**	**2918**	**2907**	**2868**	**2971**	**2832**	**2751**	**2740**	**2737**
C.V.(%)	**19**	**19**	**18**	**18**	**16**	**31**	**19**	**19**	**20**	**20**

† Effect of Paraplow treatment
‡ Effect of current crop
§ Effect of previous crop
¶ ns Effect not significant ($p<0.10$)
  * Effect significant ($p<0.10$)
  ** Effect significant ($p<0.05$)
  *** Effect significant ($p<0.01$)
Effects of interactions between variables

Table B.5. Analysis of variance of penetration resistance at different depths. Experiment *RTN*, 25 June 1993.

	DEPTH (mm)									
EFFECT	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
PPLW †	ns¶	ns	ns	*	**	**	ns	ns	ns	*
CROP ‡	ns	ns	ns	ns	ns	ns	*	**	**	*
PREV §	***	***	***	***	**	ns	ns	ns	ns	ns
PPLW*CROP #	ns	ns	ns	ns	**	***	**	***	***	**
CROP*PREV #	ns	***	***	***	***	**	**	*	ns	ns
PPLW*PREV #	ns	ns	ns	ns	ns	ns	ns	*	**	*
PPLW*PREV*CROP #	ns	ns	ns	ns	ns	ns	ns	ns	ns	*
MEAN (kPa)	**528**	**822**	**910**	**883**	**829**	**797**	**775**	**767**	**780**	**822**
C.V.(%)	**48**	**33**	**32**	**32**	**34**	**34**	**32**	**32**	**33**	**32**

EFFECT	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**
PPLW	*	*	*	**	***	***	***	***	***	***
CROP	***	***	***	***	ns	ns	ns	ns	ns	ns
PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*CROP	*	*	*	*	ns	ns	ns	ns	ns	ns
CROP*PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV	ns	ns	ns	ns	*	ns	ns	ns	ns	*
PPLW*PREV*CROP	**	**	ns	ns	ns	ns	ns	ns	ns	ns
MEAN (kPa)	**871**	**904**	**940**	**989**	**1017**	**1040**	**1058**	**1070**	**1069**	**1077**
C.V.(%)	**29**	**28**	**29**	**28**	**25**	**24**	**24**	**23**	**23**	**20**

EFFECT	**315**	**330**	**345**	**360**	**375**	**390**	**405**	**420**	**435**	**450**
PPLW	***	**	**	***	**	***	**	**	**	**
CROP	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*CROP	**	**	**	**	ns	ns	ns	ns	ns	ns
CROP*PREV	ns	ns	ns	*	*	**	**	***	**	**
PPLW*PREV	ns	**	**	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV*CROP	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
MEAN (kPa)	**1102**	**1103**	**1116**	**1135**	**1170**	**1215**	**1268**	**1332**	**1393**	**1450**
C.V.(%)	**19**	**20**	**18**	**19**	**18**	**17**	**16**	**15**	**16**	**16**

† Effect of Paraplow treatment
‡ Effect of current crop
§ Effect of previous crop
¶ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)
\# Effects of interactions between variables

Table B.6. Analysis of variance of penetration resistance at different depths. Experiment *RTN*, 29 Nov.1993.

	DEPTH (mm)									
EFFECT	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
BLOCK	ns¶	ns	ns	ns	ns	ns	ns	ns	ns	*
PPLW †	ns	**	*	*	ns	ns	ns	ns	ns	ns
CROP ‡	ns	ns	*	ns	ns	ns	ns	ns	ns	ns
PREV §	**	**	***	**	**	**	**	ns	ns	ns
PPLW*CROP #	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CROP*PREV #	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV #	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV*CROP #	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
MEAN (kPa)	**961**	**1539**	**1935**	**1986**	**2194**	**2258**	**2365**	**2279**	**2247**	**2205**
C.V.(%)	**91**	**67**	**47**	**49**	**50**	**41**	**43**	**35**	**36**	**34**

EFFECT	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**
BLOCK	*	*	ns	ns	ns	ns	ns	ns	ns	ns
PPLW	ns	ns	*	*	**	**	**	*	ns	ns
CROP	ns	ns	ns	*	ns	ns	*	*	ns	ns
PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*CROP	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CROP*PREV	ns	*	**	**	**	ns	ns	ns	*	**
PPLW*PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns0
PPLW*PREV*CROP	ns	*	ns	ns	ns	ns	ns	ns	ns	ns
MEAN (kPa)	**2211**	**2127**	**2065**	**2095**	**2097**	**2010**	**1935**	**1881**	**1900**	**1834**
C.V.(%)	**33**	**36**	**37**	**37**	**37**	**38**	**41**	**38**	**36**	**34**

EFFECT	**315**	**330**	**345**	**360**	**375**	**390**	**405**	**420**	**435**	**450**
BLOCK	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CROP	ns	ns	ns	**	ns	ns	ns	ns	ns	ns
PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*CROP	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CROP*PREV	ns	*	*	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV*CROP	ns	ns	ns	ns	ns	ns	*	ns	ns	ns
MEAN (kPa)	**1857**	**1806**	**1814**	**1784**	**1804**	**1807**	**1858**	**1847**	**1863**	**1908**
C.V.(%)	**42**	**34**	**38**	**42**	**37**	**35**	**35**	**34**	**30**	**34**

† Effect of Paraplow treatment
‡ Effect of current crop
§ Effect of previous crop
¶ ns Effect not significant (p<0.10)

* Effect significant (p<0.10)
** Effect significant (p<0.05)
*** Effect significant (p<0.01)
\# Effects of interactions between variables

Table B.7. Analysis of variance of penetration resistance at different depths. Experiment *C14*, 24 June 1993.

	DEPTH (mm)									
EFFECT	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
BLOCK	ns §	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW †	ns	ns	ns	13 %	*	**	**	**	***	***
PREV ‡	**	*	11 %	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV¶	ns	*	ns	ns	**	***	ns	ns	ns	ns
MEAN (kPa)	**528**	**822**	**910**	**883**	**829**	**797**	**775**	**767**	**780**	**822**
C.V.(%)	**46**	**34**	**27**	**23**	**22**	**24**	**25**	**25**	**28**	**29**

EFFECT	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**
BLOCK	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW	***	***	**	***	***	***	***	***	***	***
PREV	ns	ns	ns	ns	ns	ns	ns	**	***	***
PPLW*PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
MEAN (kPa)	**871**	**904**	**940**	**989**	**1017**	**1040**	**1058**	**1070**	**1069**	**1077**
C.V.(%)	**28**	**28**	**27**	**24**	**23**	**22**	**23**	**23**	**23**	**23**

EFFECT	**315**	**330**	**345**	**360**	**375**	**390**	**405**	**420**	**435**	**450**
BLOCK	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW	***	***	**	**	*	*	12%	ns	ns	ns
PREV	***	***	***	***	*	ns	ns	ns	ns	ns
PPLW*PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	**
MEAN (kPa)	**1102**	**1103**	**1116**	**1135**	**1170**	**1215**	**1268**	**1332**	**1393**	**1450**
C.V.(%)	**26**	**23**	**23**	**23**	**23**	**23**	**22**	**22**	**23**	**23**

† Effect of Paraplow treatment
‡ Effect of previous crop
§ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)
¶ Effects of interactions between variables

Table B.8. Analysis of variance of penetration resistance at different depths. Experiment *C14*, 25 Nov. 1993.

