SOIL PHYSICAL PROPERTIES AND ROOT DENSITY UNDER ZERO AND CONVENTIONAL TILLAGE IN THREE MANITOBA SOILS

A Thesis
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by

Daniel L. Martino

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ABSTRACT

The trend toward reduced or zero tillage systems may bring about changes in the physical environment for crop roots. A study was conducted on three Manitoba soils (Marquette heavy clay, Fortier silty clay loam, and Souris loamy sand) with the objectives of: a) assessing the effects of contrasting tillage systems on various soil physical properties; and b) relating these effects to wheat or barley response. The zero (ZT) and conventional (CT) tillage treatments had been established between 3 and 10 years prior to the initiation of the study. Penetrometer resistance, bulk density, soil moisture, pore size distribution and oxygen diffusion rate were measured at various depths and times during two growing seasons.

The effects of the tillage systems were generally low, particularly in the poorly structured Souris loamy sand. Penetration resistance in the top 10 cm of soil tended to be higher under ZT than CT. ZT also tended to produce a higher proportion of macropores (>100 μm in diameter) near the soil surface, suggesting a better preservation of biopores under this system. The aeration status of the roots may have been impaired at the beginning of the growing seasons at the finer-textured soils, but there was no evidence of a negative effect of aeration on the final root density profiles of wheat. The cone index varied markedly in time, and was related to changes in the soil water content. The proportion of roots penetrating the soil was negatively related to the resistance to cone penetration. The relationship obtained suggested that no roots penetrated the soil when the cone index was over 2 MPa. However, in most situations, roots were able to grow in soil with high mechanical impedance, probably by making use of spatial and temporal heterogeneity in the soil structure.

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INTRODUCTION

An increasing proportion of the agricultural land in the world is cropped under some form of reduced or zero tillage. A number of factors are responsible for this, among them: the accelerated incidence of soil erosion in many agricultural regions; the need for expanding cropping areas without compromising the future productivity; the possibility of increasing the efficiency of water use; the increased public concern for environment preservation; the depletion of fossil fuel reserves; and the availability of herbicides, particularly glyphosate, providing alternative ways of eliminating weed competition to crops other than tillage.

The soil physical condition is affected by the tillage system, and the effect varies according to the implements used, soil type, and climate, among many other factors. Four physical properties of the soil directly affect crop productivity: water availability, oxygen diffusion, temperature, and mechanical resistance (Letey 1985). The assessment of the optimum levels of these variables is made difficult by their complex interrelations and their variation in time. The mechanical resistance offered by the soil to growing plant organs is a function of the strength properties of the soil and the presence of a continuous system of macropores (Barley and Greacen 1967) and interacts with two of the other basic properties mentioned above: soil moisture and oxygen diffusion. The lack of tillage and the traffic of heavy machinery may lead to high mechanical resistance and low aeration levels, which could impair the adequate root development.

A study was conducted during the 1989 and 1990 growing seasons on three Manitoba soils of contrasting textures, which had been managed with different tillage systems for a number of years. The study had the following objectives: (a) to identify and quantify the effects of tillage systems on the soil mechanical resistance and some other physical properties, and their spatial and temporal variability; and (b) to relate those effects to behaviour of wheat and barley crops, in particular the final root density profiles.

LITERATURE REVIEW

1. Soil Mechanical Resistance and Root Growth

1.1 Factors Determining Mechanical Resistance

Plant roots growing in a porous medium have to overcome mechanical resistance. This is achieved either by penetrating pre-existent pores and channels big enough to accomodate the roots (Wiersum 1957), which offer little resistance; or by deforming the structure of the medium. Barley and Greacen (1967) postulated three types of deformation produced by plant organs in soils: a) tensile failure, caused mainly by thick roots; b) shear failure without compression, which would occur in pure cohesive media, like saturated clays, and c) shear failure with compression, which is the most common way in which roots deform unsaturated soils. They defined bearing capacity of the soil as the axial pressure that has to be applied to penetrate it, and it consists of three components: the pressure at the tip of the root (q_p), adhesion, and skin friction (both usually lumped together as q_f).

The bearing capacity of a soil depends on its strength properties. Soil strength is the maximal stress which can be induced in a given soil body without causing it to fail (Hillel 1980). Since roots mainly cause shearing failure and compression, the fundamental soil properties that ultimately determine the mechanical resistance of the soil to growing roots are shearing strength -which is a function of cohesiveness and angle of internal friction- and compressibility of the soil.

Among the numerous factors affecting these basic strength properties, particle size distribution, moisture content (Ayers and Perumpral 1982, Williams and Shaykewich 1970) and porosity or bulk density (Hartge 1978) appear as the most important in relation to agricultural production.

In saturated soils, cohesiveness and angle of internal friction are at their minimum, resulting in minimum soil strength. Thus, decreasing the water content results in increased shearing strength. In addition, when soil becomes unsaturated, water present in the soil pores acts as a compressive force, by drawing soil particles together. This further increases the soil resistance to shearing failure, resulting in an effective shearing stress which is higher than that determined by cohesiveness and angle of internal friction. The difference between effective shearing stress and shearing stress depends upon the soil matric potential. Williams and Shaykewich (1970) showed that decreasing the soil water potential increased the effective shearing stress so long as the degree of saturation (i.e. the degree of contact between the solid and liquid phases) was maintained at a high level. Therefore, the relationship between soil matric potential and effective stress is expected to be unique for each soil. Since soil water retention characteristic curves basically depend on the particle size distribution and structure (Gupta et al 1989), these two factors would be the most important in determining that relationship.

Hartge (1978) found that the shearing stress of a sandy soil, which had previously been compacted by different loads, was increased as the soil porosity declined. He suggested that both cohesion and angle of internal friction were properties not only of the soil material itself, but of the soil structure as well.

Resistance to cone penetration increases exponentially as the soil dries, the effect being more marked at high bulk densities (Ayers and Bowen 1987, Ayers and Perumpral 1982, Camp and Lund 1968, Gerard et al 1982, Henderson et al 1988, Mirreh and Ketcheson 1973, Taylor and Gardner 1963, Taylor and Ratliff 1969). This is the consequence of the increase in cohesiveness with decreasing soil moisture, and increase in the angle of internal friction with high bulk density. The resistance to compression also increases as the soil water potential decreases (Hillel 1980) and as bulk density increases. The two latter effects combine with those of the basic strength properties in determining high penetration resistances.

Since both moisture content and bulk density are largely variable in agricultural soils, it is expected that crop roots will normally be exposed to different levels of mechanical resistance during a growing season. The understanding of this time variation is very important in studying the relations between root growth and soil mechanical resistance.

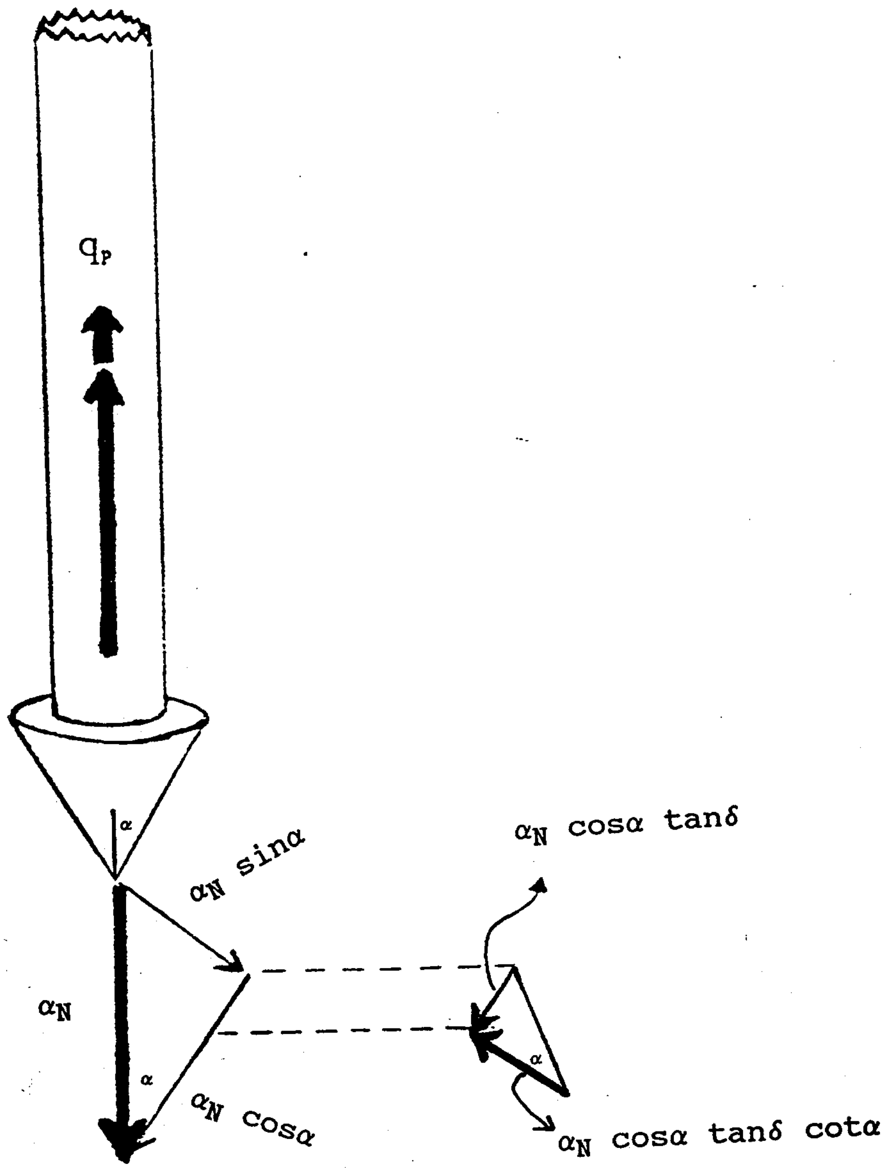
1.2 The Use of Metal Probes to Measure Mechanical Resistance

The complexity of the mechanisms and their interactions involved in soil strength and compressibility make the direct measurement of mechanical resistance very difficult. The use of metal probes of static penetration is a widespread method for empirically determining mechanical resistance of soil, cone penetrometers being the most popular type. Many different designs have been used in a wide range of applications, from civil engineering studies to determination of density of wood chips stored in bins (Perumpral 1987), to root growth studies.

The pressure at the tip of the penetrating probe (q_p) has two components: the normal stress (σ_N) on the soil and the friction between the soil and the cone. This is expressed as:

$$q_p = \sigma_N \ (1 + \tan \delta \ \cot \alpha) \tag{1}$$

where δ is the angle of soil-metal friction, and α is the included semi-angle of the cone (Fig. 1). The normal stress on the soil is largely the most complex component. As discussed below, the heterogeneous nature of the soil causes some



α = included semiangle

σ_N = normal stress

$\sigma_N \sin\alpha$ = component of σ_N normal to the cone face

$\sigma_N \sin\alpha \cot\alpha$ = component of σ_N in the direction of the cone face

$\sigma_N \sin\alpha \cot\alpha \tan\delta$ = soil-metal friction

$\sigma_N \cot\alpha \tan\delta$ = vertical component of the soil-metal friction

δ is the angle of soil-metal friction

Figure 1. Diagram of the forces involved in a penetrometer-soil system.

deviations from this ideal relationship.

Farrell and Greacen (1966) provided the first theoretical analysis of soil-probe mechanics for agricultural soils. They considered compressibility along with strength properties to calculate σ_N, which was equated to the pressure necessary to form a spherical cavity around the tip of the cone. The volume of the cone was assumed to be accomodated by compressing the soil, causing plastic deformation in the region adjacent to the probe, and elastic deformation outside this zone. The calculated values for samples from three soils of varying bulk densities and water potentials were within 10% of those measured with a penetrometer. The radius of the plastic zone was calculated to be 6 to 10 times the radius of the probe. Despite the good agreement between theoretical and experimental results, some limitations of the model are recognized: a) the assumption of spherical deformation would not hold close to the soil surface, where the stress is mobilized as upheaval of soil around the probe; b) because the soil is not a fluid, σ_N may not be equal to the pressure necessary to form the spherical cavity; and c) the frictional component of the point resistance can be large, and therefore, the calculated resistances would be sensitive to changes in the assumed coefficient.

In a later work, Greacen _et al_ (1968) determined that the spherical model predicted well the experimental values of mechanical resistance only when a blunt probe (α=30°) was used, but overestimated by a factor of 3 the values obtained with a sharp (α=5°) probe. Estimations were greatly improved when it was assumed that the sharp probe creates a cylindrical rather than a spherical cavity. This would also be the way in which roots deform the soil.

1.3 Probe Factors Affecting Penetrometer Resistance

Equation (1) predicts a decrease in the frictional component of penetration resistance as α increases. Bengough and Mullins (1991) determined that penetrometer resistance measured with 30 and 5° semiangle probes in sandy soils was 2.1 and 2.7 MPa, respectively. However, in practice a minimum occurs near 15-20° (Koolen and Vaandrager 1984, Voorhees et al 1975) after which the cone resistance starts to rise again. Fritton (1990) suggested that the fact that spherical expansion, which would occur at semi-angles greater than 5° (Greacen et al 1968) requires larger pressures than cylindrical expansion, would have been the reason for this effect. This can be visualized by considering that blunt probes compact the soil in the path of the probe creating a body of soil that moves ahead of it, increasing the frictional resistance offered by the soil. Sharp cones, on the other hand, only compact the soil laterally, and this would not cause any interference.

Taylor and Ratliff (1969) reported that penetration resistance measured by a 3.18-mm-diameter, 30°-semiangle cone was 1.33 times larger than that measured by a cylindrical (equivalent to 90° semiangle) penetrometer with a diameter of 4.8 mm. This seems to contradict the existence of a minimum in the relation between resistance and probe angle. However, the results might have been affected by the different diameters of the probes used, as discussed below.

The size of the probe is an additional factor affecting the measured stress, although no effect would be expected according to equation (1). If the size of soil aggregates and primary particles is significant in relation to the probe diameter, the pressure (not total force) necessary to penetrate the soil increases as the probe size decreases.

Whiteley and Dexter (1981) found that, as expected, the force required increased linearly as a function of the projected area of the cone, for probes ranging between 1 and 2 mm diameter, but the function had a positive intercept. The authors explained this was due to what they termed an extra component of the probe diameter. It can be shown that the point pressure (q_p) is a quadratic function of the inverse of the diameter, with infinite pressure at zero diameter, and asymptotically approaching a minimum pressure as the diameter increases. If the 'extra' component is low, that minimum is reached at relatively low probe diameter. They found that the extra component was around 0.6 mm for a wide range of soils in

Australia. Using this figure, and assuming that the resistance is constant when it is 10% over the minimum, it can be calculated that the minimum cone diameter that does not affect the measured resistance would be in the order of 12 mm.

The reasons for the effect of probe size are not completely clear. A hypothesis is that a large proportion of the aggregates that make contact with the probe are pushed downwards if the probe is fine, which would be associated with high resistance, while this proportion decreases as the size increases. Bradford (1980) did not find any difference in resistances between 3.76- and 5.14-mm diameter probes, although the smaller probe showed larger variability in measurements, indicating an effect of soil structure.

Since soil compression is a time-dependent process, the rate of penetration can also modify the measured values of point resistance. Slowly moving probes would allow the soil particles being stressed to rearrange and transmit the pressure to particles located further away, with the result of a relatively lower reaction on the probe in comparison with faster penetrating probes. In addition, when a probe is introduced into a soil, it causes tensile failure, which may relieve stress at the tip. Because this stress relief is time-dependent, the effect would be greater with slowly moving probes (Voorhees et al 1975). The increase in penetration resistance with rate of penetration was shown by Waldron and Constantin (1970) with fine probes moving at <1 mm.min^{-1} in a loam soil and by Voorhees et al (1975) with 2.4-to-5-mm probes of varying angle at similar speeds, for a clay and a sandy loam. At higher speeds and with larger diameter cones, the effect would be negligible (Bradford et al 1971). On the other hand, Cockroft et al (1969) found that increasing penetration rate from 0.175 to 60 mm h^{-1} decreased q_p from 19.0 to 10.4 bar in a saturated clay. The effect was attributed to a local increase in the pore water pressure around the penetrating cone, which reduces the soil strength, the impact being higher with faster penetrations because of the low hydraulic conductivity of clays. This effect would be negligible in unsaturated or coarse-textured soils.