	DEPTH (mm)									
EFFECT	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
BLOCK	* ¶	ns	ns	ns	ns	ns	ns	**	ns	ns
PPLW †	ns	ns	ns	ns	**	***	*	ns	*	***
CROP ‡	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PREV §	ns	ns	ns	*	**	**	ns	ns	*	ns
PPLW*CROP.#	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CROP*PREV #	*	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV #	**	ns	ns	*	ns	ns	ns	ns	ns	ns
PPLW*PREV*CROP #	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
MEAN (kPa)	**1118**	**1504**	**1770**	**1913**	**1993**	**1939**	**1944**	**1978**	**1984**	**1888**
C.V.(%)	**34**	**27**	**22**	**17**	**17**	**15**	**18**	**21**	**17**	**16**

EFFECT	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**
BLOCK	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW	***	***	***	***	***	***	***	***	***	***
CROP	ns	ns	ns	ns	**	***	***	**	ns	ns
PREV	ns	ns	**	***	***	***	***	**	**	**
PPLW*CROP	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CROP*PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV*CROP	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
MEAN (kPa)	**1795**	**1761**	**1698**	**1672**	**1678**	**1550**	**1587**	**1517**	**1522**	**1424**
C.V.(%)	**13**	**19**	**20**	**22**	**18**	**12**	**13**	**15**	**19**	**15**

EFFECT	**315**	**330**	**345**	**360**	**375**	**390**	**405**	**420**	**435**	**450**
BLOCK	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW	**	**	**	**	*	*	ns	ns	ns	ns
CROP	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*CROP	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CROP*PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV*CROP	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
MEAN (kPa)	**1407**	**1485**	**1380**	**1407**	**1438**	**1373**	**1424**	**1490**	**1435**	**1468**
C.V.(%)	**21**	**19**	**16**	**13**	**12**	**13**	**15**	**11**	**12**	**12**

† Effect of Paraplow treatment
‡ Effect of current crop
§ Effect of previous crop
¶ ns Effect not significant ($p<0.10$)

* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)
# Effects of interactions between variables

Table B.9. Analysis of variance of penetration resistance at different depths. Experiment *C14*, 7 June 1994.

	DEPTH (mm)									
EFFECT	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
BLOCK	ns¶	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW †	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CROP ‡	ns	ns	ns	ns	*	**	**	**	ns	ns
PREV §	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*CROP #.	ns	*	**	***	***	**	*	**	***	*
CROP*PREV #	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV #	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV*CROP #	*	**	***	**	ns	ns	ns	ns	ns	ns
MEAN (kPa)	**820**	**1043**	**1123**	**1120**	**1088**	**1060**	**1072**	**1079**	**1086**	**1077**
C.V.(%)	**48**	**40**	**31**	**29**	**25**	**21**	**23**	**27**	**22**	**29**

EFFECT	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**
BLOCK	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW	**	***	**	***	**	**	**	**	***	***
CROP	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PREV	ns	*	*	ns	ns	ns	ns	ns	ns	ns
PPLW*CROP	ns	ns	ns	ns	ns	ns	ns	ns	ns	*
CROP*PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV	*	**	**	**	ns	ns	ns	ns	ns	ns
PPLW*PREV*CROP	ns	ns	ns	ns	ns	ns	ns	ns	ns	*
MEAN (kPa)	**1055**	**1072**	**1065**	**1061**	**1060**	**1058**	**1053**	**1048**	**1052**	**1064**
C.V.(%)	**28**	**30**	**31**	**28**	**25**	**23**	**21**	**22**	**22**	**22**

EFFECT	**315**	**330**	**345**	**360**	**375**	**390**	**405**	**420**	**435**	**450**
BLOCK	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW	***	***	**	**	**	ns	ns	ns	ns	ns
CROP	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*CROP	*	**	ns	ns	ns	ns	ns	ns	ns	ns
CROP*PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*PREV*CROP	**	**	**	**	**	*	ns	ns	ns	ns
MEAN (kPa)	**1093**	**1130**	**1167**	**1203**	**1249**	**1296**	**1341**	**1390**	**1430**	**1472**
C.V.(%)	**21**	**20**	**21**	**21**	**20**	**24**	**23**	**21**	**21**	**20**

† Effect of Paraplow treatment
‡ Effect of current crop
§ Effect of previous crop
¶ ns Effect not significant ($p<0.10$)

* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)
# Effects of interactions between variables

Table B.10. Analysis of variance of penetration resistance at different depths. Experiment *C14*, 29 Dec.1994.

	DEPTH (mm)									
EFFECT	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
BLOCK	ns§	ns	**	*	**	ns	ns	*	*	ns
PPLW †	**	**	**	***	***	***	***	***	***	***
CROP ‡	*	**	***	***	***	***	*	ns	ns	ns
PPLW*CROP ¶	ns	ns	ns	ns	ns	ns	ns	ns	*	**
MEAN (kPa)	**716**	**1059**	**1365**	**1483**	**1552**	**1553**	**1584**	**1657**	**1688**	**1625**
C.V.(%)	**32**	**31**	**33**	**29**	**28**	**26**	**23**	**24**	**24**	**25**

EFFECT	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**
BLOCK	ns	ns	ns	ns	*	**	**	*	ns	ns
PPLW	***	***	***	***	***	***	***	***	**	*
CROP	ns	**	***	***	***	***	***	***	*	**
PPLW*CROP	*	ns	**	***	**	ns	ns	ns	ns	ns
MEAN (kPa)	**1584**	**1522**	**1467**	**1456**	**1417**	**1429**	**1374**	**1313**	**1284**	**1257**
C.V.(%)	**24**	**23**	**22**	**23**	**25**	**28**	**27**	**27**	**25**	**26**

EFFECT	**315**	**330**	**345**	**360**	**375**	**390**	**405**	**420**	**435**	**450**
BLOCK	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CROP	*	*	ns	ns	ns	ns	ns	ns	ns	ns
PPLW*CROP	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
MEAN (kPa)	**1243**	**1256**	**1251**	**1246**	**1264**	**1300**	**1340**	**1372**	**1414**	**1440**
C.V.(%)	**26**	**21**	**21**	**22**	**19**	**18**	**19**	**20**	**22**	**21**

† Effect of Paraplow treatment
‡ Effect of current crop
§ ns Effect not significant ($p<0.10$)
  * Effect significant ($p<0.10$)
  ** Effect significant ($p<0.05$)
  *** Effect significant ($p<0.01$)
¶ Effects of interactions between variables.

Table B.11. Analysis of variance of penetration resistance at different depths. Experiment *C13*, 6 May 1993.