The wide variation of types of penetrometers in use causes difficulties in interpreting the meaning of a measured resistance and comparing values obtained with different instruments. Fritton (1990) attempted to standardize cone index values reported in the literature by correcting them for size, angle, shaft friction, penetration rate, sample size and depth of measurement. However, the correlation between corrected and measured values was relatively weak.

Since σ_N is the basic soil property to be measured, and the variations in penetrometer design mostly affect the frictional component of the point resistance, it would be desirable to either estimate the latter, or reduce it to a minimum. This could be achieved by rotating the probe as it advances into the soil (Barley and Greacen 1967, Waldron and

Constantin 1970), which would dissipate friction in the tangential direction. Armbruster et al (1990) developed an improved design of penetrometer which measures only σ_N by means of a force transducer located behind the cone tip. Measurements were up to 40% lower as compared with the conventional design, the difference being essentially friction.

1.4 Root Growth in Soil Media

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. These relationships can be expressed as follows:

$$\frac{dL}{L}\frac{1}{dt}=\phi\,(P-Y-M) \qquad (2)$$

where L is root length (m) capable of growth (Bar-Yosef and Lambert 1981), ϕ is the coefficient of extensibility of the root ($s^{-1}.MPa^{-1}$), P is the turgor pressure (MPa), Y is the threshold elasticity of the cell walls (MPa) and M is the soil mechanical resistance (MPa).

The maximum pressure that roots can exert (P - Y) 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 (Pfeffer 1893, compiled by Gill and Bolt 1955, Misra et al 1986b), and therefore, no growth could be expected when the resistance of the medium (M) 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 2-3×10^{-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 1987) 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 1987, 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).

Whiteley and Dexter (1983) studied the behaviour of roots in cracks of an untilled fine sandy loam. Their work provides a very good insight into the process of root growth in soils. Pea, rape and safflower roots growing in cracks oriented at angles >45° with respect to the horizontal had higher rates of elongation than the roots growing through peds, even when the crack width was less than the root diameter. When roots encountered horizontal ped surfaces, they travelled horizontally for at least 1 or 2 cm before penetrating the aggregate, and this distance increased with soil strength.

1.5 Bulk Density, Cone Index and Root Growth

Compaction and consolidation of the soil cause a shift in the pore size distribution, by decreasing the proportion of large pores, and augmenting that of smaller pores. This translates into a linearization of the water retention characteristic curves (Gupta et al 1989). Therefore, it can be expected that an increase in soil bulk density would restrict the movement of roots in soil. Veihmeyer and Hendrickson (1948) determined threshold densities above which sunflower roots did not enter the soil to be about 1.75 $g.cm^{-3}$ for sands and between 1.46 and 1.63 $g.cm^{-3}$ for clays. However, the magnitude of bulk density is dependent upon the soil texture and it does not provide information about the distribution of pore sizes, which is the basic parameter related to root proliferation. More importantly, bulk density is not related to the ease with which the pores are deformed. The soil strength as measured by a penetrometer, also called cone index, 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 cone index is an empirical determination, it appears to be a more fundamental property than bulk density because 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, 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 is 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 2 to 6 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 resistances were 3 to 5 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 than 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 resistances, adequate aeration of the roots is impaired, and the rate of elongation increases rather than decreases at low cone indeces (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 matric potential, the effect of mechanical impedance on root elongation may have been distorted either by a decline in water availability at high resistances (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 such 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) measured 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. Tillage Systems and Soil Physical Properties

The physical environment where crop roots develop is directly or indirectly determined by the method employed to prepare the seedbed. A wide diversity of tillage systems are presently in use in the world, producing various degrees of pulverization, inversion and depths of disrupted soil (Griffith et al 1986). The extremes of this spectrum are the direct drilling on undisturbed soil, and the systems based on moldboard ploughing and disc cultivations.

In this section, the physical condition of the soil produced by these two extremes, as well as the impact on the growth of roots, is analyzed.

2.1 Soil Moisture and Temperature

The net flux of radiant energy reaching the soil surface determines the scope and direction of the thermal energy and moisture exchanges within the soil-atmosphere system, and consequently, the energy availability for biological processes, such as photosynthesis and respiration. As a result of diverse tillage operations, various amounts and space distributions of surface residues can be obtained. Tillage systems also differ in the surface roughness of the soil. These two factors -residues and roughness- play a major role in the partition of energy at the soil-atmosphere interface, and regulate the soil temperature and moisture regimes.

The presence of plant residues on the soil surface increases the reflectivity of short wave radiation (Enz et al 1988), reduces the thermal conductivity (Gupta et al 1981) protecting the soil from extreme variations in temperature, alters the wind profile (Smika 1983), and acts as a snow trap in cold climates (Benoit et al 1986) and as a water reservoir in arid regions (Ross et al 1985). The increased surface roughness of tilled soils has two consequences on the rate of the vertical exchange processes. Firstly, it may cause the development of a thicker boundary layer, decreasing the intensity of forced convective movements. Secondly, it leads to an enlargement of the surface area in which free or neutral convection transfers take place (Ross et al 1985).

Generally, as a result of reduced evaporation rates, no-tilled soils usually conserve more moisture than tilled soils (Mielke et al 1986, Power et al 1986, Steiner 1989). In western Canada, the maximum differences occur early in the spring (Gauer et al 1982, Nyborg and Mahli 1989).

Numerous studies support the conclusion that tilled soils are subjected to more drastic variations in temperature than no-tilled soils (Benoit et al 1986, Gupta et al 1983, Ross et al 1985). Compared to plowed land, soils under zero tillage are cooler during the spring (Carter and Rennie 1985, Gauer et al 1982) and warmer during the winter (Benoit et al 1986). The effect of residue cover on soil temperature depends upon the moisture content. If soil moisture is high, most radiant energy is dissipated as evaporation and differences between tillage systems will be minimal, unless there is a difference in moisture content. However, under dry conditions, heat capacity of the soil declines, and the incoming energy is used to warm the soil. In this case, soils lacking an insulating layer of residues are affected more (Enz et al 1988). The insulating effect of the residue cover can be partly offset by a higher thermal conductivity in zero-till soils caused by a higher density.

2.2 Bulk Density, Pore Size Distribution and Mechanical Impedance

Any tillage operation causes an initial loosening of topsoil, the extent of which is dependent upon the tool used, soil type and environmental factors. The resultant soil structure is not static, but changes with time by the action of slumping by rain, plant growth, machinery traffic and natural aggregation by wetting-drying and freezing-thawing cycles, tending towards a characteristic equilibrium.

The near surface bulk density of soils under zero tillage is usually higher than that of ploughed soils (Bauder et al 1985, Coote and Ramsey 1983, Hammel 1989, Hill and Cruse 1985, Radcliffe et al 1988) with the maximum difference occurring in the surface 5 to 25 cm (Chan et al 1987, Culley et al 1987, Finney and Knight 1973, Francis et al 1987, Gantzer and Blake 1978, Goss et al 1984, Mielke et al 1986, Pelegrin et al 1990, Tollner et al 1984). One reason for this difference is the use of heavy machinery, which is required to seed on undisturbed soil, on soils that usually have a high moisture content in relation to previously disrupted soils. In addition, no-tilled soils undergo a large number of wetting and drying cycles without being disrupted, which in the long term causes a reduction in the soil volume.

For these reasons, equilibrium density under direct drilling is likely to be higher than for conventionally tilled soils. However, in some cases the differences in bulk density are not evident by the time of crop emergence (Burch et al 1986, Dalal 1989, Hill and Cruse 1985). Various reasons for this have been cited: insufficient number of years since establishment of treatments (Hill and Cruse 1985); amelioration of the soil structure under zero tillage due to root proliferation (Blevins et al 1985); improved aggregate size and stability with zero tillage (Burch et al 1986, Chan and Mead 1988, Dalal 1989, Francis et al 1987); and wheel traffic in wet spring conditions, particularly in low organic matter soils, associated with conventional tillage systems, which can eliminate the tilth produced by fall tillage (Culley et al 1987, Hammel 1989, Johnson et al 1989). Unger and Fulton (1990) reported a higher bulk density in the topsoil of a clay loam under conventional tillage, compared to an adjacent zero-tilled field. However, the validity of this result is questionable in view of the statistical technique used.

Changes in soil density are mainly associated with variations in the macroporosity. Cultivated land usually has a larger proportion of macropores (Finney and Knight 1973, Francis et al 1988, Goss et al 1984, Pelegrin et al 1990, Radcliffe et al 1988, Tollner et al 1984), although in some cases, higher macroporosities are observed under direct drilling (Chan and Mead 1988, Cootey and Ramsey 1983, Culley et al 1987) probably because of the presence of biochannels, as discussed below.

Tillage systems also affect the characteristics of soil pores. Under zero tillage, activity of the soil fauna is enhanced, which results in larger earthworm populations (Ehlers et al 1983, Francis et al 1987). Also, in undisturbed soils, channels created by old roots remain intact after they decompose. Gantzer and Blake (1978) determined that the number of biochannels, mostly originated by earthworms, was an average of 1225 and 712 m^{-2} in zero- and conventional tillage, respectively. Even though the difference was very small in terms of total porosity, it played a substantial role in the fluid and root movements in soil. Because of the radial compaction caused by roots, their channels are more stable than those formed by earthworms (Blackwell et al 1988). These authors also determined that vertical channels such as those created by primary roots are more resistant to the soil overburden and machinery traffic pressures.

Shrinkage cracks have been observed to be more persistent and deeper in direct-drilled soils (Ellis and Barnes 1980). These, along with the biochannels, produce a vertically-oriented porosity (Francis et al 1988) with an improved continuity (Chan and Mead 1988, Ellis and Barnes 1980, Goss et al 1984) under zero tillage. This is reflected in the commonly observed higher infiltration rates in this system (Burch et al 1986, Chan and Mead 1988, Francis et al 1988, Loch and Coughlan 1984, Radcliffe et al 1988).

Penetrometer resistance patterns roughly reflect the differences in bulk density between tillage systems. Cone indexes are usually higher in the topsoil under zero tillage (Ball and O'Sullivan 1982, Burch et al 1986, Coote and Ramsey 1983, Culley et al 1987, Francis et al 1987, Hammel 1989, Hill and Cruse 1985, Mahli and O'Sullivan 1990, Pelegrin et al 1990, Ross and Cox 1981). Very frequently, the opposite is observed in the subsurface, owing to the presence of a plough pan or a naturally compacted horizon (Bauder et al 1985, Ehlers et al 1983, Larney and Kladivko 1989, Radcliffe et al 1988, Tollner et al 1984). These plough pans can be very persistent. Radcliffe et al (1988) reported that in a sandy clay loam with low organic matter and no expanding clays, even after 20 years of no cultivation, a compacted subsurface layer was still evident. Coote and Ramsey (1983) found that penetration resistance at field capacity was higher for no-tillage in two coarse-textured soils, despite the opposite trend in bulk density. This was attributed to the poor structure, with lower porosity, in the tilled soils. The large angle of friction of sandy soils could also have been responsible for this result.

2.3 Aeration

The modifications of soil porosity discussed in the previous section induce variations in the aeration regime of roots. The reduced total porosity and the frequently higher water contents in no-tilled soils lead to increased degrees of saturation, i.e., reduced air-filled porosities (Boone et al 1976, Francis et al 1987, Gantzer and Blake 1978, Mielke et al 1986).

The aeration status of a soil can be conveniently estimated by determining the oxygen diffusion rate to a platinum microelectrode (Lemon and Erickson 1952). The critical values below which root growth and function are impaired have been determined to be in the order of 0.2 to 0.33 $\mu g\ O_2.cm^{-2}.min^{-1}$ (Erickson 1982, Stolzy and Letey 1964). The presence of dense rooting systems in soils of high bulk density may lead to very low levels of oxygen diffusion (Asady and Smucker 1989). Such conditions resemble those occurring in no-tilled land. However, Coote and Ramsey (1983) determined that the oxygen diffusion rate at a matric potential of -10 kPa was always above those critical levels in coarse-textured soils for both zero- and conventional tillage, while in heavier soils, the rates fell below those values only in the tilled soils. These results suggest that the reduced air-filled porosity under zero tillage is compensated for by the presence of a continuous system of biochannels and cracks, which would be very effective in ensuring an adequate supply of oxygen.

2.4 Root Growth

It was shown in previous sections how the soil mechanical resistance and the characteristics of the soil porous system are altered by the method of preparing the seedbed. If the development of crop roots is not limited by nutritional factors, those variations in soil physical properties regulate the density and distribution of roots in the profile.

Owing to surface compaction, root length densities in the upper soil layers under zero tillage are usually greater than those under ploughed soils (Bauder et al 1985, Ellis and Barnes 1980, Francis et al 1987, Tollner et al 1984). The main effects in wheat seem to be a decline in the rate of elongation of the primary and secondary seminal roots, as well as an induction of profuse lateral branching (Ellis and Barnes 1980, Finney and Knight 1973).

As a consequence of the improved pore continuity under zero tillage, roots are more homogeneously distributed through the soil profile than under conventional tillage (Goss et al 1984). Ehlers et al (1983) found that the penetration resistances over which root growth rates were halted were 3.6 and 4.9 MPa for the upper horizon of conventional- and zero-tilled soils, respectively, reflecting the effects of the improved pore system in the latter soils. The importance of biopores for the root development of wheat was stressed in a model by Jakobsen and Dexter (1988). They estimated that 1.5 to 2.0% of the soil volume occupied by biopores is enough to ensure maximum root penetration. In high strength soils, bioporosities as low as 0.1% significantly improved rooting depth.

3. Summary

Soil mechanical impedance, water and oxygen availability, and temperature are the four fundamental properties of the physical environment that govern root development. This review concentrated in the relations between the first factor and root growth, as well as in the interactions with oxygen and water availability. The effect of the tillage system on this physical environment was also analysed.

The soil mechanical impedance to root development can be adequately described by measuring the resistance to cone penetration, and certain characteristics of the pore system, such as the pore size distribution and the continuity of the macropores. The cone index integrates some soil properties, namely, the shearing strength (determined by the cohesiveness and the angle of internal friction) and the compressibility, which affect directly the growth of roots.

Several characteristics of cone penetrometers affect the magnitude of stress measured. The interference caused by soil-probe friction (Fig. 1) can be minimized by using cones with semiangles of 15°. The point pressure increases as the cone diameter decreases below certain limit, which some workers have determined was about 12 mm. Increasing the rate of penetration also increased the measured resistance by the soil, particularly at speeds lower than 1 mm h^{-1}. The use of standard procedures would be very desirable in order to interpret and compare results from different sources.

The maximum axial pressure that roots can exert was shown to be less than 1.3 MPa. Their growth in the presence of soil stresses higher than this value is made possible by the heterogeneous nature of the soil, i.e. the presence of biopores and cracks. The radial root pressures are also important in enlarging pores, increasing the total axial force, alleviating the stress at the tip of the root, and providing anchorage to the axial forces.

Numerous authors have reported empirical relations between cone index and root growth. Two important factors affecting this relationship are the water availability and the aeration status of the soil. In field studies or experiments done with undisturbed samples, the presence of biopores and cracks also affected the response functions of root growth to penetrometer resistance.

The bulk density of the topsoil under no-tillage is usually higher than under ploughing, mainly due to the traffic of heavy machinery and to volume changes after a large number of wetting-drying and freezing-thawing cycles. Tillage systems also differ in the distribution of pore sizes, and the continuity of the porous system. The presence of root and earthworm channels under zero tillage plays an important role in the fluid and root movements in the soil.

Penetration resistance in the topsoil is usually higher under zero tillage than conventional tillage, while the opposite is commonly found at deeper soil layers, particularly where moldboard ploughs have been heavily used. Because of the high mechanical impedance under zero tillage, roots in these soils have frequently been reported to be concentrated in the topsoil. The reduced total porosity and the frequently higher water contents in no-tilled soils result in high degrees of saturation, i.e., reduced air-filled porosities. The high root density and the low air-filled porosity may lead to restrictions in the oxygen diffusion to roots growing in the surface layer of no-tilled soils. However, it has been shown that this restriction can be compensated for by a continuous system of macropores and the short distance to the atmosphere.

MATERIALS AND METHODS

Field determinations were done during two growing seasons (1989 and 1990) in three soils. Some physical properties of these soils are shown in Table 1. A description of each experiment follows.

Table 1. Physical properties of the surface horizon of the three soils used, determined on disturbed samples.

	Souris (SW30-10-18W)	**Fortier** (3W-A 1624)	**Marquette** (NW31-12-1E)
Sand %	87	18	10
Silt %	6	42	23
Clay %	7	40	66
TEXTURE	Loamy Sand	Silty Clay Loam	Heavy Clay
Particle Density $g.cm^{-3}$	2.60	2.52	2.65
Field Capacity %[1]	12	35	45
Lower Limit %[1]	6	24	29
Liquid Limit %[1]	17	56	70
Plastic Limit %[1]	17	38	45

[1] expressed as gravimetric water content

1. Experimental Sites

1.1 Souris

A tillage x fertilization experiment was established in 1987 on a Souris loamy sand near Brandon, Manitoba (30-10-18W). The experiment had a split-plot design with four replicates. Two tillage treatments (conventional and zero tillage) were applied to main plots, which were 17 by 11 m. Conventional tillage (CT) consisted of one fall cultivation plus two spring cultivations with simultaneous harrowing every year. All sub-plots received a basic fertilization of 130 kg $N.ha^{-1}$, 25 kg $P.ha^{-1}$ and 30 kg $S.ha^{-1}$, and variable rates of K and Cl. Most determinations were done in plots receiving 100 kg $K.ha^{-1}$. Penetrometer resistance was measured in all sub-plots. Fertilizer was incorporated in both Zero tillage (ZT) and CT, causing some soil disturbance in the ZT plots. Spring wheat cv. 'Columbus' was seeded in 1989, and spring barley in 1990, both in rows 20 cm apart.

1.2 Fortier

A randomized complete block experiment with two tillage treatments (CT and ZT) and four replicates was established in 1979 on a Fortier silty clay loam near Portage la Prairie, Manitoba. Plots were 15 m by 30 m. Each block had one CT and seven ZT plots. These had been managed with various crop rotations until 1982, and subsequently, homogeneously with a continuous cereal rotation. Spring wheat cv. 'Katepwa' was seeded both in 1989 and 1990.

In the fall of 1989 two ZT plots in each block were tilled, one with a moldboard plow, and the other with a chisel plow. Spring cultivation was the same for all tilled plots. Penetration resistance and root density were the only variables measured in the treatments added in 1990.

1.3 Marquette

A farm field was divided into three 3.6-ha areas, and each of them received a different tillage system. The soil was a Marquette-Red River heavy clay, located near Grosse Isle, Manitoba (NW31-12-1E). Treatments started in 1987. Minimum tillage (MT) consisted of two tandem disc operations in the fall plus a heavy duty cultivation and harrowing in the spring. CT was similar, except that two cultivations were performed in the spring. In 1990 this treatment (CT) was eliminated. ZT received two harrowings each year which caused some disturbance in the soil surface. Spring wheat cv. 'Neepawa' was seeded in both years.

All measurements were done adjacent to the boundaries between treatments, which resulted in four sampling areas (50 m by 20 m each): ZT, MT(North), MT(South) and CT. In 1990, only two sampling areas were used (ZT and MT).

2. Procedures

2.1 Penetration Resistance

Penetration resistance was measured by a hand-held recording cone penetrometer (Anderson et al 1980) to a depth of 52.5 cm in 3.5-cm increments. The number of replications varied according to the sampling date, and was between 16 and 24 (Souris), 20 and 30 (Fortier), and 50 and 60 per plot (Marquette). The cone used had an included semi-angle of 15° and a diameter of 12.83 mm. The penetration rate was approximately 10 $mm.s^{-1}$. The soil moisture content was determined simultaneously with each penetration resistance measurement.

At the Marquette site, penetration resistance at the 4-leaf stage was measured in points 1 m apart, along a transect perpendicular to the border between treatments in 1989, and in points 2 m apart along three transects in 1990. The location in the field of each sample was recorded in these cases.

Penetration resistance was also measured at crop maturity, in 50 random points within each sampling area in 1989 and 1990.

At the Souris and Fortier sites, measurements were made three times in every season: at the four-leaf stage, at mid-tillering and at crop maturity (Tables 9 and 15).

2.2 Bulk Density

Bulk density was determined by the 'auger' method (Zwarich and Shaykewich 1969), to 60-cm depth in 15-cm increments. Cylindrical holes approximately 10 cm in diameter, and 15 cm in depth, were made with an Iwan-type auger. The soil taken from the holes was weighed, and its moisture content determined in the laboratory. The diameter at the base of the hole was measured with a caliper, and the mean height with a ruler. The number of replicates sampled was four (1989) and two (1990) per plot in the Souris and Fortier soils, respectively, at the crop stages indicated in Tables 9 and 15. At the Marquette soil, eight and four sites per plot were sampled at the mid-tillering stage in 1989 and 1990, respectively. Samples were arranged in a 5 m x 5 m grid pattern at the boundary between sampling areas.

2.3 Pore Size Distribution

The equivalent cylindrical radius of the soil pores was derived from the equation relating the rise of water in a capillary tube against the force of gravity to the capillary diameter:

$$h = \frac{2T\cos\alpha}{rdg} \qquad (3)$$

where h is the height of the water column (m), T is the surface tension of water (0.0727 $\mathrm{Nm^{-1}}$ at 20°C), α is the angle of contact between the water surface and the tube (assumed to be 0 for soils), r is the radius (m) of the largest pore which is filled with water, d is the density of water (10^3 $\mathrm{kg.m^{-3}}$), and g is the acceleration due to gravity (9.81 $\mathrm{m.s^{-2}}$). Evaluating all the constants, and solving for r, equation (3) can be expressed as follows:

$$r = \frac{14.8}{h} \qquad (4)$$

where r is now expressed in μm.

Undisturbed soil cores were taken in copper cylinders (4.0 cm diameter and 1.5 cm height) from a depth of 10 cm. The number of samples taken was three (Fortier and Souris) and 12 (Marquette) per plot. The cores were placed on tension plates, and the water content at 1, 3, 9, 27 and 81 cm of water tension was determined, corresponding to 1480, 493, 164, 55 and 18 μm pore radius, respectively. Equilibration time at each water tension varied between 2 and 4 weeks, being shorter for the sandy soil.

2.4 Oxygen Diffusion Rate

The flow rate of oxygen to a Pt electrode with a potential of -0.65 V with respect to a Ag/AgCl electrode, was derived from the amperage of the electric current generated, according to the method proposed by Lemon and Erickson (1952). The equilibration time was 4.5 minutes. The oxygen diffusion rate was measured at four sites in each plot, with 10 replications in each of those positions. The Pt microelectrodes were placed at 10-cm depth in all cases. This parameter was only measured at the mid-tillering stage in 1990 in all three sites.

2.5 Plant Density and Yield

The plant population densities after emergence were determined by counting the number of plants in 1-m portions of the crop rows. Eight counts per plot were made at the Fortier and Souris soils, and 20 at the Marquette site.

After crop maturity, the aerial portion of four 1-m^2 areas within each plot was harvested, and the weight of grain and straw determined. At Souris (1989) grain yield was determined by using a combine.

2.6 Root Density

Root density was determined by the 'core-break' method (Böhm 1979). Soil cores 7.5-cm in diameter were taken at the end of the growing season in each site, and the number of roots visible on the exposed faces after breaking the cores at the desired depth was recorded. Root counts were made at 7.5, 22.5, 37.5 and 52.5 cm of depth. In the Fortier and Souris experiments, six sites per plot were sampled in 1989, and eight in 1990. At Marquette, the number of samples per plot was 12 and 15 in 1989 and 1990, respectively.

In 1989, samples were dried at 60°C for 48 hours, and stored in plastic bags. Root counts were made 60 to 90 days later. In 1990, counts were made directly in the field, and no samples were stored.

2.7 Statistical Procedures

Data from the Fortier and Souris experiments were analyzed by conventional statistical procedures. Where different depths were involved, the model used for the analysis of variance corresponded to a strip-plot design (Gomez and Gomez 1984), with depths being the non-randomized source of variation.

Due to the lack of experimental design, conventional statistical methods could not be employed at Marquette. In most cases, the standard deviation around the treatment means was the only estimation of experimental error. Penetrometer resistance data at the four-leaf stage was analyzed by geostatistical procedures (Oliver 1987, Trangmar et al 1985, Warrick et al 1986). Semivariograms were produced for all depths corresponding to the ZT and MT(North) areas. Semivariances were calculated as:

$$\gamma(h) = \frac{1}{2n} \Sigma [Z(x+h) - Z(x)]^2 \qquad (5)$$

where n is the number of data pairs separated by distance h, and Z(x) is the value of the variable considered at position x.

The semivariances obtained were fitted to a spherical model of the form:

$$\gamma(h)=C_0+C\left[\frac{3h}{2a}-\frac{1}{2}\left(\frac{h}{a}\right)^3\right] \quad \text{for } 0<h\le a \qquad (5)$$

$$\gamma(h)=C_0+C \quad \text{for } h>a$$

where γ = semivariance (MPa^2)

h = lag distance (m)

a = range (m)

C_0 = nugget variance (MPa^2)

C_0+C = sill variance (MPa^2)

The range corresponds to the maximum distance within which measurements are spatially correlated; nugget is the portion of the total variance corresponding to distances less than the minimum lag distance used; and sill is the maximum variance obtained when points separated by distances larger than the range are considered. When the model was statistically significant ($p<0.05$), the range, nugget and sill parameters were used to estimate by block kriging (Trangmar et al 1985) the penetration resistance and its variance for a 6-m^2 area at the boundary between the treatments. Estimates from ZT and MT(North) were compared, and the variance estimates were used as experimental error.

RESULTS AND DISCUSION

1. Marquette Heavy Clay

1.1 Mechanical Impedance

Penetration resistance increased with depth, reaching levels over 3 MPa below 30 to 40 cm, at the beginning of the growing season in 1989 (Fig. 2). This indicates conditions that would completely supress root growth, except for that occurring through macropores and large biochannels. If plot averages are compared, there was no difference between zero tillage (ZT) and minimum tillage (MT) in the top 20 cm of soil, while under MT, penetration resistance was larger than in ZT below that depth (Fig. 2a). However, when comparing both sampling areas within MT (Fig. 2b), a variation larger than that between tillage treatments was observed. When the position of the measurements was considered, it was found that soil strength was spatially correlated. Semivariograms were produced for all depths corresponding to the ZT and MT(North) areas (Table 2). The range is the distance within which measurements are spatially correlated. It varied between 0 and 36 m. The nugget reflects the portion of the total variance corresponding to distances less than the minimum lag used (1 m). The sill is the variance obtained when points that are separated by distances larger than the range are considered.

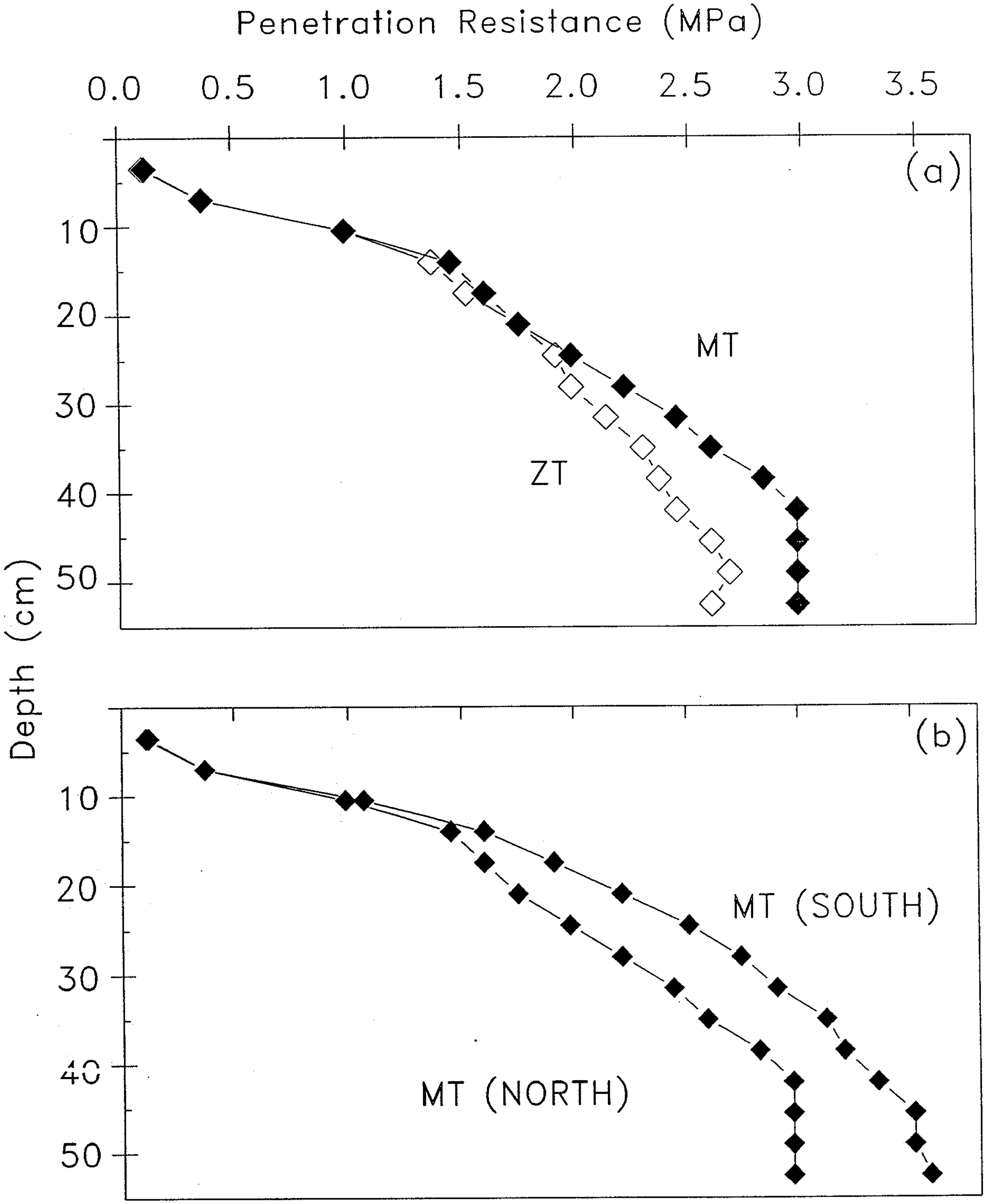


Figure 2. Penetrometer resistance profiles at the four-leaf stage, Marquette 1989. Points are the average of 50 positions. (a) Comparison between ZT and MT(North). (b) Comparison between both MT areas.

Table 2. Semivariogram parameters for penetration resistance at the 4-leaf stage of the crop. Marquette, 1989.