	DEPTH (mm)									
EFFECT	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
BLOCK	*‡	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW †	ns	ns	ns	*	***	***	***	***	***	*
MEAN (kPa)	293	530	604	669	740	785	815	849	875	918
C.V.(%)	61	52	43	31	28	16	25	31	34	38
EFFECT	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**
BLOCK	ns	ns	ns	ns	ns	ns	*	*	*	ns
PPLW †	**	*	**	*	ns	**	***	***	***	***
MEAN (kPa)	915	892	925	948	979	1084	1173	1297	1419	1349
C.V.(%)	33	35	26	24	23	23	25	28	28	28
EFFECT	**315**	**330**	**345**	**360**	**375**	**390**	**405**	**420**	**435**	**450**
BLOCK	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW †	***	**	ns	ns	ns	ns	ns	ns	ns	ns
MEAN (kPa)	1212	1058	982	930	946	998	1068	1129	1165	1217
C.V.(%)	28	33	35	35	30	36	33	31	31	30

† Effect of Paraplow treatment
‡ ns Effect not significant ($p<0.10$)
  * Effect significant ($p<0.10$)
  ** Effect significant ($p<0.05$)
  *** Effect significant ($p<0.01$)

Table B.12. Analysis of variance of penetration resistance at different depths. Experiment *C13*, 24 Nov.1993.

	DEPTH (mm)									
EFFECT	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
BLOCK	ns‡	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW †	ns	ns	ns	*	***	***	***	***	***	***
MEAN (kPa)	**391**	**751**	**952**	**1007**	**1018**	**1007**	**988**	**967**	**953**	**979**
C.V.(%)	**59**	**38**	**34**	**28**	**22**	**21**	**22**	**23**	**25**	**22**

EFFECT	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**
BLOCK	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW †	***	***	***	***	**	**	*	**	***	***
MEAN (kPa)	**1028**	**1036**	**1014**	**996**	**984**	**1015**	**1053**	**1084**	**1080**	**1057**
C.V.(%)	**24**	**20**	**17**	**18**	**21**	**28**	**29**	**27**	**23**	**18**

EFFECT	**315**	**330**	**345**	**360**	**375**	**390**	**405**	**420**	**435**	**450**
BLOCK	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW †	***	*	*	**	*	**	***	***	***	***
MEAN (kPa)	**1036**	**1051**	**1076**	**1110**	**1149**	**1215**	**1301**	**1358**	**1408**	**1461**
C.V.(%)	**20**	**23**	**22**	**21**	**22**	**21**	**17**	**16**	**15**	**14**

† Effect of Paraplow treatment

‡ ns Effect not significant ($p<0.10$)

* Effect significant ($p<0.10$)

** Effect significant ($p<0.05$)

*** Effect significant ($p<0.01$)

Table B.13. Analysis of variance of penetration resistance at different depths. Experiment *C13*, 21 Jan. 1994.

	DEPTH (mm)									
EFFECT	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
BLOCK	ns‡	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW †	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
MEAN (kPa)	**784**	**1124**	**1328**	**1408**	**1382**	**1387**	**1438**	**1453**	**1411**	**1317**
C.V.(%)	**91**	**73**	**57**	**45**	**37**	**32**	**33**	**38**	**33**	**34**
EFFECT	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**
BLOCK	ns	ns	ns	ns	*	**	*	ns	ns	ns
PPLW †	ns	ns	ns	ns	*	**	**	**	**	**
MEAN (kPa)	**1264**	**1214**	**1212**	**1226**	**1255**	**1281**	**1252**	**1208**	**1186**	**1180**
C.V.(%)	**38**	**42**	**42**	**37**	**31**	**30**	**32**	**32**	**30**	**29**
EFFECT	**315**	**330**	**345**	**360**	**375**	**390**	**405**	**420**	**435**	**450**
BLOCK	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW †	*	ns	ns	ns	ns	ns	ns	ns	ns	ns
MEAN (kPa)	**1227**	**1260**	**1301**	**1310**	**1332**	**1368**	**1391**	**1378**	**1385**	**1401**
C.V.(%)	**30**	**31**	**29**	**27**	**24**	**22**	**19**	**18**	**20**	**21**

† Effect of Paraplow treatment
‡ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)

Table B.14. Analysis of variance of penetration resistance at different depths. Experiment *C13*, 1 June 1994.

	DEPTH (mm)									
EFFECT	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
BLOCK	ns‡	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW †	ns	ns	ns	ns	ns	*	ns	ns	ns	ns
MEAN (kPa)	**873**	**1086**	**1244**	**1227**	**1210**	**1207**	**1212**	**1198**	**1160**	**1133**
C.V.(%)	**72**	**56**	**55**	**43**	**41**	**39**	**33**	**34**	**38**	**40**

EFFECT	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**
BLOCK	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW †	ns	**	***	***	***	***	***	***	***	**
MEAN (kPa)	**1139**	**1143**	**1184**	**1215**	**1239**	**1238**	**1240**	**1259**	**1230**	**1228**
C.V.(%)	**36**	**30**	**29**	**28**	**30**	**29**	**33**	**33**	**33**	**31**

EFFECT	**315**	**330**	**345**	**360**	**375**	**390**	**405**	**420**	**435**	**450**
BLOCK	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW †	***	***	***	**	*	ns	ns	ns	ns	ns
MEAN (kPa)	**1257**	**1277**	**1304**	**1343**	**1381**	**1420**	**1432**	**1455**	**1496**	**1542**
C.V.(%)	**32**	**30**	**27**	**26**	**24**	**23**	**21**	**21**	**21**	**23**

† Effect of Paraplow treatment

‡ ns Effect not significant ($p<0.10$)

* Effect significant ($p<0.10$)

** Effect significant ($p<0.05$)

*** Effect significant ($p<0.01$)

Table B.15. Analysis of variance of penetration resistance at different depths. Experiment *C15*, 23 Nov. 1993.

	DEPTH (mm)									
EFFECT	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
BLOCK	ns‡	ns	ns	ns	ns	*	*	ns	ns	ns
PPLW †	ns	ns	**	***	***	***	***	***	***	***
MEAN (kPa)	**573**	**1290**	**1582**	**1518**	**1385**	**1180**	**1043**	**954**	**908**	**835**
C.V.(%)	**59**	**41**	**36**	**31**	**32**	**33**	**34**	**27**	**25**	**24**
EFFECT	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**
BLOCK	ns	ns	ns	ns	*	*	*	**	***	***
PPLW †	***	***	***	***	***	***	***	***	***	***
MEAN (kPa)	**812**	**806**	**819**	**830**	**868**	**892**	**940**	**995**	**1065**	**1137**
C.V.(%)	**20**	**18**	**18**	**19**	**18**	**19**	**19**	**16**	**14**	**11**
EFFECT	**315**	**330**	**345**	**360**	**375**	**390**	**405**	**420**	**435**	**450**
BLOCK	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW †	***	***	***	***	***	***	***	***	***	***
MEAN (kPa)	**1182**	**1218**	**1279**	**1360**	**1422**	**1473**	**1523**	**1569**	**1580**	**1605**
C.V.(%)	**18**	**19**	**17**	**14**	**13**	**18**	**14**	**15**	**16**	**17**

† Effect of Paraplow treatment
‡ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)

Table B.16. Analysis of variance of penetration resistance at different depths. Experiment *C15*, 20 Jan.1994.

	DEPTH (mm)									
EFFECT	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
BLOCK	**‡	**	***	***	***	**	ns	ns	ns	ns
PPLW †	ns	ns	**	***	***	***	ns	ns	ns	ns
MEAN (kPa)	**651**	**964**	**1214**	**1349**	**1462**	**1838**	**1920**	**1986**	**2009**	**1975**
C.V.(%)	**48**	**37**	**33**	**31**	**28**	**29**	**30**	**29**	**28**	**31**

EFFECT	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**
BLOCK	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW †	ns	ns	ns	**	ns	ns	ns	ns	ns	ns
MEAN (kPa)	**1975**	**1950**	**2005**	**1810**	**1779**	**1807**	**1710**	**1876**	**1607**	**1572**
C.V.(%)	**31**	**33**	**29**	**25**	**21**	**18**	**18**	**19**	**25**	**29**

EFFECT	**315**	**330**	**345**	**360**	**375**	**390**	**405**	**420**	**435**	**450**
BLOCK	ns	ns	ns	*	*	**	***	**	***	***
PPLW †	ns	ns	*	**	***	***	***	ns	ns	ns
MEAN (kPa)	**1631**	**1649**	**1656**	**1831**	**1705**	**1734**	**1771**	**1666**	**1658**	**1664**
C.V.(%)	**21**	**22**	**19**	**19**	**19**	**20**	**19**	**18**	**24**	**24**

† Effect of Paraplow treatment
‡ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)

Table B.17. Analysis of variance of penetration resistance at different depths. Experiment *C15*, 13 May 1994.

	DEPTH (mm)									
EFFECT	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
BLOCK	ns ‡	ns	ns	ns	ns	ns	ns	ns	ns	**
PPLW †	ns	*	***	***	***	***	***	***	***	***
MEAN (kPa)	**583**	**866**	**1035**	**1113**	**1162**	**1158**	**1106**	**1066**	**1017**	**996**
C.V.(%)	**66**	**56**	**41**	**34**	**32**	**31**	**30**	**28**	**27**	**26**

EFFECT	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**
BLOCK	**	ns	*	***	***	***	ns	ns	ns	ns
PPLW †	***	***	***	***	***	**	ns	ns	ns	ns
MEAN (kPa)	**980**	**968**	**937**	**942**	**947**	**971**	**987**	**991**	**1011**	**1067**
C.V.(%)	**26**	**28**	**30**	**33**	**36**	**36**	**39**	**40**	**42**	**39**

EFFECT	**315**	**330**	**345**	**360**	**375**	**390**	**405**	**420**	**435**	**450**
BLOCK	ns	*	**	**	ns	ns	ns	ns	**	**
PPLW †	ns	*	*	ns	ns	ns	ns	ns	ns	ns
MEAN (kPa)	**1075**	**1094**	**1098**	**1115**	**1158**	**1184**	**1222**	**1240**	**1275**	**1346**
C.V.(%)	**38**	**34**	**33**	**32**	**30**	**29**	**28**	**27**	**26**	**26**

† Effect of Paraplow treatment
‡ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)

Table B.18. Analysis of variance of soil moisture content (% by weight) at different depths. Experiment *RTN*, 27 July 1992.

	DEPTH (mm)		
EFFECT	**0-150**	**150-300**	**300-450**
BLOCK	ns ¶	ns	ns
PPLW †	ns	ns	ns
PREV ‡	ns	ns	ns
POS §	ns	ns	ns
PREV*POS #	ns	ns	ns
PPLW*PREV #	ns	ns	**
PPLW*POS #	**	ns	ns
PPLW*PREV*POS #	ns	ns	ns
MEAN (% by weight)	**29.5**	**29.1**	**31.9**
C.V.(%)	**23**	**11**	**22**

† Effect of Paraplow treatment
‡ Effect of previous crop
§ Effect of position within plots
¶ ns Effect not significant (p<0.10)
* Effect significant (p<0.10)
** Effect significant (p<0.05)
*** Effect significant (p<0.01)
\# Effects of interactions between variables

Table B.19. Analysis of variance of soil moisture content (% by weight) at different depths. Experiment *RTN*, 17 Aug.1992.

	DEPTH (mm)		
EFFECT	**0-150**	**150-300**	**300-450**
BLOCK	**¶	***	*
PPLW †	*	*	ns
PREV ‡	ns	ns	ns
POS §	*	ns	ns
PREV*POS #	ns	ns	ns
PPLW*PREV #	ns	*	ns
PPLW*POS #	ns	ns	ns
PPLW*PREV*POS #	ns	ns	ns
MEAN (% by weight)	**24.9**	**29.2**	**31.2**
C.V.(%)	**5**	**10**	**8**

† Effect of Paraplow treatment
‡ Effect of previous crop
§ Effect of position within plots
¶ ns Effect not significant (p<0.10)
 * Effect significant (p<0.10)
 ** Effect significant (p<0.05)
 *** Effect significant (p<0.01)
Effects of interactions between variables

Table B.20. Analysis of variance of soil moisture content (% by weight) at different depths. Experiment *RTN*, 17 Sep.1992.

	DEPTH (mm)	
EFFECT	**0-150**	**150-300**
BLOCK	**#	ns
PPLW †	ns	ns
CROP ‡	ns	*
PREV §	ns	ns
POS ¶	*	**
PPLW*CROP ††	ns	**
CROP*PREV ††	ns	**
PPLW*PREV ††	ns	ns
PPLW*POS ††	ns	ns
PPLW*PREV*CROP ††	ns	ns
MEAN (% by weight)	**26.8**	**23.5**
C.V.(%)	**10**	**9**

† Effect of Paraplow treatment
‡ Effect of current crop
§ Effect of previous crop
¶ Effect of position within plots
# ns Effect not significant (p<0.10)
* Effect significant (p<0.10)
** Effect significant (p<0.05)
*** Effect significant (p<0.01)
†† Effects of interactions between variables

Table B.21. Analysis of variance of soil moisture content (% by weight) at different depths. Experiment *RTN*, 14 Oct.1992.

	DEPTH (mm)	
EFFECT	**0-150**	**150-300**
BLOCK	ns #	ns
PPLW †	ns	*
CROP ‡	ns	n s
PREV §	ns	ns
POS ¶	***	***
PPLW*CROP ††	ns	ns
CROP*PREV ††	ns	ns
PPLW*PREV ††	ns	ns
PPLW*POS ††	ns	ns
PPLW*PREV*CROP ††	*	ns
MEAN (% by weight)	**15.7**	**16.6**
C.V.(%)	**8**	**12**

† Effect of Paraplow treatment
‡ Effect of current crop
§ Effect of previous crop
¶ Effect of position within plots
# ns Effect not significant (p<0.10)
* Effect significant (p<0.10)
** Effect significant (p<0.05)
*** Effect significant (p<0.01)
†† Effects of interactions between variables

Table B.22. Analysis of variance of soil moisture (% by weight) and bulk density (Mg m^3) at different depths. Experiment *RTN*, 25 June 1993.