		Spherical Model			
TREAT	DEPTH (cm)	RANGE (m)	NUGGET (MPa^2)	SILL (MPa^2)	VARIANCE (MPa^2)
ZT	3.5	<1	--	--	0.005
ZT	7.0	<1	--	--	0.039
ZT	10.5	7	0.109	0.194	0.178
ZT	14.0	21	0.059	0.145	0.122
ZT	17.5	23	0.043	0.093	0.079
ZT	21.0	6	0.015	0.148	0.137
ZT	24.5	7	0.038	0.246	0.211
ZT	28.0	7	0.079	0.282	0.267
ZT	31.5	7	0.089	0.334	0.316
ZT	35.0	12	0.189	0.458	0.391
ZT	38.5	8	0.146	0.371	0.363
ZT	42.0	8	0.151	0.412	0.415
ZT	45.5	13	0.164	0.501	0.519
ZT	49.0	<1	--	--	0.557
ZT	52.5	36	0.258	0.571	0.507
MT	3.5	<1	--	--	0.005
MT	7.0	<1	--	--	0.028
MT	10.5	6	0.069	0.125	0.104
MT	14.0	4	0.021	0.045	0.041
MT	17.5	4	0.044	0.071	0.066
MT	21.0	3	0.047	0.113	0.105
MT	24.5	4	0.059	0.175	0.161
MT	28.0	5	0.097	0.271	0.247
MT	31.5	5	0.026	0.361	0.317
MT	35.0	8	0.051	0.383	0.341
MT	38.5	10	0.109	0.539	0.399
MT	42.0	16	0	0.674	0.379
MT	45.5	19	0	0.708	0.429
MT	49.0	19	0	0.827	0.415
MT	52.5	17	0	0.662	0.663

There was good agreement between the sill estimated by the model and the real variance (Table 2). The analysis reduced the variances by 38 to 100% as shown by the ratio nugget/sill.

The semivariogram parameters from both ZT and MT were used to estimate the penetration resistance and its variance by ordinary block kriging in a 6-m^2 common area located in the border between the treatments (Fig.3a, 1989). This analysis revealed the existence of a compacted layer of soil at a depth of 10 cm in ZT with respect to MT, while no significant differences were apparent in the rest of the profile. The lack of spatial correlation for the top 7 cm of soil, where differences between treatments would likely have been greater due to the traffic of machinery and the lack of tillage (Hammel 1989, Pelegrin et al 1990), may be explained by the harrowing that was uniformly applied to all the treatments just before seeding.

Similar trends were observed in 1990 (Fig. 3b). However, no spatial correlation was detected in this case. There are two possible reasons for this: in the first place, the lag spacing used in 1990 was 2 m, compared to only 1 m in 1989, and the measurements were more concentrated around the border line between treatments. This would increase the difficulty of detecting any correlation, although the magnitude of the ranges in 1989 (up to 36 m) would suggest that the lag distance of 2 m should have been adequate. In addition, the values for penetration resistance at the lowest depths in 1990 were substantially lower than those in the first year. This result was probably associated with the higher soil moisture content in 1990 (Table 3). It is likely that the spatial

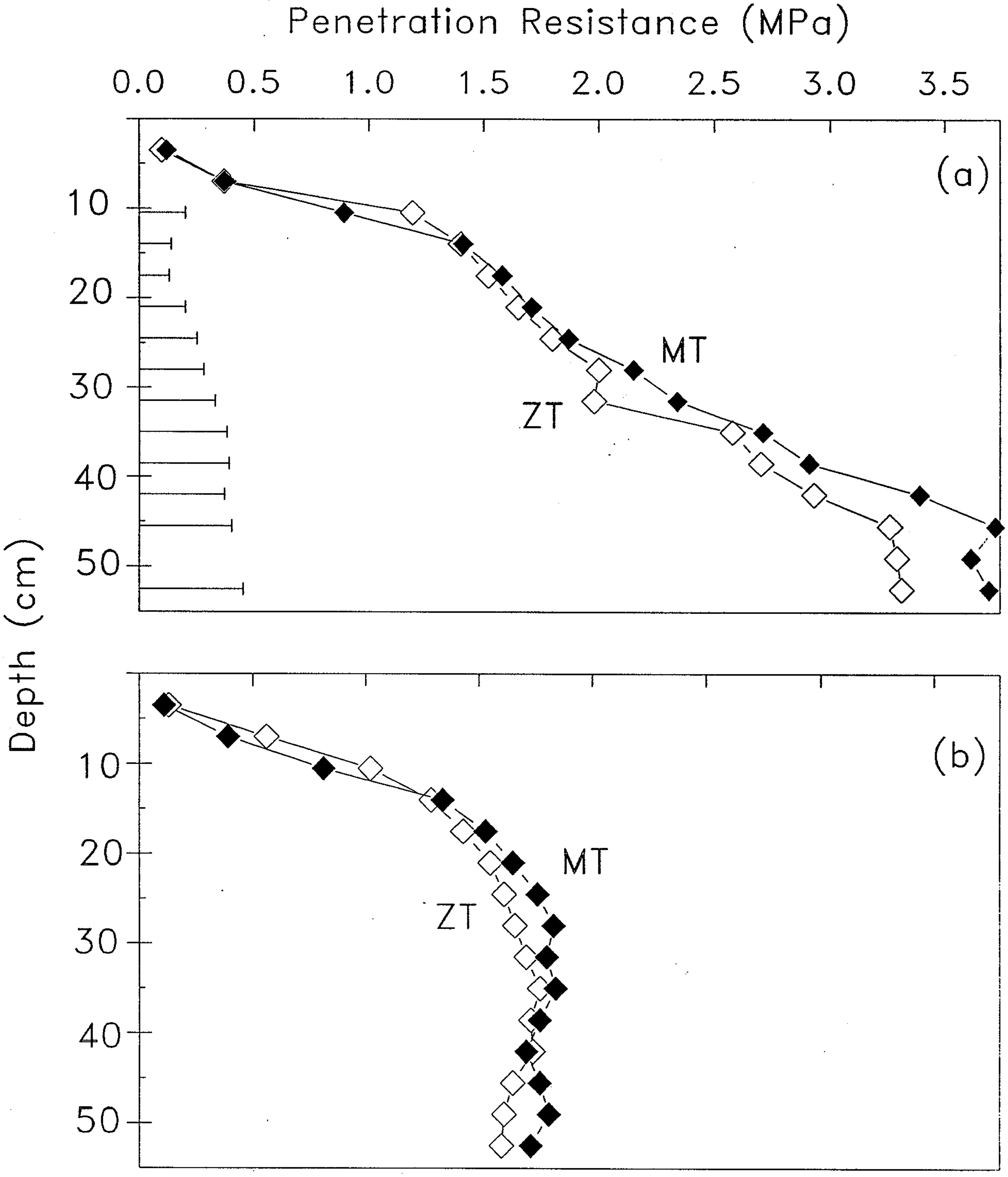


Figure 3. Penetrometer resistance profiles at the four-leaf stage, Marquette. (a) 1989. Kriging estimates from MT(North) and ZT data. Horizontal bars are the combined estimated standard deviations. (b) 1990.

correlation observed in 1989 was actually due to spatial variability in moisture content rather than in mechanical impedance. This is supported by the fact that the variability in soil moisture was higher in 1989, as evidenced from the coefficients of variation of moisture samples (Table 3).

Table 3. Soil moisture content (% by weight) at the 4-leaf stage of the crop for the minimum (MT) and zero (ZT) tillage areas. Values in parenthesis are coefficients of variation (%). Marquette, 1989 and 1990.

	1989		1990	
Depth (cm)	MT	ZT	MT	ZT
5	43.4 (5)	46.3 (11)	40.1 (6)	42.9 (9)
15	38.4 (10)	40.1 (5)	43.0 (4)	42.8 (7)
25	35.5 (13)	35.6 (4)	39.7 (8)	44.1 (3)
35	33.7 (13)	33.9 (6)	38.6 (7)	40.9 (3)
45	31.6 (6)	32.8 (15)	37.7 (5)	39.3 (6)

Even though an effort was made to select sampling areas of homogeneous topography, variations in microrelief would have resulted in zones with varying moisture content, particularly in relatively dry conditions, such as those in 1989. Various reports have shown that usually the structural features that determine soil strength were independent at scales over 1 m (O'Sullivan et al 1987, Perfect et al 1990), while ranges of several meters have been reported for soil water content (Warrick et al 1986).

At crop maturity, penetration resistance was higher than at the beginning of the season (Fig. 4), reflecting the decreased moisture contents. The differences between treatments were maintained throughout the crop cycle in both years.

1.2 Bulk Density and Porosity

Bulk density measured at the tillering stage also increased with depth (Fig. 5). Because of the low number of sampling sites (eight per plot), data could not be geostatistically analyzed, and thus no experimental error could be estimated to assess the significance of the differences. As with penetration resistance, it is evident that variability within MT was similar to the differences between tillage treatments (Fig. 5a). In most cases, the magnitude of the differences between treatments was less than the standard deviation of the samples taken from each area (Table 4), suggesting a negligible effect of the tillage system. The increase in bulk density that is usually observed at the surface of no-tilled soils (Hammel 1989, Radcliffe et al 1988) was not observed here. The soil disruption caused by harrowing, and the action of freezing and thawing cycles early in the spring (Blevins et al 1985) may have been factors contributing to the lack of a tillage effect. However, as suggested by cone resistance measurements, an increase in soil

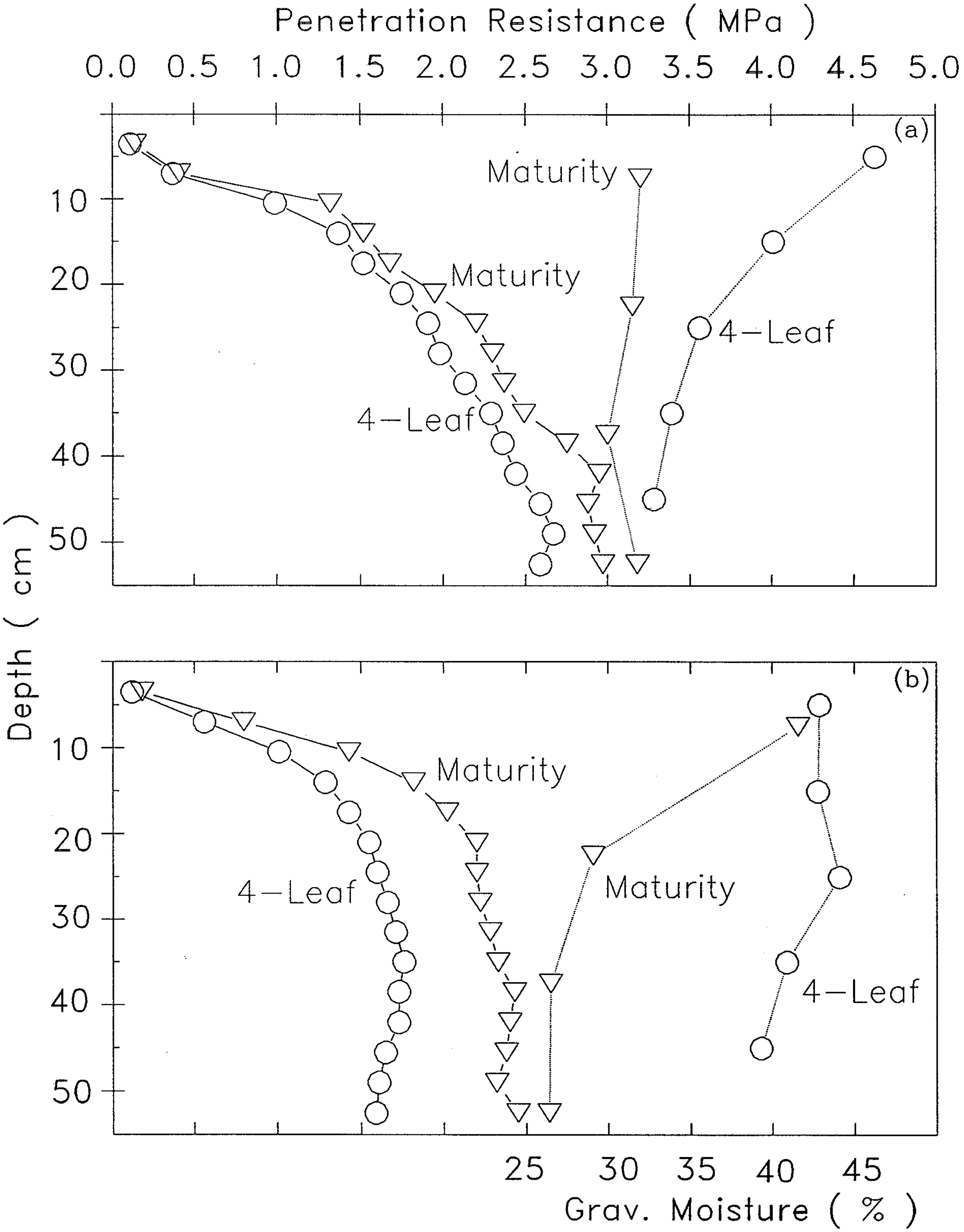


Figure 4. Penetrometer resistance (solid lines) and gravimetric water content (dashed lines) profiles for the ZT and MT(North) sampling areas at the 4-leaf stage and crop maturity at Marquette.(a) 1989.(b) 1990.

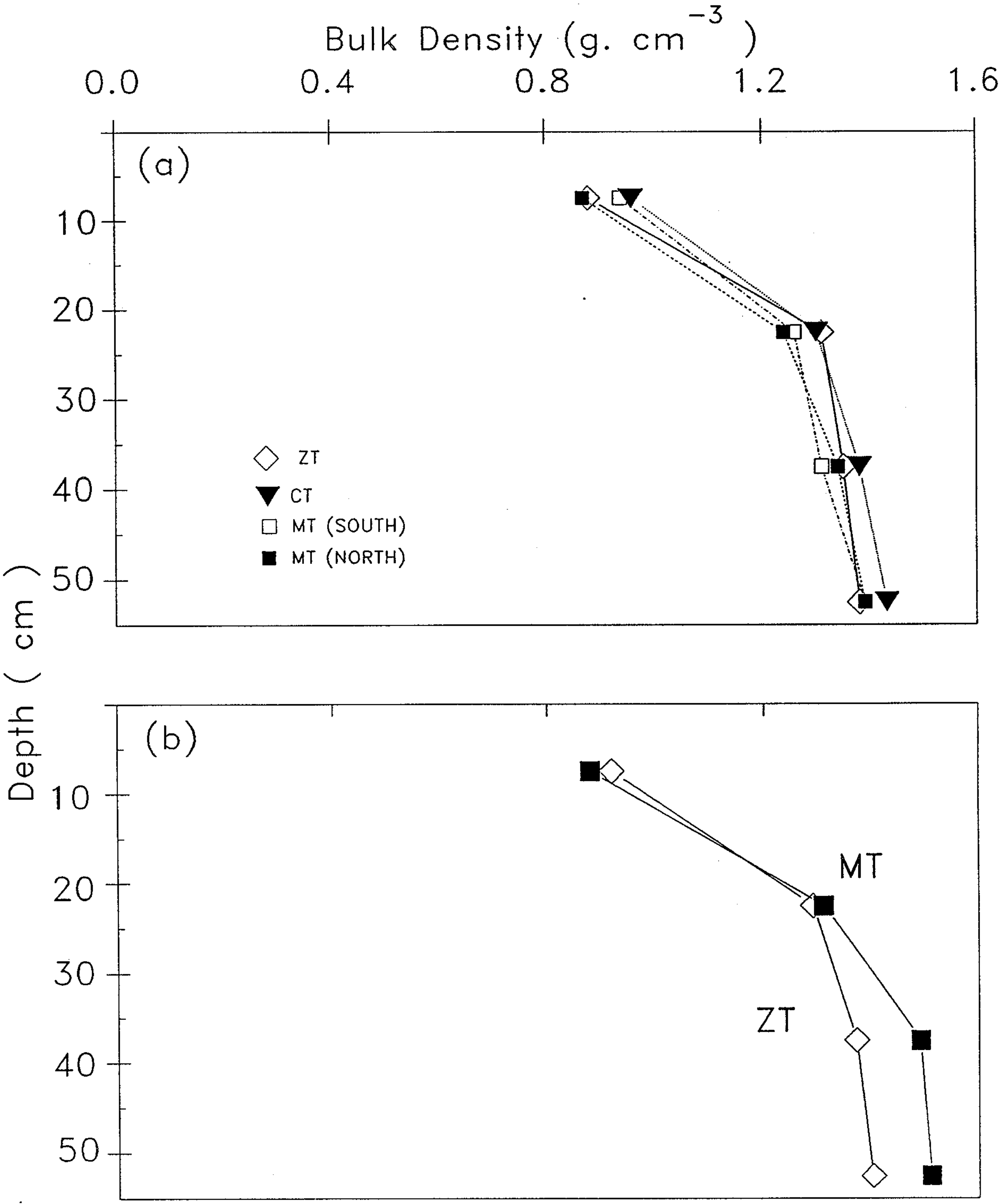


Figure 5. Bulk density profiles at mid-tillering in Marquette. (a) 1989. (b) 1990.

density at about 10 cm depth under ZT may have occurred. This was probably not detected by the method used to measure bulk density, which averaged the entire 15-cm top layer of soil.

Table 4. Soil bulk density (g.cm^{-3}) at the tillering stage of the crop for the minimum (MT) and zero (ZT) tillage areas. Values in parenthesis are standard deviations. Marquette, 1989 and 1990.

	1989		1990	
Depth (cm)	MT	ZT	MT	ZT
0-15	0.87 (0.05)	0.88 (0.07)	0.88 (0.05)	0.92 (0.09)
15-30	1.24 (0.05)	1.31 (0.05)	1.31 (0.06)	1.29 (0.12)
30-45	1.34 (0.06)	1.35 (0.07)	1.49 (0.17)	1.37 (0.11)
45-60	1.39 (0.06)	1.38 (0.13)	1.51 (0.05)	1.40 (0.05)

Soil porosities were calculated by assuming that the particle density, measured at the soil surface (2.65 g.cm^{-3}), was constant throughout the profile (Table 5). Due to the high content of expanding clay in this soil, the pore space was expected to vary widely with soil moisture. The total porosity in the topsoil was similar for MT and ZT, despite the higher moisture content under ZT, suggesting that at equivalent water contents the ZT system would have shown reduced pore space in relation to MT. On the other hand, the total porosity below 30 cm depth under MT was 5 percent lower in the second year. The reasons for this were not clear, but the low water content

(29% by volume) and high bulk density (see Table 4) registered in the second year are consistent with this low porosity.

Table 5. Total soil porosity (%) at the tillering stage of the crop for the minimum (MT) and zero (ZT) tillage areas. Values in parenthesis are moisture contents (% by volume). Marquette, 1989 and 1990.

	1989		1990	
Depth (cm)	MT	ZT	MT	ZT
0-15	67 (29)	67 (33)	67 (36)	65 (38)
15-30	53 (40)	51 (48)	51 (39)	51 (38)
30-45	49 (42)	49 (47)	44 (36)	48 (36)
45-60	48 (43)	48 (43)	43 (29)	47 (37)

1.3 Pore Size Distribution

This variable was determined only at 10 cm depth in the second season (Table 6). As discussed in the previous section, there was no effect of the tillage system on the total pore space. The distribution of pore size classes was also very similar for both treatments. A trend of higher porosity in the range from 100 to 300 μm under ZT could be observed, while MT tended to give higher microporosity (<37 μm) and total porosity. No earthworm activity was observed in this soil, and therefore, the eventual improvement of the pore system under ZT would have depended exclusively on the development of root channels. This would explain the apparent increase in the porosity between 100 and 300 μm. However, the variability in porosity within treatments was fairly large (Table 6), particularly in the large pore classes. The relatively low magnitude of the difference between treatments indicated that there was no effect of the tillage treatment.

Table 6. Pore size distribution (%) at the tillering stage of the crop for the minimum (MT) and zero (ZT) tillage areas. Values in parenthesis are standard deviations. Marquette, 1990.

	Pore Size Class (μm)					
	>987	329-987	110-329	37-110	<37	TOTAL
ZT	3.6 (1.4)	2.5 (1.7)	3.5 (1.9)	9.4 (2.1)	50.3 (6.4)	67.0 (7.3)
MT	3.7 (2.5)	2.6 (1.1)	2.8 (1.2)	8.6 (1.2)	54.2 (12.2)	69.1 (12.6)

The lack of differences between treatments could be attributed to a number of factors: a) the treatments had been practised for only 4 years at the time of sampling, and this may not have been sufficient to develop long-term effects; b) the ZT crop in the previous year had been poorly established (82 plants.m^{-2} compared to 235 plants.m^{-2} in MT), which resulted in a sparse rooting system and therefore, in a low number of root channels; and c) the shrinking and swelling cycles that this soil undergoes would offset any differences created by the tillage systems.

1.4 Oxygen Diffusion Rate

There were no differences in the aeration status of the crop measured at 10 cm depth by mid-tillering in 1990 (Table 7). According to Stolzy and Letey (1964), the values observed would not cause major restrictions in root respiration. The moisture content at the time of sampling (Table 5) corresponded to air-filled porosities in the top 15 cm of 27 and 29% for ZT and MT, respectively. Below this depth, the air-filled porosity was reduced to 8-14%, suggesting that the aeration status of the roots, in this crop stage of intense activity, may have been impaired. This negative effect would have been more important under ZT, where total porosity tended to be lower, and water content higher, than under MT.

Table 7. Oxygen diffusion rate ($\mu g\ O_2.cm^{-2}.min^{-1}$) at 10 cm depth, at the tillering stage of the crop for the minimum (MT) and zero (ZT) tillage areas. Marquette, 1990.

	Oxygen Diffusion Rate		
	Average	Std. Dev.	Range
ZT	0.28	0.16	0.14-0.39
MT	0.27	0.17	0.18-0.37

1.5 Root Density

The root density profiles measured at crop maturity are the result of the action of various plant, soil and climatic factors integrated in time, and can be used as an indication of possible physical limitations to root growth, assuming there was no interference by chemical factors. Some limitations associated with this approach and with the method used to measure root density must be recognized before analyzing the information obtained: a) the final root density profile does not provide information about the timing of development during the growing season, and therefore does not allow evaluation of the effect of short-term variations in the soil properties on root growth; b) the maximum root density in wheat usually occurs before crop maturity and considerable losses of roots, particularly the smaller ones, can occur before sampling; and c) the number of roots on exposed horizontal surfaces of soil can be related in different ways to the root length density (length of roots per unit volume of soil), depending on the predominant direction of growth. However, the method has proven to be useful in comparing relative distributions of roots in the field (Drew and Saker 1980).

The root profiles were similar in both years (Table 8). MT gave higher root density than ZT, especially at the lower depths. In general, root density values were slightly lower in 1989 than in 1990, probably due to some root decomposition in the period between sampling and counting in the first season. In 1990, counting was made directly in the field. The low values for ZT below 30 cm in 1989 may have been related to the poor establishment of the crop in that year.

Table 8. Final root density (cm^{-2}) for the minimum (MT) and zero (ZT) tillage areas. Marquette, 1989 and 1990.

	1989		1990	
Depth (cm)	MT	ZT	MT	ZT
0-15	2.0	1.9	2.0	1.7
15-30	1.0	0.7	1.0	0.8
30-45	1.0	0.4	1.1	0.7
45-60	0.7	0.2	1.2	0.7

The higher root penetration under MT was consistent in both seasons, and this can be further confirmed by observing the spatial distribution of the root profiles in the two transects where samples were taken (Fig. 6). A discontinuity in the root density curves for the lower depths was observed at the boundary between treatments, in both transects. The higher penetration resistance at 10 cm depth observed under ZT (Figs. 3a and 3b) may have been one factor responsible for this result. In addition, as it was discussed in a previous section, the higher moisture content under ZT may have caused

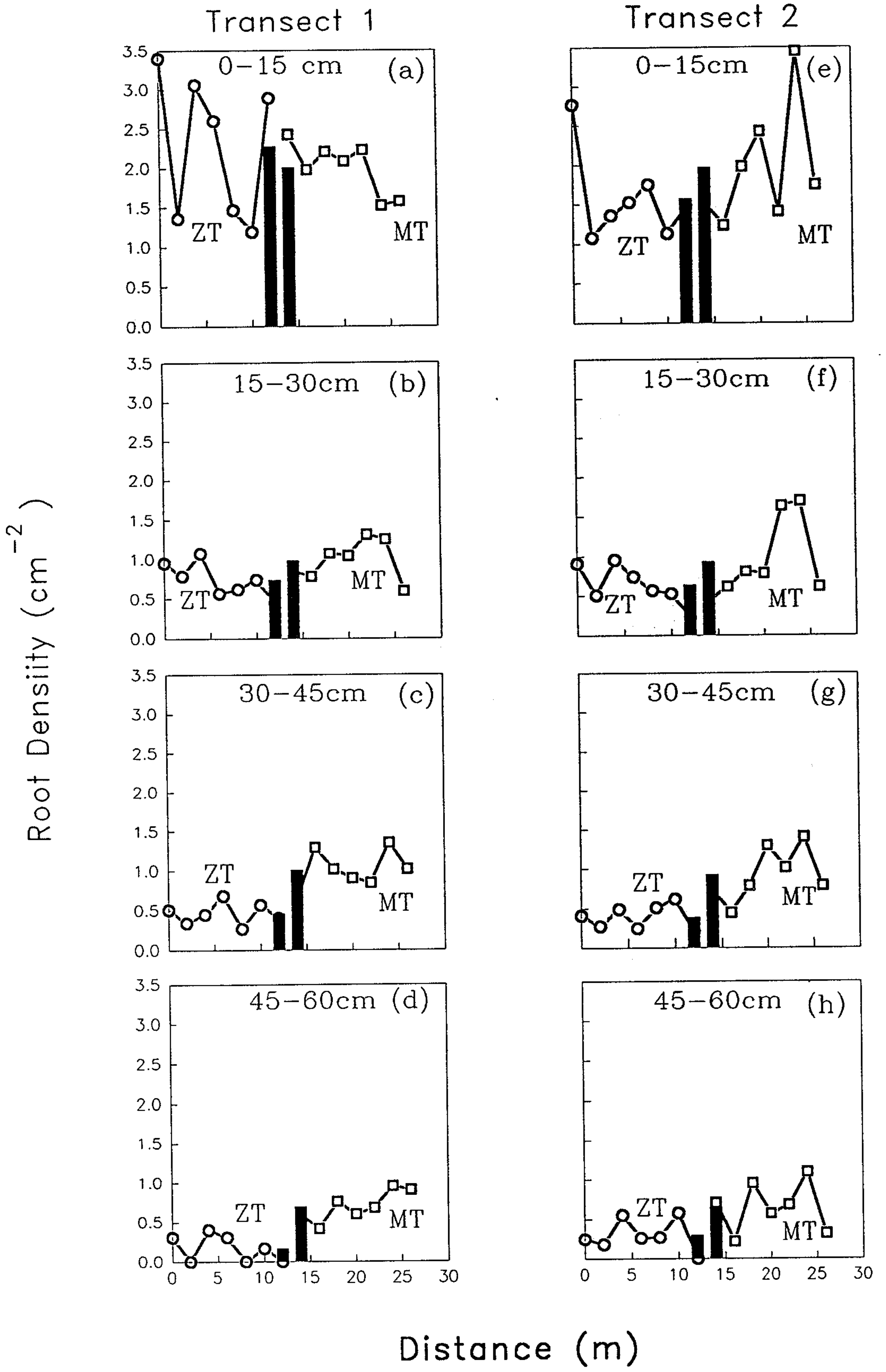


Figure 6. Root density at crop maturity, measured along two transects. Marquette 1990. (a)-(d) Transect 1. (e)-(h) Transect 2. Bars represent treatment averages.

more frequent incidence of limiting rates of oxygen diffusion to the roots. No differences were observed in pore size distribution. However, this determination did not include shrinkage cracks, which were observed (not measured) to occur more frequently under MT, possibly as a result of more extreme variations in the soil water content. The roots in the MT system would have been able to penetrate the soil along these cracks reaching lower depths than in ZT.

2. Fortier Silty Clay Loam

At a given soil depth, the effects of tillage treatment were nonsignificant ($p<0.05$) for almost all variables measured (mechanical impedance, bulk density, oxygen diffusion rate, root density, grain yield and yield components) in all sampling dates. This was also true of the interaction tillage x depth. The only exception was the pore size distribution at 10-cm depth, which was significantly affected by the tillage system (see section 2.3). On the other hand, depth effect was always significant for bulk density, penetration resistance and root density. A summary of the significance of the different effects determined by analysis of variance is presented in Table 9.

Table 9. Significance of the effects (p<0.05) of the different sources of variation as determined by analysis of variance, for all the variables measured at different sampling dates. Fortier, 1989 and 1990.

		1989			1990		
Variable	Effect	4-leaf	Tillering	Maturity	4-leaf	Tillering	Maturity
Bulk Density	Block	* †	-	NS	*	NS	-
	Tillage	NS	-	NS	NS	NS	-
	Depth	*	-	*	*	*	-
	T x D	NS	-	NS	NS	NS	-
Mechanical Impedance	Block	*	*	*	*	*	*
	Tillage	NS	NS	NS	NS	NS	NS
	Depth	*	*	*	*	*	*
	T x D	NS	NS	NS	NS	NS	NS
Moisture (% vol)	Block	*	*	*	*	*	-
	Tillage	NS	NS	NS	NS	NS	-
	Depth	*	NS	*	*	*	-
	T x D	NS	NS	NS	NS	NS	-
Porosity (10 cm)	Block	-	-	-	-	NS	-
	Tillage	-	-	-	-	NS	-
Macropores (10 cm)	Block	-	-	-	-	NS	-
	Tillage	-	-	-	-	*	-
O.D.R. (10 cm)	Block	-	-	-	-	NS	-
	Tillage	-	-	-	-	NS	-
Root Density	Block	-	-	NS	-	-	*
	Tillage	-	-	NS	-	-	NS
	Depth	-	-	*	-	-	*
	T x D	-	-	NS	-	-	NS
Grain Yield	Block	-	-	NS	-	-	-
	Tillage	-	-	NS	-	-	-
Shoot yield	Block	-	-	NS	-	-	-
	Tillage	-	-	NS	-	-	-

† '*' denotes significant, and 'NS' non-significant effects (p<0.05)
'-' indicates that no measurements were made at a given sampling date

The lack of significance can be attributed to the relative weakness of the effects and to the fact that where differences between treatments occurred, it was only at a few depths, and they were overshadowed in the analysis of variance by the large number of depths with no differences. This will be discussed in detail for each of the variables in the following sections.

2.1 Mechanical Impedance

The top 15 cm of soil were more compacted under ZT than CT as evidenced from penetration resistance data (Fig. 7). The reverse tended to occur between 15 and 30 cm, although the difference between tillage treatments was statistically significant ($p<0.05$) only at the 10.5-cm depth. The same behaviour was observed in both years studied, and these soil strength profiles are similar to those obtained in the Marquette experiment. These results reveal the different modes of action of the compacting forces in the two tillage systems. While in ZT most compaction occurs by the action of wheel traffic and soil slumping at the surface, in CT compaction at a certain depth was caused by the tillage implements used.

The reduced subsurface strength under ZT may have been due to several factors: increased soil moisture content (Gauer _et al_ 1982, Griffith _et al_ 1986), aggregation by natural agents (wetting-drying and freezing-thawing cycles), and the lack of destruction of biochannels. The latter was probably an important factor in this experiment, as shown by the pore size distributions (Table 12).