	Soil Moisture		**Bulk Density**	
	DEPTH (mm)			
EFFECT	**0-75**	**75-150**	**0-75**	**75-150**
BLOCK	ns ¶	ns	ns	ns
PPLW †	ns	ns	*	ns
CROP ‡	ns	ns	ns	*
PREV §	ns	ns	ns	ns
PPLW*CROP #	ns	ns	ns	ns
CROP*PREV #	ns	ns	ns	ns
PPLW*PREV #	ns	ns	ns	ns
PPLW*PREV*CROP #	ns	ns	*	ns
MEAN (% by weight)	**23.4**	**22.6**	**1.29**	**1.35**
C.V.(%)	**7**	**8**	**6**	**5**

† Effect of Paraplow treatment
‡ Effect of current crop
§ Effect of previous crop
¶ ns Effect not significant (p<0.10)
  * Effect significant (p<0.10)
  ** Effect significant (p<0.05)
  *** Effect significant (p<0.01)
\# Effects of interactions between variables

Table B.23. Analysis of variance of soil moisture (% by weight) and bulk density (Mg m^3) at different depths. Experiment *RTN*, 29 Nov.1993.

	Soil Moisture			Bulk Density		
	DEPTH (mm)					
EFFECT	**0-150**	**150-300**	**300-450**	**0-150**	**150-300**	**300-450**
BLOCK	* ¶	ns	ns	*	***	ns
PPLW †	ns	ns	ns	ns	ns	*
CROP ‡	ns	ns	ns	ns	ns	ns
PREV §	*	ns	**	***	ns	ns
PPLW*CROP #	ns	ns	ns	ns	ns	ns
CROP*PREV #	ns	ns	ns	ns	ns	ns
PPLW*PREV #	**	ns	**	*	ns	ns
PPLW*PREV*CROP #	ns	ns	ns	*	ns	ns
MEAN (% by weight)	**25.1**	**26.6**	**21.7**	**1.29**	**1.20**	**1.16**
C.V.(%)	**16**	**13**	**18**	**4**	**8**	**12**

† Effect of Paraplow treatment
‡ Effect of current crop
§ Effect of previous crop
¶ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)
# Effects of interactions between variables

Table B.24. Analysis of variance of soil moisture (% by weight) and bulk density (Mg m^3) at different depths. Experiment *C14*, 24 June 1993.

	Soil Moisture		Bulk Density	
	DEPTH (mm)			
EFFECT	**0-75**	**75-150**	**0-75**	**75-150**
BLOCK	ns ¶	ns	ns	ns
PPLW †	ns	ns	ns	ns
CROP ‡	ns	ns	ns	ns
PREV §	ns	ns	ns	ns
PPLW*CROP #	ns	ns	ns	ns
CROP*PREV #	ns	ns	ns	ns
PPLW*PREV #	ns	ns	ns	ns
PPLW*PREV*CROP #	ns	ns	ns	ns
MEAN (% by weight)	**23.3**	**24.1**	**1.29**	**1.27**
C.V.(%)	**11**	**6**	**3**	**5**

† Effect of Paraplow treatment
‡ Effect of current crop
§ Effect of previous crop
¶ ns Effect not significant (p<0.10)
# Effects of interactions between variables

Table B.25. Analysis of variance of soil moisture (% by weight) and bulk density (Mg m^{3}) at different depths. Experiment *C14*, 25 Nov.1993.

	Soil Moisture			**Bulk Density**		
	DEPTH (mm)					
EFFECT	**0-150**	**150-300**	**300-450**	**0-150**	**150-300**	**300-450**
BLOCK	* ¶	ns	ns	ns	ns	ns
PPLW †	**	**	**	**	**	ns
CROP ‡	ns	ns	ns	ns	ns	ns
PREV §	ns	ns	ns	ns	ns	ns
PPLW*CROP #	ns	ns	ns	*	ns	ns
CROP*PREV #	**	*	ns	**	ns	ns
PPLW*PREV #	ns	*	ns	**	ns	ns
PPLW*PREV*CROP #	ns	ns	ns	ns	ns	ns
MEAN (% by weight)	**26.8**	**25.8**	**21.5**	**1.28**	**1.26**	**1.24**
C.V.(%)	**12**	**18**	**13**	**6**	**5**	**10**

† Effect of Paraplow treatment
‡ Effect of current crop
§ Effect of previous crop
¶ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)
\# Effects of interactions between variables

Table B.26. Analysis of variance of soil moisture (% by weight) and bulk density (Mg m^3) at different depths. Experiment *C14*, 7 June 1994..

	Soil Moisture			Bulk Density		
	DEPTH (mm)					
EFFECT	**0-150**	**150-300**	**300-450**	**0-150**	**150-300**	**300-450**
BLOCK	ns ¶	**	ns	ns	ns	ns
PPLW †	ns	ns	ns	ns	ns	ns
CROP ‡	ns	ns	ns	ns	ns	ns
PREV §	ns	ns	ns	ns	ns	ns
PPLW*CROP #	*	ns	ns	ns	ns	ns
CROP*PREV #	ns	ns	ns	ns	ns	ns
PPLW*PREV #	ns	ns	ns	ns	ns	ns
PPLW*PREV*CROP #	**	**	ns	ns	ns	ns
MEAN (% by weight)	**28.7**	**31.3**	**30.4**	**1.28**	**1.27**	**1.35**
C.V.(%)	**4**	**8**	**12**	**8**	**7**	**13**

† Effect of Paraplow treatment
‡ Effect of current crop
§ Effect of previous crop
¶ ns Effect not significant (p<0.10)
 * Effect significant (p<0.10)
 ** Effect significant (p<0.05)
 *** Effect significant (p<0.01)
Effects of interactions between variables

Table B.27. Analysis of variance of soil moisture (% by weight) and bulk density (Mg m^3) at different depths. Experiment *C14*, 19 Aug. 1994..

	Soil Moisture			Bulk Density		
	DEPTH (mm)					
EFFECT	**0-150**	**150-300**	**300-450**	**0-150**	**150-300**	**300-450**
BLOCK	ns §	ns	*	ns	ns	ns
PPLW †	*	ns	ns	ns	ns	ns
PREV ‡	ns	ns	ns	ns	ns	ns
PPLW*PREV ¶	ns	ns	ns	ns	ns	**
MEAN (% by weight)	**27.5**	**31.2**	**31.6**	**1.22**	**1.27**	**1.32**
C.V.(%)	**6**	**9**	**5**	**6**	**7**	**4**

† Effect of Paraplow treatment
‡ Effect of previous crop
§ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
¶ Effects of interactions between variables

Table B.28. Analysis of variance of soil moisture (% by weight) and bulk density (Mg m^3) at different depths. Experiment *C14*, 29 Dec.1994..

	Soil Moisture			Bulk Density		
	DEPTH (mm)					
EFFECT	**0-150**	**150-300**	**300-450**	**0-150**	**150-300**	**300-450**
BLOCK	ns §	ns	***	ns	ns	**
PPLW †	**	ns	ns	ns	*	*
CROP ‡	***	***	ns	ns	*	ns
PPLW*CROP ¶	ns	ns	ns	ns	ns	ns
MEAN (% by weight)	**20.2**	**26.5**	**29.3**	**1.19**	**1.25**	**1.33**
C.V.(%)	**12**	**7**	**7**	**5**	**4**	**5**

† Effect of Paraplow treatment
‡ Effect of current crop
§ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
¶ Effects of interactions between variables

Table B.29. Analysis of variance of soil moisture (% by weight) and bulk density (Mg m^{3}) at different depths. Experiment *C13*, 24 Nov. 1993..