As the growing season proceeded, and the soil tended to become drier, the levels of soil strength increased (Fig. 8), reaching values of up to 1.7 MPa at a depth of 20 to 30 cm by the mid-season in 1989 (Fig. 8a). The most vigorous root development would be expected at this time. Such soil

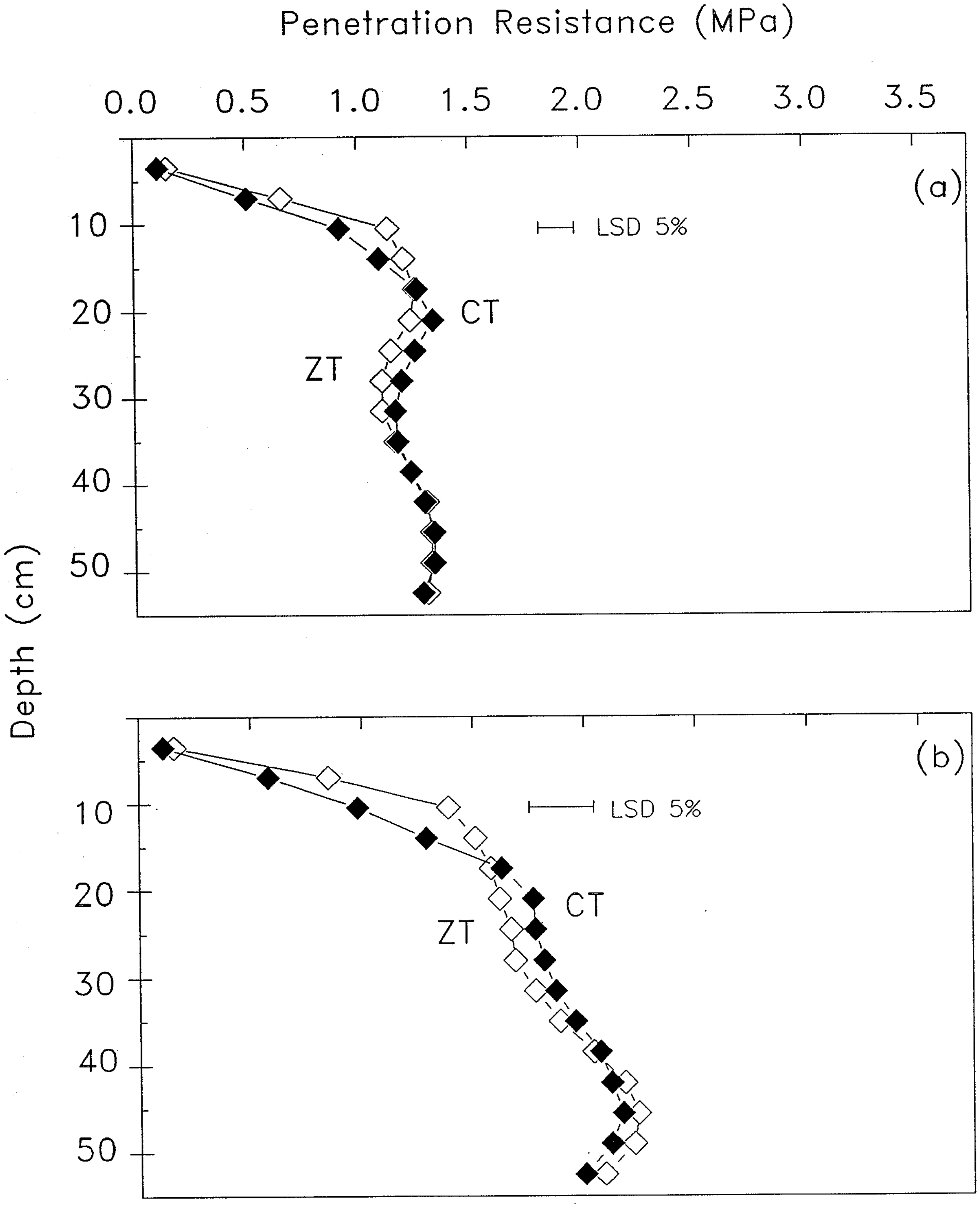


Figure 7. Penetrometer resistance profiles at the four-leaf stage in Fortier for the ZT and CT treatments. (a) 1989. (b) 1990. Bars indicate LSD's ($p<0.05$) where treatments differed at a given depth.

resistance levels would have reduced, but not completely impeded root growth (Cockroft _et al_ 1969, Ehlers _et al_ 1983, Taylor _et al_ 1966). In the 1990 season, initial soil strength levels were somewhat larger, presumably as a consequence of the lower water content. The differences between tillage systems were present in both growing seasons.

The two tillage treatments introduced in 1990 (moldboard and chisel plow) were effective in reducing the surface compaction of the ZT plots (Fig. 9). While the effect of the moldboard plow was restricted to the upper 15 to 20 cm (Fig. 9b), the chisel plow also caused some reduction in the soil strength at the deeper soil layers (Fig. 9a), which was significant ($p<0.05$) at the 45-cm depth. One possible explanation is that the chisel could have improved the infiltration of water from autumn rainfalls, causing higher soil moisture contents and therefore, lower strengths deep in the soil. This is supported by the fact that most of the variation in penetration resistance was explained by changes in the soil water content, as will be discussed below. Unfortunately, soil moisture content was not determined for these two treatments, and this hypothesis could not be tested.

The magnitude of the variations in penetration resistance with soil moisture can be illustrated by the effects of a single 32-mm rain event during the tillering stage of the crop in 1990 (Fig. 10). Even though the moisture contents three days after the rain were only slightly increased in the

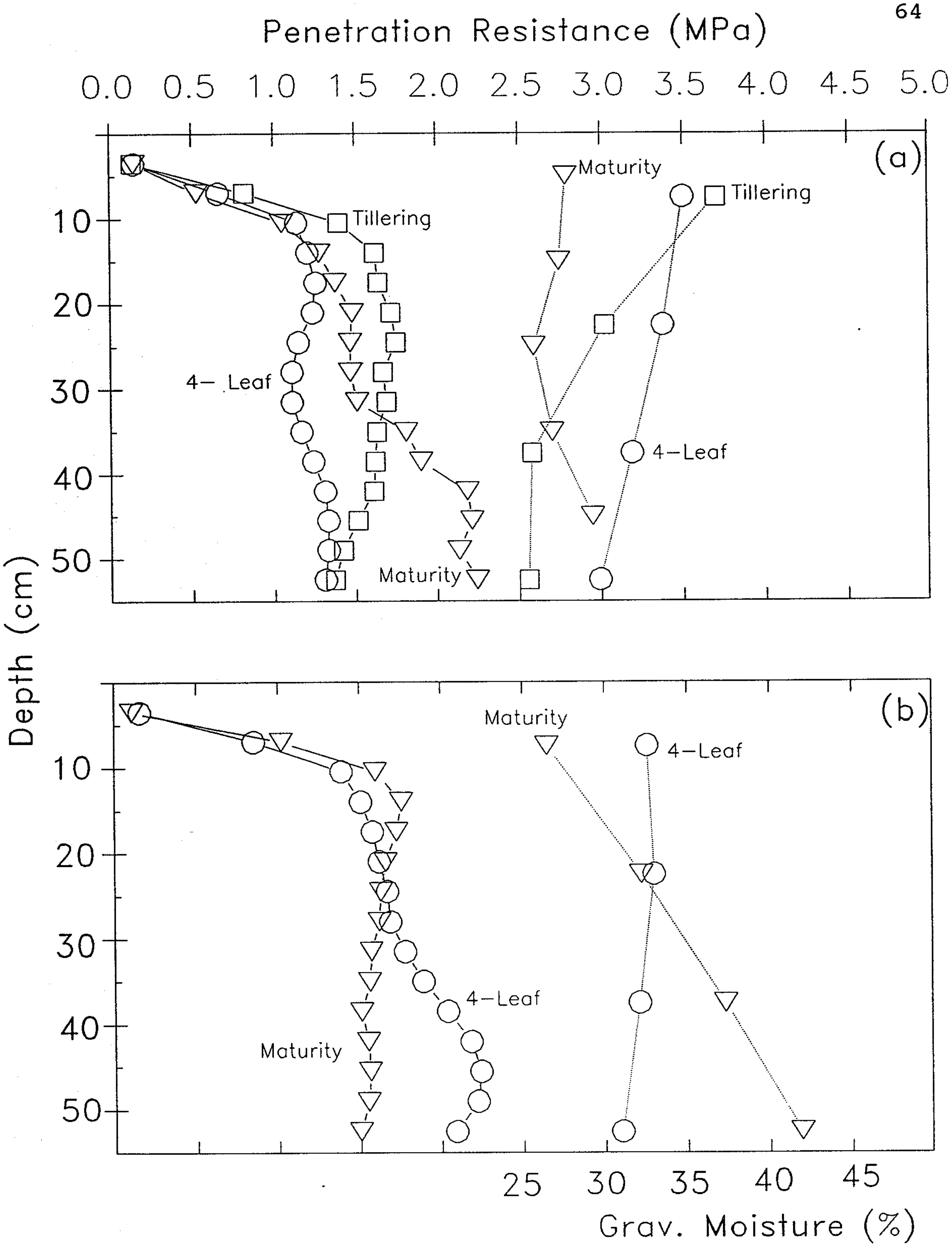


Figure 8. Evolution in time of the penetrometer resistance (solid lines) and gravimetric soil moisture (dashed lines) profiles for the ZT treatment at Fortier. (a) 1989. (b) 1990.

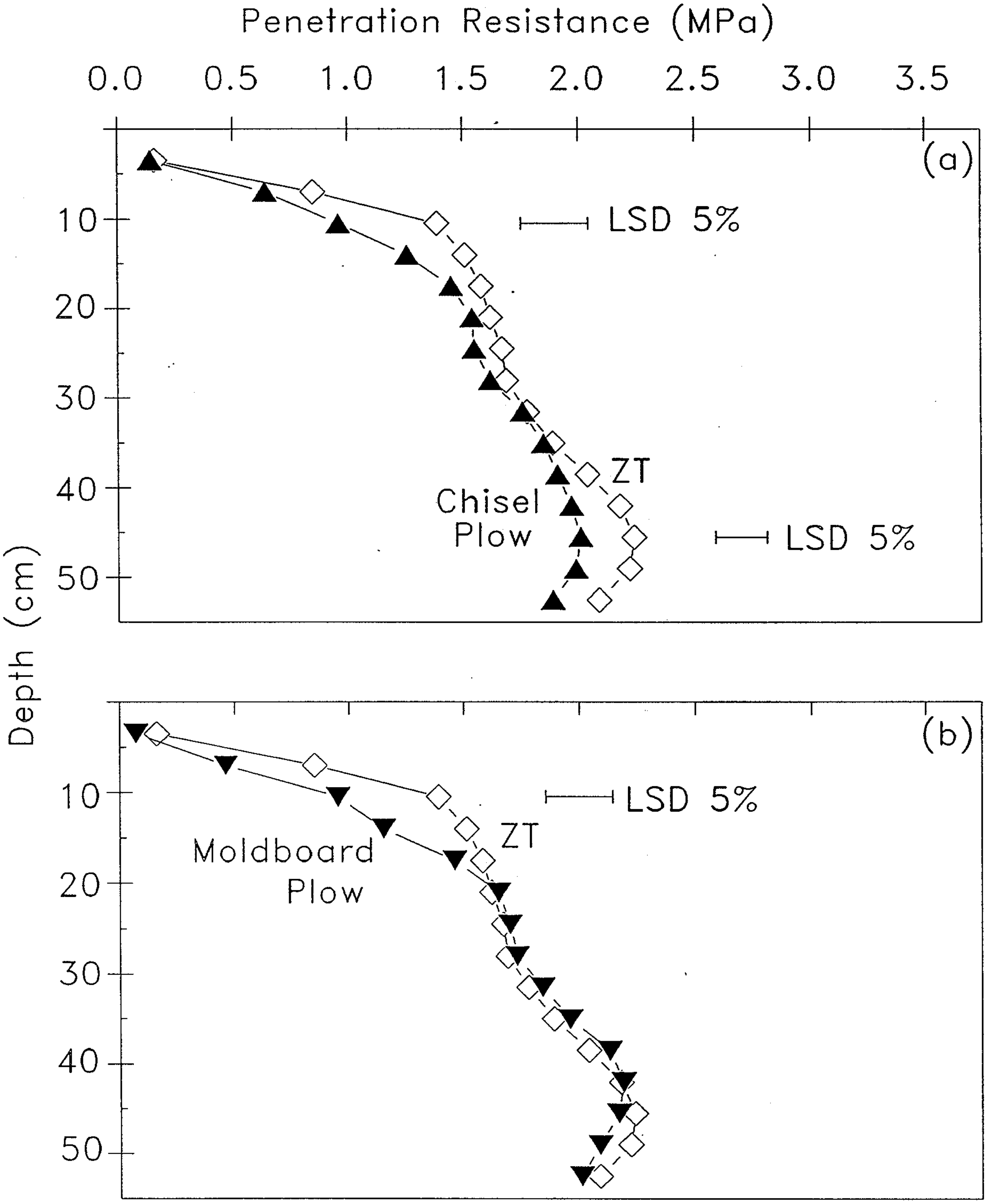


Figure 9. Penetrometer resistance profiles at the four-leaf stage for the chisel and moldboard plow treatments at Fortier, 1990. Comparison between ZT and chisel plow (a) and ZT and moldboard plow (b).

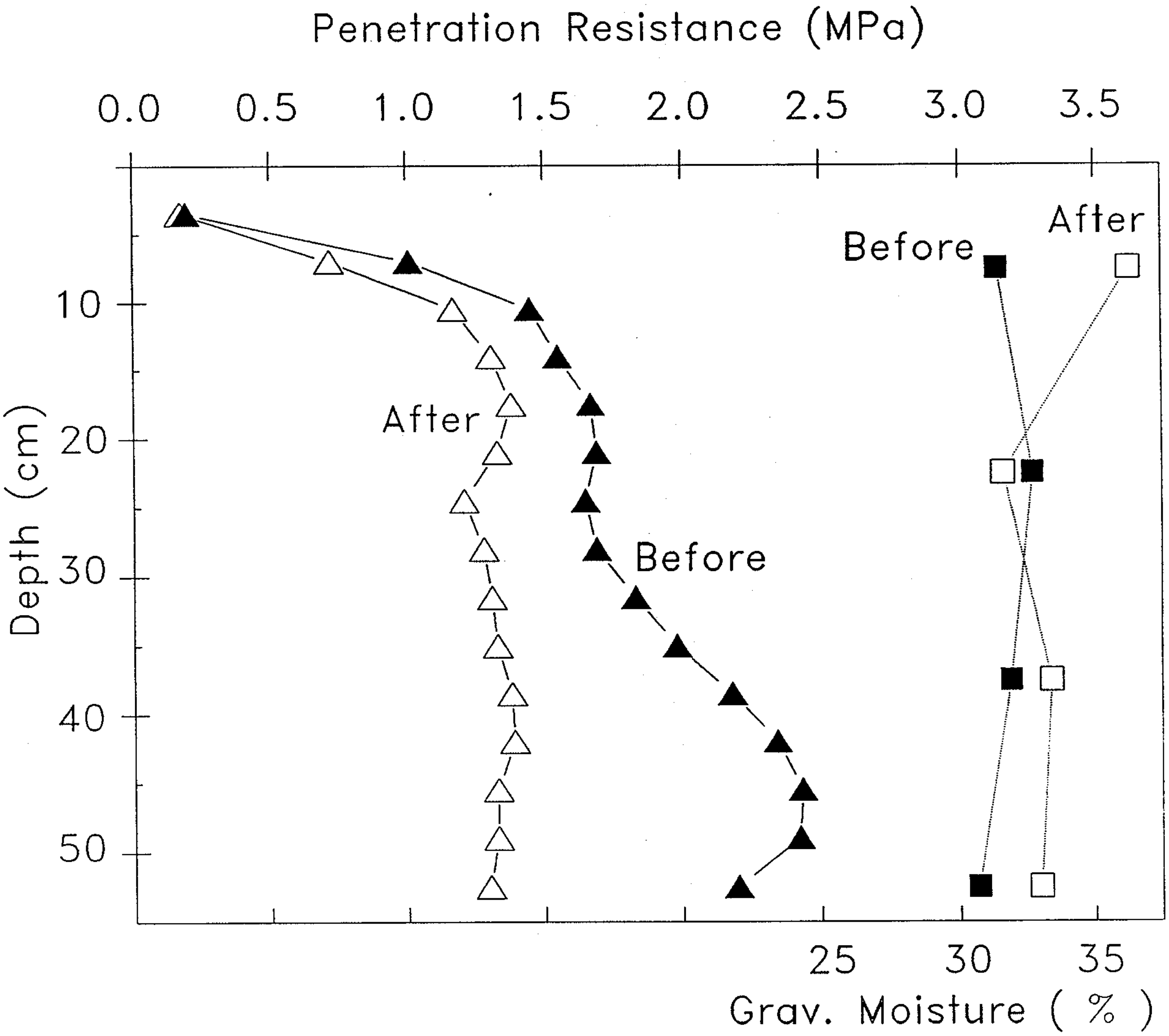


Figure 10. Effect of a 32-mm rainfall on the penetrometer resistance profile under ZT at Fortier.

subsoil, the levels of mechanical impedance were reduced by up to 50%. The effect of rainfall on penetration resistance in the deepest soil layers was higher under ZT (not shown), suggesting an improved infiltrability in this treatment. Such dramatic short-term variations in soil strength could be very important in the dynamics of penetration of soil by roots, and this suggested that the minimum values of penetration resistance would be the most relevant in determining the effect of this parameter on root growth.

2.2 Bulk Density and Porosity

Bulk density at the beginning of the first season was significantly higher under ZT than CT in the top 15 cm of soil (Table 10), while no differences were detected at lower depths. This difference had disappeared by harvest time, when bulk density profiles for both treatments were virtually identical. Despite the decreased soil moisture content, bulk density at harvest (1989) was lower than at the four-leaf stage, particularly at lower depths. No explanation could be found for this result.

Table 10. Bulk density (g.cm^{-3}) and gravimetric soil moisture content (%) at different sampling dates: (a) 4-leaf stage 1989; (b) harvest 1989; (c) 4-leaf stage 1990; and (d) tillering 1990. Fortier.

	CT				ZT			
DEPTH (cm)	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)
				Bulk Density (g.cm^{-3})				
0-15	1.00	0.97	1.06	0.96	1.09	0.99	1.12	1.02
15-30	1.31	1.24	1.26	1.24	1.29	1.24	1.32	1.28
30-45	1.35	1.24	1.37	1.35	1.38	1.22	1.33	1.23
45-60	1.40	1.24	1.47	1.47	1.43	1.24	1.46	1.36
				Moisture Content (% by weight)				
0-15	36	36	30	29	35	37	33	26
15-30	33	29	33	30	34	30	33	25
30-45	32	23	31	31	32	26	32	30
45-60	31	25	30	30	30	26	31	31

The lack of a permanent difference suggests that both treatments, even after being established for ten years, would have the same equilibrium bulk density. Cultivation in the CT would cause only a temporary departure from that equilibrium, and the tilth created would disappear within each growing season by the action of wheel traffic and slumping by rain. Similar trends occurred in the 1990 season, although the effects were not statistically significant, probably because the number of samples per plot was reduced in the second year, resulting in larger experimental errors.

Total porosities were calculated from bulk density data, by assuming that the particle density measured in the topsoil (2.52 g.cm^{-3}) was constant throughout the profile (Table 11).

Porosity in the topsoil under ZT was 1 to 3 percent units less than under CT, the difference being significant (p<0.05) only at the 4-leaf stage in 1989, as discussed above.

Table 11. Total porosity (%), air-filled porosity and volumetric soil moisture content (%) at different sampling dates: (a) 4-leaf stage 1989; (b) harvest 1989; (c) 4-leaf stage 1990; and (d) tillering 1990. Fortier.

	CT				ZT			
DEPTH (cm)	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)
				Porosity (%)				
0-15	60	62	58	62	57	61	56	60
15-30	48	51	50	51	49	51	48	49
30-45	46	51	46	46	45	52	47	51
45-60	44	51	42	42	43	51	42	46
				Moisture Content (% by volume)				
0-15	36	35	32	28	38	37	37	27
15-30	43	36	42	37	44	37	44	32
30-45	43	29	42	42	44	32	43	37
45-60	43	31	44	44	43	32	45	42
				Air-filled Porosity (% by volume)				
0-15	24	27	26	34	19	24	19	33
15-30	5	15	8	14	5	14	4	17
30-45	3	22	4	4	1	20	4	14
45-60	1	20	0	0	0	19	0	4

Due to this lower porosity and higher water content (Table 11), air-filled porosity under ZT was usually significantly less (P<0.05) than under CT. The average air-filled porosity at the 4-leaf stage in the top 15 cm of soil was 19 and 25% for ZT and CT, respectively (Table 11). Below this soil layer, no differences were observed.

2.3 Pore Size Distribution

At the 10 cm depth, ZT showed a larger proportion of pores in the range between 300 and 1000 μm than CT, while the opposite occurred for pores smaller than 37 μm in diameter (Table 12). This increase in microporosity under CT would have been caused by deterioration of soil structure produced by cultivation.

Table 12. Pore size distribution (% of total volume) at 10-cm depth, at the tillering stage, for the conventional (CT) and zero (ZT) tillage treatments. Fortier, 1990.

	Pore Size Class (μm)					
	>987	329-987	110-329	37-110	<37	TOTAL
ZT	0.78 a†	1.97 a	1.79 a	2.02 a	77.10 b	83.66 a
CT	0.83 a	0.56 b	1.31 a	2.02 a	79.01 a	83.73 a

† Means followed by the same letter within each column did not differ significantly ($p<0.05$)

Soil tillage increases the proportion of macropores (Dexter 1976, Finney and Knight 1973, Gupta <u>et al</u> 1989), and this should have been reflected in an increased frequency of large (>1 mm) pores under CT. This did not occur. The relatively large macroporosity under ZT would reveal the presence of persistent biochannels. Considering the size of the pore class showing the largest effect (300-1000 μm), these biochannels would have been mostly originated by roots (Hamblin <u>et al</u> 1985). An intense earthworm activity was visually observed in this soil, particularly in the ZT plots, and this may also have contributed to larger soil pores under this system. It must be pointed out that the technique used to measure the pore size distribution may not be the most suitable to detect differences between treatments in earthworm channel frequency. Sample cores were 12.6 cm^2 in cross sectional area, and only 4 cores were obtained per plot. Gantzer and Blake (1978) reported that the number of earthworm channels under ZT and CT was 1225 and 712 m^{-2}, respectively, showing a very large spatial variability. Expressed in terms of the sample size used in the present study, these figures would translate into only 1.5 and 0.9 channels per sample, respectively. Thus, a very large number of replicates would have been required in order to obtain representative samples.

The total porosity, defined as the volumetric water content at saturation, did not differ between the two treatments (Table 12). This was in agreement with the results of the bulk density determinations already discussed. However, the magnitude of this total porosity (84%) was much higher than that shown in Table 11 (56 to 58%). Only part of this difference could be attributed to volume expansion at saturation. One possible explanation for the remainder of the difference is that the cloth used to support the sample may have retained extra water at 0 cm tension, resulting in inflated water contents.

2.4 Oxygen Diffusion Rate

This determination was made only at the tillering stage in the 1990 growing season. At 10-cm depth there was no difference in the oxygen diffusion rates under ZT and CT (Table 13).

Table 13. Oxygen diffusion rate ($\mu g\ O_2.cm^{-2}.min^{-1}$) at 10-cm depth, at the tillering stage of the crop for the conventional (CT) and zero (ZT) tillage treatments. Fortier, 1990.

	Oxygen Diffusion Rate	
	Average	C.V. (%)
ZT	0.32	34
CT	0.30	46

The magnitude of oxygen diffusion rate ($0.3\ \mu g\ O_2\ cm^{-2}\ min^{-1}$) is just above the limiting values for adequate aeration of the roots (Stolzy and Letey 1964). However, it must be considered that the soil water content at the time of sampling was not very high (Table 11), corresponding to air-filled porosities at 10-cm depth in the order of 30%. Therefore, it could be expected that when lower air-filled porosities occurred, i.e. at the beginning of both seasons and at the lowest depths (Table 11), root respiration rate would have been impaired to some extent.

The variability of within-plot replications, as measured by the average coefficients of variation, was higher for CT than ZT (Table 13). This would reflect the higher variability in the pore size distribution observed under CT (Table 12) and suggests that the distribution of locations with adequate aeration levels within the soil would be more clustered under CT as compared to ZT. If aeration was a limiting factor for root activity, space distribution of root density in the mesoscopic (10^{-3}-10^{0} m) scale would likely follow such pattern, although this was not evaluated in this study. The homogeneity of distribution of roots in the mesoscopic scale would have important consequences on the uptake of low-mobility nutrients, such as P, from the soil (Clarkson 1985).

2.5 Root Density

The root profiles for the different treatments in 1989 and 1990 are shown in Fig. 11 along with the corresponding penetration resistance data measured at the 4-leaf stage. The root densities measured in 1990 are higher than those in 1989. As discussed before, this would have been at least partly related to the storage period of the samples in 1989. Within each year, there were no significant ($p<0.05$) differences

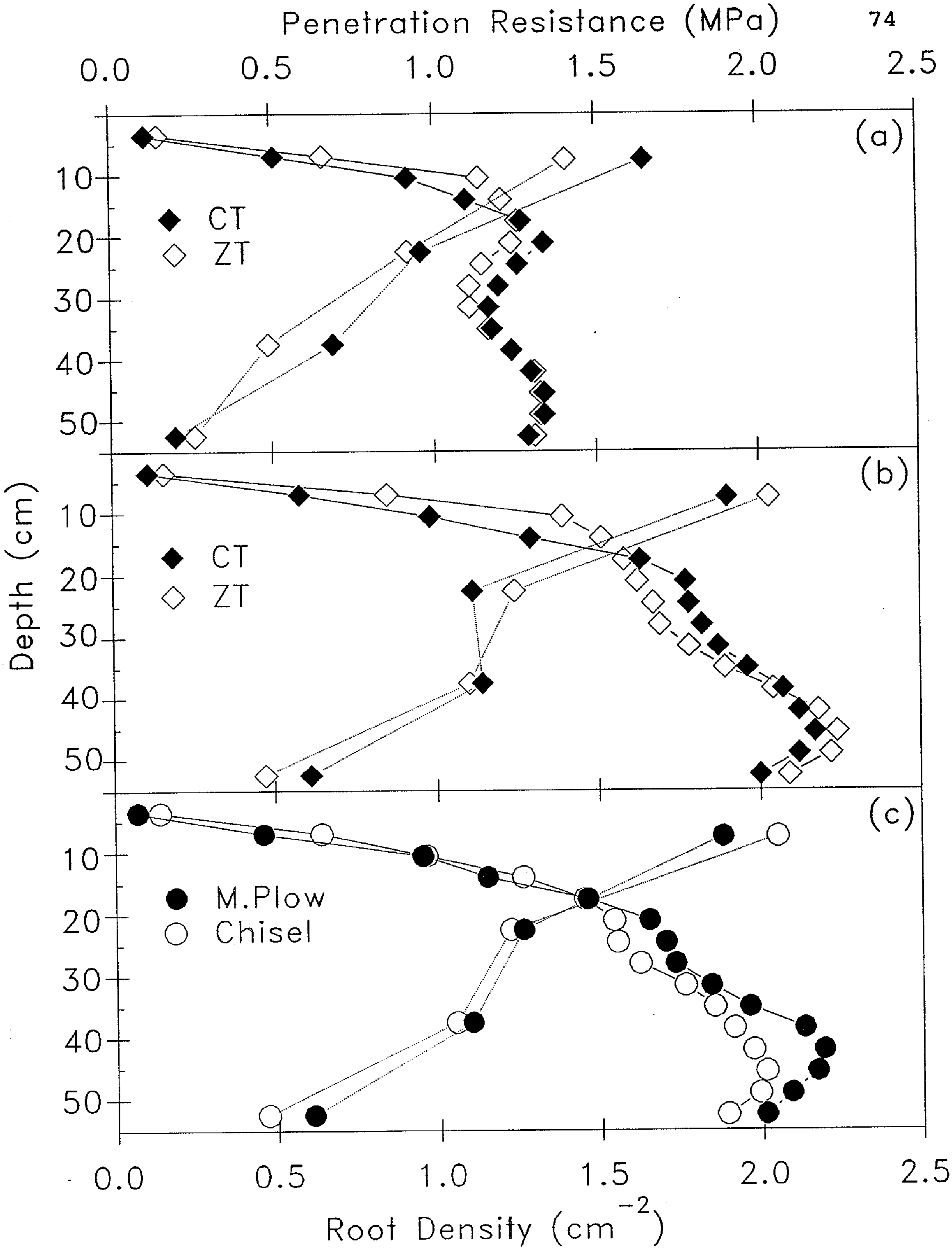


Figure 11. Penetrometer resistance at the four-leaf stage (solid lines), and root density (dashed lines) profiles at Fortier. (a) CT and ZT, 1989. (b) CT and ZT, 1990. (c) moldboard and chisel plows.

between treatments. When considering the treatment averages there was no evident relationship between resistance and penetration. The higher surface compaction under ZT was not translated into lower root penetration. This suggests the existence of a continuous pore system or the presence of abundant biochannels and cracks through which roots developed, overcoming high mechanical impedances in this treatment.

2.6 Crop Yield

Crop yield parameters were measured in 1989 only. Yields were relatively high as compared to the normal for the region. There were no differences in final grain yield or in yield components (Table 14). This suggests that differences in productivity were not a factor in determining any effect of treatments on root density

Table 14. Plant density, above-ground dry matter at harvest, final spike density, grain yield per spike and grain yield for the conventional (CT) and zero (ZT) tillage treatments. Fortier, 1990.

	Plant Density $pl.m^{-2}$	Shoot Yield $Mg.ha^{-1}$	Spike Density $sp.m^{-2}$	Spike Yield $g.sp^{-1}$	Grain Yield $Mg.ha^{-1}$
ZT	303 a†	11.2 a	626 a	0.57 a	3.54 a
CT	286 a	11.1 a	612 a	0.58 a	3.52 a

† Means followed by the same letter within each column did not differ significantly ($p<0.05$)

3. Souris Loamy Sand

As in the experiment at the Fortier soil, the effect of tillage treatments on soil physical properties was nonsignificant ($p<0.05$) for most of the variables studied in all sampling dates. This was also true of the interaction tillage x depth (Table 15). Shoot dry matter production was the only exception: due to a higher plant density, ZT outyielded CT in total dry matter, but the grain yield was the same because of a compensation effect in the number of kernels per spike. On the other hand, depth effect was always significant for bulk density, penetration resistance and root density (Table 15).

In contrast to the Fortier experiment, the lack of significance of tillage treatments on the various parameters considered seemed to be a general phenomenon at all depths, as will be shown in detail for each of the variables in the following sections.

Table 15. Significance of the effects ($p<0.05$) of the different sources of variation as determined by analysis of variance, for all the variables measured at the different sampling dates. Souris, 1989 and 1990.

		1989			1990		
Variable	Effect	4-leaf	Tillering	Maturity	4-leaf	Tillering	Maturity
Bulk Density	Block	* †	-	NS	*	-	NS
	Tillage	NS	-	NS	NS	-	NS
	Depth	*	-	*	*	-	*
	T x D	NS	-	NS	NS	-	NS
Mechanical Impedance	Block	NS	*	NS	NS	NS	NS
	Tillage	NS	NS	NS	NS	NS	NS
	Depth	*	*	*	*	*	*
	T x D	NS	NS	NS	NS	NS	NS
Moisture (% vol)	Block	NS	*	NS	NS	-	NS
	Tillage	NS	NS	*	NS	-	NS
	Depth	*	*	NS	NS	-	*
	T x D	NS	NS	NS	NS	-	NS
Porosity (10 cm)	Block	-	-	-	-	NS	-
	Tillage	-	-	-	-	NS	-
Macropores (10 cm)	Block	-	-	-	-	NS	-
	Tillage	-	-	-	-	NS	-
O.D.R. (10 cm)	Block	-	-	-	-	NS	-
	Tillage	-	-	-	-	NS	-
Root Density	Block	-	-	-	-	-	NS
	Tillage	-	-	-	-	-	NS
	Depth	-	-	-	-	-	*
	T x D	-	-	-	-	-	NS
Grain Yield	Block	-	-	NS	-	-	-
	Tillage	-	-	NS	-	-	-
Shoot yield	Block	-	-	NS	-	-	-
	Tillage	-	-	*	-	-	-

† '*' denotes significant, and 'NS' non-significant effects ($p<0.05$)
'-' indicates that no measurements were made at a given sampling date

3.1 Mechanical Impedance

Both treatments had essentially the same behaviour with respect to soil mechanical impedance near the soil surface at the 4-leaf stage (Fig. 12). The differences occurring deep in the soil in 1989 (Fig. 12a) were likely the result of a variation in soil moisture. At depths below 40 cm, penetration resistance under ZT was lower than under CT, which coincided with a higher water content in the former.