	Gravimetric			Bulk Density		
	DEPTH (mm)					
EFFECT	**75**	**225**	**375**	**75**	**225**	**375**
BLOCK	**‡	ns	**	ns	ns	ns
PPLW †	**	ns	ns	*	**	ns
MEAN (% by weight)	**29.6**	**29.1**	**29.1**	**1.21**	**1.31**	**1.38**
C.V.(%)	4	9	11	3	4	7

† Effect of Paraplow treatment
‡ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)

Table B.30. Analysis of variance of soil moisture (% by weight) and bulk density (Mg m^{3}) at different depths. Experiment *C13*, 21 Jan. 1994.

	Gravimetric			Bulk Density		
	DEPTH (mm)					
EFFECT	**75**	**225**	**375**	**75**	**225**	**375**
BLOCK	***‡	**	***	ns	ns	ns
PPLW †	**	ns	ns	ns	ns	ns
MEAN (% by weight)	**28.3**	**27.6**	**25.5**	**1.40**	**1.28**	**1.34**
C.V.(%)	3	11	7	4	9	12

† Effect of Paraplow treatment
‡ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)

Table B.31. Analysis of variance of soil moisture (% by weight) and bulk density (Mg m^3) at different depths. Experiment *C13*, 1 June 1994.

	Gravimetric			Bulk Density		
	DEPTH (mm)					
EFFECT	**75**	**225**	**375**	**75**	**225**	**375**
BLOCK	ns‡	ns	ns	ns	**	ns
PPLW †	ns	ns	ns	ns	ns	ns
MEAN (% by weight)	**27.5**	**30.1**	**28.9**	**1.26**	**1.30**	**1.36**
C.V.(%)	**7**	**13**	**14**	**5**	**4**	**4**

† Effect of Paraplow treatment
‡ ns Effect not significant (p<0.10)
* Effect significant (p<0.10)
** Effect significant (p<0.05)
*** Effect significant (p<0.01)

Table B.32. Analysis of variance of soil moisture (% by weight) and bulk density (Mg m^3) at different depths. Experiment *C15*, 23 Nov. 1993.

	Gravimetric			Bulk Density		
	DEPTH (mm)					
EFFECT	**75**	**225**	**375**	**75**	**225**	**375**
BLOCK	ns‡	ns	ns	ns	ns	ns
PPLW †	ns	*	*	***	**	**
MEAN (% by weight)	**31.9**	**31.6**	**27.5**	**1.10**	**1.16**	**1.32**
C.V.(%)	**17**	**9**	**10**	**10**	**11**	**10**

† Effect of Paraplow treatment
‡ ns Effect not significant (p<0.10)
* Effect significant (p<0.10)
** Effect significant (p<0.05)
*** Effect significant (p<0.01)

Table B.33. Analysis of variance of soil moisture (% by weight) and bulk density (Mg m^3) at different depths. Experiment *C15*, 20 Jan. 1994.

	Gravimetric			Bulk Density		
	DEPTH (mm)					
EFFECT	**75**	**225**	**375**	**75**	**225**	**375**
BLOCK	ns ‡	ns	ns	ns	ns	ns
PPLW †	ns	ns	ns	*	**	**
MEAN (% by weight)	**17.9**	**16.6**	**16.8**	**1.10**	**1.15**	**1.31**
C.V.(%)	**8**	**11**	**9**	**18**	**11**	**12**

† Effect of Paraplow treatment

‡ ns Effect not significant (p<0.10)

* Effect significant (p<0.10)

** Effect significant (p<0.05)

*** Effect significant (p<0.01)

Table B.34. Analysis of variance of soil moisture (% by weight) and bulk density (Mg m^3) at different depths. Experiment *C15*, 4 Mar. 1994.

	Gravimetric			Bulk Density		
	DEPTH (mm)					
EFFECT	**75**	**225**	**375**	**75**	**225**	**375**
BLOCK	ns ‡	ns	ns	ns	ns	ns
PPLW †	ns	**	**	***	ns	**
MEAN (% by weight)	**13.0**	**13.3**	**15.8**	**1.17**	**1.25**	**1.28**
C.V.(%)	**13**	**19**	**20**	**7**	**4**	**8**

† Effect of Paraplow treatment

‡ ns Effect not significant (p<0.10)

* Effect significant (p<0.10)

** Effect significant (p<0.05)

*** Effect significant (p<0.01)

Table B.35. Analysis of variance of soil moisture (% by weight) and bulk density (Mg m^3) at different depths. Experiment *C15*,13 May 1994.

	Gravimetric			Bulk Density		
	DEPTH (mm)					
EFFECT	**75**	**225**	**375**	**75**	**225**	**375**
BLOCK	ns ‡	ns	*	ns	ns	ns
PPLW †	ns	ns	ns	**	***	ns
MEAN (% by weight)	**34.9**	**31.1**	**26.1**	**1.15**	**1.19**	**1.37**
C.V.(%)	**8**	**6**	**3**	**10**	**12**	**11**

† Effect of Paraplow treatment

‡ ns Effect not significant ($p<0.10$)

* Effect significant ($p<0.10$)

** Effect significant ($p<0.05$)

*** Effect significant ($p<0.01$)

C. Effects of Paraplow on Crop Parameters

Table C.1. Analysis of variance for corn crop parameters. Experiment *RTN*, 1991-1992

EFFECT	**Plant Density (pl/m²)**	**Grain Yield (kg/ha)**
BLOCK	***‡	**
PPLW †	***	***
MEAN	**5.6**	**2563**
C.V. (%)	**18**	**26**

† Effect of Paraplow treatment
‡ ns Effect not significant (p<0.10)
* Effect significant (p<0.10)
** Effect significant (p<0.05)
*** Effect significant (p<0.01)

Table C.2. Analysis of variance for corn crop parameters. Experiment *C14*, 1992-1993

EFFECT	**Plant Density (pl/m²)**	**Grain Yield (kg/ha)**
BLOCK	ns‡	ns
PPLW †	***	***
MEAN	**4.9**	**5333**
C.V. (%)	**16**	**8**

† Effect of Paraplow treatment
‡ ns Effect not significant (p<0.10)
* Effect significant (p<0.10)
** Effect significant (p<0.05)
*** Effect significant (p<0.01)

Table C.3. Analysis of variance for corn crop parameters. Experiment *C13*, 1992-1993

EFFECT	Plant Density (pl/m^2)	Above grourd biomass [1] (Kg/ha)	Spike density ($spikes/m^2$)	Grain Yield (kg/ha)	Grain Weight (mg)
BLOCK	*‡	ns	ns	ns	*
PPLW †	***	***	***	***	*
MEAN	4.7	11080	5.3	5160	292
C.V. (%)	11	25	17	28	5

† Effect of Paraplow treatment
‡ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)
[1] Green weight excluding spikes.

Table C.4. Analysis of variance for corn crop parameters. Experiment *C15*, 1993-1994

EFFECT	Initial Plant Density (pl/m^2)	Final Plant Density (pl/m^2)	Above ground biomass [1] (Kg/ha)	Spike density ($spikes/m^2$)	Grain Yield (kg/ha)	Grain Weight (mg)
BLOCK	ns‡	ns	ns	ns	ns	*
PPLW †	ns	***	***	***	***	***
MEAN	3.2	1.7	2656	1.4	920	288
C.V. (%)	20	40	74	48	68	10

† Effect of Paraplow treatment
‡ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)
[1] Green weight excluding spikes.

Table C.5. Analysis of variance for sunflower crop parameters. Experiment *RTN*, 1991-1992.

EFFECT	**Plant Density (pl/m²)**	**Grain Yield (kg/ha)**
BLOCK	* ‡	**
PPLW †	ns	***
MEAN	**2.4**	**1191**
C.V. (%)	**7**	**16**

† Effect of Paraplow treatment
‡ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)

Table C.6. Analysis of variance for sunflower crop parameters. Experiment *C14*, 1992-1993.

EFFECT	**Plant Density (pl/m²)**	**Grain Yield (kg/ha)**
BLOCK	ns ‡	ns
PPLW †	ns	***
MEAN	**4.7**	**2077**
C.V. (%)	**17**	**6**

† Effect of Paraplow treatment
‡ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)

Table C.7. Analysis of variance for wheat crop parameters. Experiment *RTN*, 1992.

EFFECT	Plant Density (pl/m^2)	Plant Height (cm)	Spike density (m^2)	Spike size (grains/spike)	Thousand kernel weight (g)	Grain Yield (Kg/ha)
BLOCK	*§	**	ns	**	ns	***
PPLW †	***	**	**	ns	ns	ns
PREV ‡	ns	ns	*	ns	ns	*
PPLW * PREV ¶	ns	ns	ns	ns	ns	ns
MEAN	143	77	433	20.0	38.5	4480
C.V.(%)	22	5	14	5	5	11

	14 Sep.							30 Sep.						
		Root length density (m/m^2)			Nodal root axes				Root length density (m/m^2)			Nodal root axes		
EFFECT	Rooting Depth (cm)	Sem (1)	Nod (2)	Tot	Pl (3)	Till (4)	m^2 (5)	Rooting Depth (cm)	Sem (1)	Nod (2)	Tot	Pl (3)	Till (4)	m^2 (5)
BLOCK	ns	ns	ns	ns	ns	*	ns	•	ns	ns	ns	*	ns	ns
PPLW	*	**	*	**	*	*	**	ns	*	*	**	*	ns	**
PREV	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW * PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
MEAN	18.1	162	92	255	9.3	2.7	1.4	18.3	187	151	338	165	4.5	2.6
C.V.(%)	9	22	45	23	29	26	18	8	41	35	26	27	2.4	2.3

	14 Oct.			4 Nov.			1 Dec.		
	Nodal root axes			Nodal root axes			Nodal root axes		
EFFECT	Pl (3)	Till (4)	m^2 (5)	Pl (3)	Till (4)	m^2 (5)	Pl (3)	Till (4)	m^2 (5)
BLOCK	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW	**	*	ns	ns	ns	**	ns	ns	**
PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW * PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns
MEAN	22.8	5.3	3.7	13.6	3.7	3.2	23.7	6.8	3.7
C.V.(%)	35	24	28	46	35	23	20	31	24

† Effect of Paraplow treatment
‡ Effect of previous crop
§ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)
¶ Effects of interactions between variables

(1) Seminal roots
(2) Nodal roots.
(3) Number per plant.
(4) Number per tiller
(5) Number per m^2

Table C.8. Analysis of variance for wheat crop parameters. Experiment *C14*, 1993

EFFECT	Plant Density (pl/m²)	Plant Height (cm)	Spike Density (spikes/m²)	Spike size (grains/spike)	Thousand kernel weight (g)	Grain Yield (Kg/ha)	Nodal root axes: Pl (1)	Nodal root axes: Till (2)	Nodal root axes: m² (3)
BLOCK	ns §	ns	ns	ns	**	**	ns	ns	ns
PPLW †	*	**	ns	***	**	*	**	ns	*
PREV ‡	ns	ns	ns	ns	*	ns	ns	**	ns
PPLW * PREV ¶	ns	ns	ns	ns	ns	ns	ns	ns	ns
MEAN	258	87	404	15.2	25.7	2665	22.9	21.0	7.6
C.V.(%)	11	6	37	9	6	15	21	47	28

† Effect of Paraplow treatment
‡ Effect of previous crop
§ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)
¶ Effects of interactions between variables

(1) Number per plant
(2) Number per tiller
(3) Number per m²

Table C.9. Analysis of variance for wheat crop parameters. Experiment *C13*, 1993

EFFECT	Plant Density (pl/m²)	Plant Height (cm)	Spike Density (spikes/m²)	Spike size (grains/spike)	Thousand kernel weight (g)	Grain Yield (Kg/ha)	Nodal root axes: Pl (1)	Nodal root axes: Till (2)	Nodal root axes: m² (3)
BLOCK	ns ‡	*	ns	ns	n/a	ns	ns	ns	ns
PPLW †	ns	ns	ns	ns	n/a	**	*	ns	ns
MEAN	303	85	417	15.4	n/a	2674	22.8	12.6	6.8
C.V.(%)	15	12	32	5	n/a	17	18	30	23

† Effect of Paraplow treatment
‡ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)

(1) Number per plant
(2) Number per tiller
(3) Number per m²

Table C.10. Analysis of variance for wheat crop parameters. Experiment *RTN*, 1993

EFFECT	Plant Density (pl/m²)	Plant Height (cm)	Spike Density (spikes/m²)	Spike size (grains/spike)	Thousand kernel weight (g)	Grain Yield (Kg/ha)	Nodal root axes Pl (1)	Till (2)	m² (3)
BLOCK	ns §	ns	ns	ns	ns	***	ns	ns	ns
PPLW †	ns	**	ns	*	ns	***	**	**	ns
PREV ‡	ns	*	ns	ns	*	ns	ns	**	ns
PPLW * PREV ¶	ns	ns	ns	ns	ns	ns	ns	ns	ns
MEAN	286	87	481	16.0	26.6	2631	27.0	16.8	7.5
C.V.(%)	13	3	42	7	7	9	23	49	30

† Effect of Paraplow treatment
‡ Effect of previous crop
§ ns Effect not significant (p<0.10)
* Effect significant (p<0.10)
** Effect significant (p<0.05)
*** Effect significant (p<0.01)
¶ Effects of interactions between variables

(1) Number per plant
(2) Number per tiller
(3) Number per m²

Table C.11. Analysis of variance for wheat crop parameters. Experiment *C14*, 1994

EFFECT	Plant Density (pl/m²)	Plant Height (cm)	Spike Density (spikes/m²)	Spike size (grains/spike)	Thousand kernel weight (g)	Grain Yield (Kg/ha)	Nodal root axes Pl (1)	Till (2)	m² (3)
BLOCK	ns §	ns	*	***	ns	ns	ns	**	ns
PPLW †	***	*	**	**	*	***	ns	ns	ns
PREV ‡	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPLW * PREV ¶	ns	ns	ns	ns	ns	ns	ns	ns	ns
MEAN	214	74	422	17.9	36.5	4553	25.2	11.2	6.1
C.V.(%)	10	3	9	3	3	19	31	22	29

† Effect of Paraplow treatment
‡ Effect of previous crop
§ ns Effect not significant (p<0.10)
* Effect significant (p<0.10)
** Effect significant (p<0.05)
*** Effect significant (p<0.01)
¶ Effects of interactions between variables

(1) Number per plant
(2) Number per tiller
(3) Number per m²

Table C.12. Analysis of variance for barley crop parameters. Experiment *RTN*, 1992

EFFECT	Plant Density (pl/m²)	Plant Height (cm)	Spike Density (spikes/m²)	Spike size (grain/spike)	Thousand kernel weight (g)	Grain Yield (1) (Kg/ha)	Bird Damage (2)
BLOCK	ns §	ns	**	**	ns	***	***
PPLW †	***	*	*	ns	ns	**	*
PREV ‡	**	ns	ns	ns	*	ns	ns
PPLW * PREV ¶	ns	ns	ns	ns	ns	**	ns
MEAN	225	59	481	21.7	50.6	3718	4.25
C.V. (%)	9	10	17	6	4	14	24

	14 Sep.				30 Sep.						14 Oct.		
		Nodal root axes			Root length density (m / m²)			Nodal root axes			Nodal root axes		
EFFECT	Rooting Depth (cm)	Pl (3)	Till (4)	m² (5)	Sem (6)	Nod (7)	Tot	Pl (3)	Till (4)	m² (5)	Pl (3)	Till (4)	m² (5)
BLOCK	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns
PPLW	**	ns	**	*	ns	ns	ns	ns	**	**	**	ns	ns
PREV	ns	ns	ns	ns	**	**	**	ns	ns	ns	ns	ns	ns
PPLW * PREV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
MEAN	16.0	8.7	2.2	2.7	347	257	604	15.6	3.8	5.0	18.8	5.0	4.4
C.V.(%)	13	18	35	28	25	22	23	19	16	17	25	24	20

	4 Nov.			1 Dec.		
	Nodal root axes			Nodal root axes		
EFFECT	Pl (3)	Till (4)	m² (5)	Pl (3)	Till (4)	m² (5)
BLOCK	ns	ns	ns	ns	ns	ns
PPLW	ns	*	ns	**	**	ns
PREV	*	ns	ns	ns	ns	ns
PPLW * PREV	*	ns	ns	ns	ns	ns
MEAN	12.3	3.5	2.9	26.6	5.6	5.7
C.V.(%)	24	28	34	43	21	40

† Effect of Paraplow treatment
‡ Effect of previous crop
§ ns Effect not significant (p<0.10)
* Effect significant (p<0.10)
** Effect significant (p<0.05)
*** Effect significant (p<0.01).
¶ Effects of interactions between variables

(1) Data corrected covariable "bird damage"
(2) Squared root of percent loss
(3) Number per plant
(4) Number per tiller
(5) Number per m²
(6) Seminal roots
(7) Nodal roots

Table C.13. Analysis of variance for barley crop parameters. Experiment *C14*, 1993

EFFECT	Plant Density (pl/m²)	Plant Height (cm)	Spike Density (spikes/m²)	Spike size (grains/spike)	Thousand kernel weight (g)	Grain Yield (Kg/ha)	Nodal root axes Pl (1)	Till (2)	m² (3)
BLOCK	ns §	ns	***	ns	***	**	ns	**	*
PPLW †	***	**	***	**	ns	***	ns	*	*
PREV ‡	ns	ns	ns	ns	ns	*	ns	*	ns
PPLW *PREV ¶	*	ns	ns	*	ns	ns	ns	ns	ns
MEAN	240	73	464	19.0	42.8	3224	21.8	9.4	6.5
C.V.(%)	8	11	25	10	5	24	28	25	39

† Effect of Paraplow treatment
‡ Effect of previous crop
§ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)

(1) Number per plant
(2) Number per tiller
(3) Number per m^2

Table C.14. Analysis of variance for barley crop parameters. Experiment *RTN*, 1993

EFFECT	Plant Density (pl/m²)	Plant Height (cm)	Spike Density (spikes/m²)	Spike size (grains/spike)	Thousand kernel weight (g)	Grain Yield (Kg/ha)	Nodal root axes Pl (1)	Till (2)	m² (3)
BLOCK	** §	ns	*	ns	***	**	ns	***	ns
PPLW †	ns	ns	ns	ns	ns	*	ns	**	ns
PREV ‡	ns	ns	*	ns	ns	ns	**	**	*
PPLW *PREV ¶	ns	ns	ns	ns	ns	ns	ns	ns	ns
MEAN	242	69	379	19.4	42.2	15.36	19.3	9.0	5.9
C.V.(%)	14	11	27	7	11	30	16	30	29

† Effect of Paraplow treatment
‡ Effect of previous crop
§ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)
¶ Effects of interactions between variables

(1) Number per plant
(2) Number per tiller
(3) Number per m^2

Table C.15. Analysis of variance for barley crop parameters. Experiment *C14*, 1994

EFFECT	Plant Density (pl/m²)	Plant Height (cm)	Spike Density (spikes/m²)	Spike size (grains/spike)	Thousand kernel weight (g)	Grain Yield (Kg/ha)	Nodal root axes Pl (1)	Till (2)	m² (3)
BLOCK	ns §	ns	***	ns	ns	***	ns	ns	ns
PPLW †	**	**	ns	**	*	**	*	**	ns
PREV ‡	ns	ns	ns	ns	**	ns	ns	ns	ns
PPLW *PREV ¶	ns	ns	ns	ns	ns	ns	ns	ns	ns
MEAN	235	60	403	19.4	51.8	3675	25.3	10.3	6.2
C.V.(%)	14	8	13	6	7	24	17	29	32

† Effect of Paraplow treatment
‡ Effect of previous crop
§ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)
¶ Effects of interactions between variables

(1) Number per plant
(2) Number per tiller
(3) Number per m²

Table C.16. Analysis of variance for sunflower crop parameters. Experiment *C13*, 1993/94.

Effect	Plant Density (pl/m²)	Head area § (m²/ha)
BLOCK	ns ‡	ns
PPLW †	ns	**
Mean	2.3	493
C.V. (%)	25	31

† Effect of Paraplow treatment
‡ ns Effect not significant ($p<0.10$)
* Effect significant ($p<0.10$)
** Effect significant ($p<0.05$)
*** Effect significant ($p<0.01$)
§ This variable was used as an estimator of grain yield

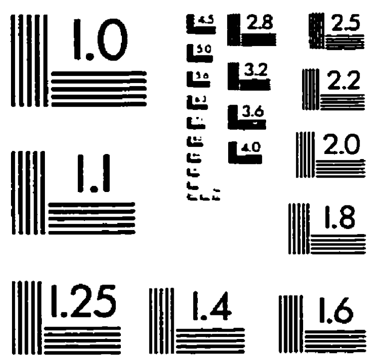
Table C.17. Analysis of variance for canola crop parameters. Experiment *C13*, 1994.

EFFECT	**Plant Density (pl/m^2)**	**Grain yield (ton/ha)**
BLOCK	ns ‡	ns
PPLW †	ns	ns
Mean	62	2.9
C.V. (%)	14	18

† Effect of Paraplow treatment

‡ ns Effect not significant ($p<0.10$)
  * Effect significant ($p<0.10$)
  ** Effect significant ($p<0.05$)
  *** Effect significant ($p<0.01$)

IMAGE EVALUATION TEST TARGET (QA-3)



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APPLIED IMAGE, Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989