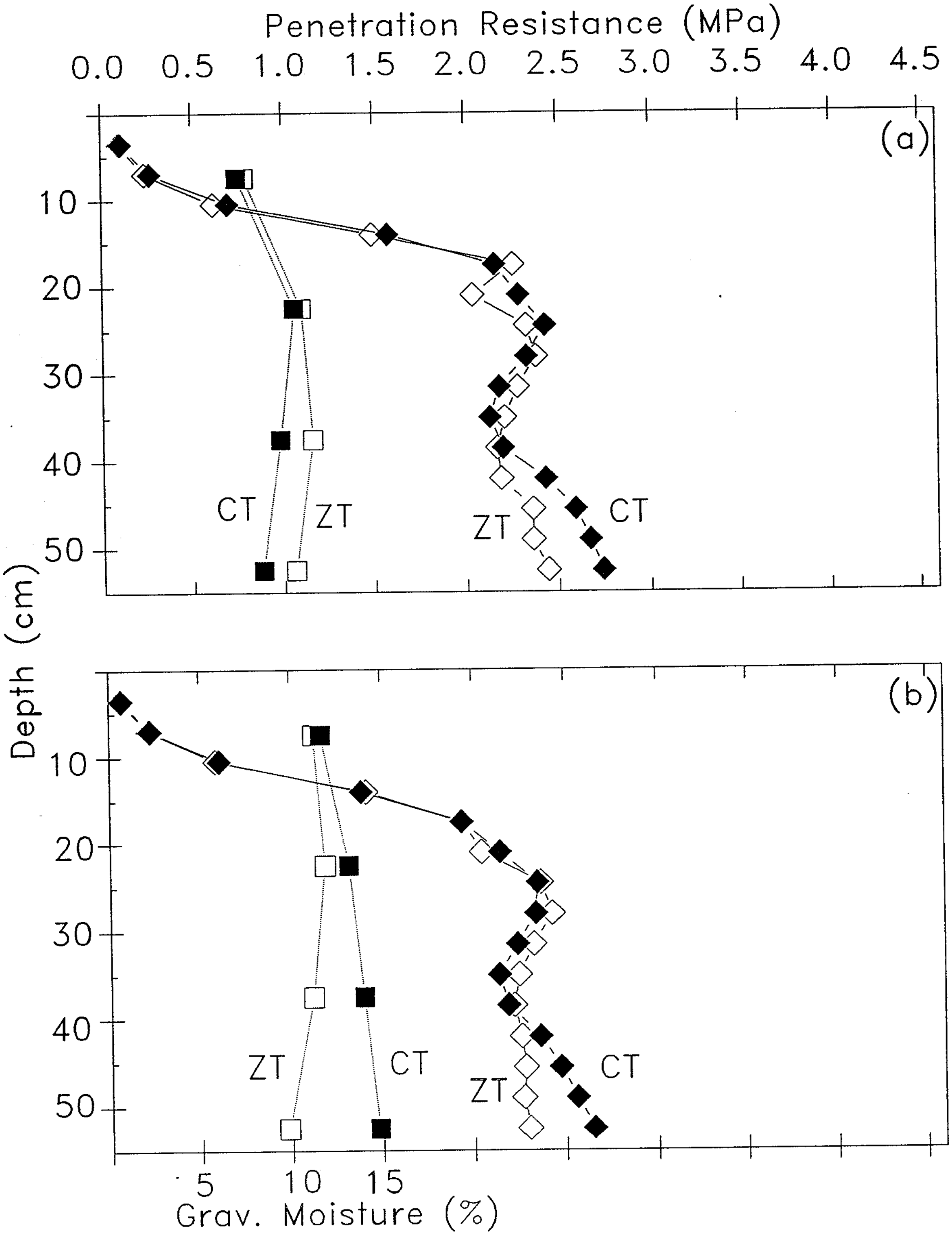


Figure 12. Penetration resistance (solid lines) and gravimetric water content (dashed lines) at the 4-leaf stage at Souris. (a) 1989. (b) 1990.

The magnitude of the mechanical resistance above 10 cm depth was low compared to the other two sites, and this could be attributed to the poorly developed structure of this soil, which would permit that primary soil particles be easily pushed aside as the cone probe advances. At increasing depths, the overburden pressure, which is high in this soil due to the high bulk density, caused by a large sand content, becomes larger, and the particles can not be easily displaced. In this case, the resistance to cone penetration depends on the soil compressibility, which due to the low porosity, is low for sandy soils, thus resulting in high resistances. There was a sharp increase in the resistance to penetration between 10 and 20 cm of depth, regardless of the tillage system, resulting in values above 2 MPa, which remained relatively constant with depth.

The effect of ZT reducing subsurface compaction observed in the other two sites was still not evident by the fourth year after treatments were established. There are two possible reasons for this: firstly, the poor conditions for root growth in this soil (see Section 3.5) would cause biochannels to form at a very slow rate, or not at all; secondly, the low clay and organic matter content of this soil would be a limitation for natural aggregation and would cause the collapse of newly formed aggregates and biochannels.

In both years studied, soil strength increased dramatically through the season (Fig. 13), presumably due to

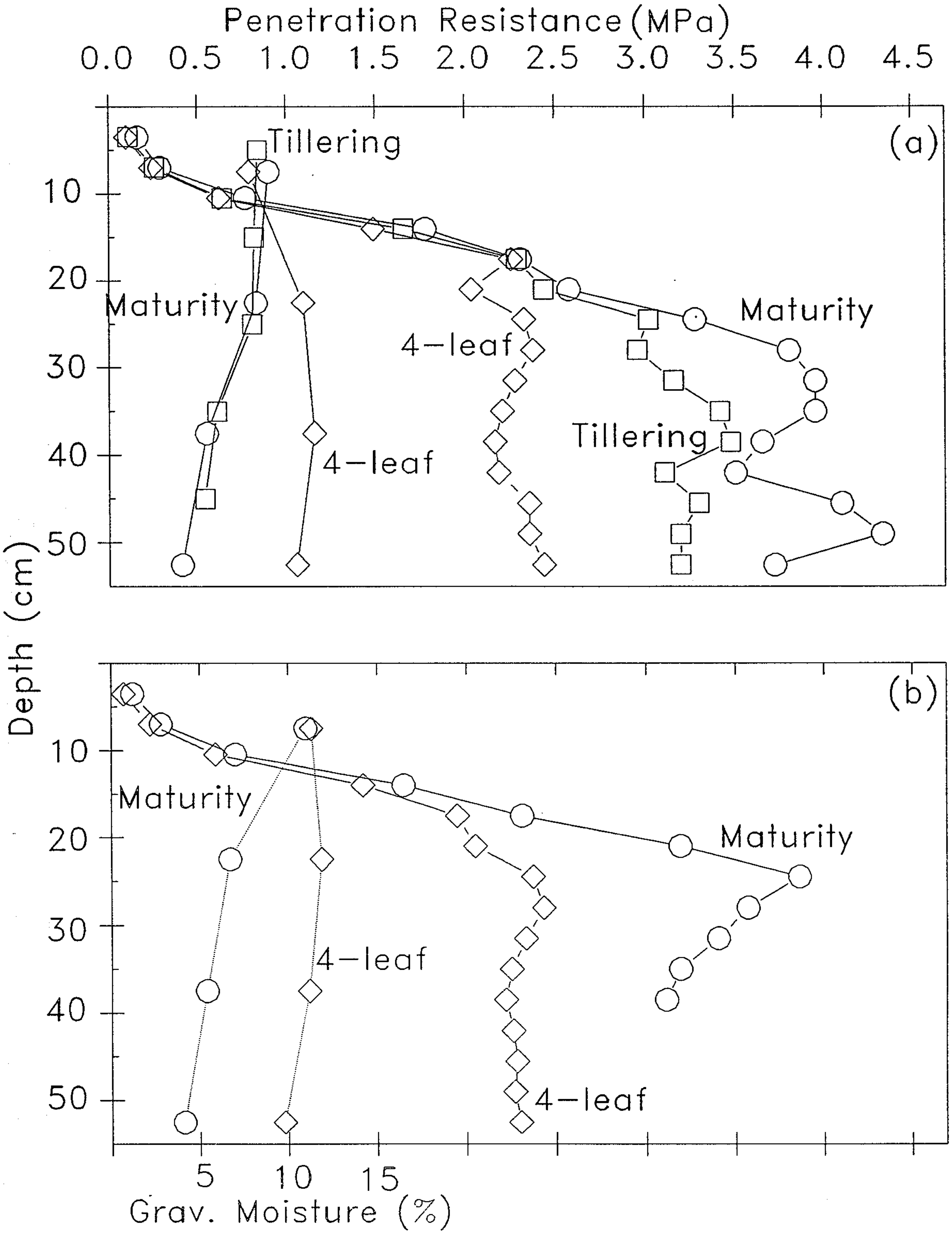


Figure 13. Penetration resistance (solid lines) and soil moisture (dotted lines) profiles at the different sampling dates for the ZT treatment. Souris. (a) 1989. (b) 1990.

the drying of the soil. The resistance to penetration values that were reached at mid-tillering (1989) and crop maturity (over 4 MPa) indicate an extreme case of mechanical impedance to root growth.

The measured penetration resistances in this soil would have included a large frictional component (Fig. 1) owing to the large angle of internal friction characteristic of sandy soils (Williams and Shaykewich 1970), particularly in dry conditions. However, even after making some allowance for this factor, it can be safely concluded that the root penetration of the soil matrix below a depth of 10 to 15 cm, would have been completely inhibited in this soil, and that profile penetration by roots would have depended primarily on the existence of macropores and cracks.

3.2 Bulk Density and Porosity

The soil bulk density was not affected by the tillage system (Table 16). Both treatments showed identical profiles at all sampling dates. The relatively high levels of bulk density, compared to the other two soils included in the present research, reflect the high sand content, and low porosity of the Souris soil.

Table 16. Bulk density (g.cm^{-3}) and gravimetric soil moisture content (%) at different sampling dates: (a) 4-leaf stage 1989; (b) harvest 1989; (c) 4-leaf stage 1990; and (d) harvest 1990. Souris.

	CT				ZT			
DEPTH (cm)	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)
				Bulk Density (g.cm^{-3})				
0-15	1.47	1.35	1.44	1.46	1.45	1.36	1.41	1.42
15-30	1.60	1.57	1.59	1.62	1.64	1.56	1.63	1.69
30-45	1.72	1.74	1.70	1.66	1.73	1.76	1.75	1.65
45-60	1.76	1.81	1.77	1.75	1.76	1.77	1.75	1.73
				Moisture Content (% by weight)				
0-15	8	9	12	11	8	9	11	11
15-30	11	8	13	7	11	8	12	8
30-45	10	5	14	5	12	5	11	6
45-60	9	4	15	4	11	4	10	5

Total porosities were calculated from bulk density data, by assuming that the particle density measured in the topsoil (2.60 g.cm^{-3}) was constant throughout the profile (Table 17). Porosity at each soil layer was similar for both treatments, and remained unchanged throughout the duration of this study, suggesting that the structure modifications, if any, caused by annual tillage operations were only ephemeral, and not detectable during the period of crop development.

Table 17. Total porosity (%) and volumetric soil moisture content (%) at different sampling dates: (a) 4-leaf stage 1989; (b) harvest 1989; (c) 4-leaf stage 1990; and (d) harvest 1990. Souris.

	CT				ZT			
DEPTH (cm)	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)
				Porosity (%)				
0-15	43	48	45	44	44	48	46	45
15-30	38	40	39	38	37	40	37	35
30-45	33	33	35	36	33	32	33	37
45-60	32	30	32	33	32	32	33	33
				Moisture Content (% by volume)				
0-15	11	12	17	16	11	12	16	16
15-30	17	12	21	11	18	13	19	13
30-45	17	9	24	9	20	9	20	10
45-60	15	8	26	7	19	7	17	8

There were no significant differences in the soil water content with the exception of the lowest depth at the 4-leaf stage of the crop in 1990 (Tables 16 and 17), where for reasons that are not apparent, the moisture content under CT was measureably higher than ZT.

The benefits of ZT in storing soil moisture (Power et al 1986, Steiner 1989) were not observed in this experiment. There are two main reasons for this: a) the practice of incorporating the fertilizer used at this site eliminated the presence of surface residues, which are usually responsible for reducing incident radiation on the soil and rates of evaporation (Enz et al 1988, Ross et al 1985); and b) the low productivity would have resulted in the accumulation of low amounts of surface residues, thus resulting in noneffective snow trapping during the winter (Benoit et al 1986).

3.3 Pore Size Distribution

The two tillage systems did not differ in the distribution of pore sizes (Table 18) at the 10-cm depth by the 1990 mid-season. Considering the lack of changes in porosity with time (Table 17), and the poor stucture of this soil, differences in pore size distribution are not likely to have occurred at other times either.

Table 18. Pore size distribution (%) at 10-cm depth, at the tillering stage, for the conventional (CT) and zero (ZT) tillage treatments. Souris, 1990.

	Pore Size Class (μm)					
	>987	329-987	110-329	37-110	<37	TOTAL
ZT	4.45 a	1.30 a	2.65 a	13.21 a	28.58 a	50.19 a
CT	2.98 a	1.51 a	2.46 a	13.07 a	30.81 a	50.83 a

† Means followed by the same letter within each column did not differ significantly ($p<0.05$)

There was a trend toward higher porosity over 1000 μm under ZT, and higher microporosity under CT, although the effects were not statistically significant. This, however, agrees with the general trend at the other two sites, particularly with respect to an increased microporosity under

CT, and may well be the expression of incipient long-term changes which would occur very slowly in this soil. The results for porosity greater than 1000 μm seem to be too large, probably due to experimental error. One possible explanation could be that when equilibrated at 0 cm water tension, some extra water might have remained in spaces between the soil cores and the cloth mesh used to support them, resulting in saturation water contents higher than the real values. This seemed to be supported by the fact that total porosity determined by the water content at saturation (50%, Table 18) was somewhat larger than that determined from bulk density data (45%, Table 17), in a soil that should not possess swelling properties.

3.4 Oxygen Diffusion Rate

The aeration status of the roots measured at 10-cm depth during mid-tillering in the 1990 season did not reveal any differences between the tillage treatments, neither in the magnitude of the oxygen diffusion rates nor in their variability (Table 19).

Table 19. Oxygen diffusion rate ($\mu g\ O_2.cm^{-2}.min^{-1}$) at 10-cm depth, at the tillering stage of the crop for the

conventional (CT) and zero (ZT) tillage treatments. Souris, 1990.

	Oxygen Diffusion Rate	
	Average	C.V. (%)
ZT	0.78	27
CT	0.80	25

The levels of oxygen diffusion rate in this soil indicate that aeration of the roots was not impaired (Stolzy and Letey 1964). From Table 17 it can be calculated that the air-filled porosity in the top 15 cm of soil was always above 30%, even at the beginning of the growing season, when water contents were the highest. The air-filled porosity declined only slightly with depth, suggesting that the supply of oxygen to the roots would have been adequate.

3.5 Root Density

Only the ZT system was sampled in 1989. The final root density profiles for both years, along with the penetration resistance data are shown in Fig. 14. The density of roots was much higher in 1989, when wheat was grown, compared to the barley crop in 1990. Considering that in 1989 root counts were made a few months after the samples were taken, it is probable that the difference between years would have been even greater. Barley has been shown to be more sensitive to

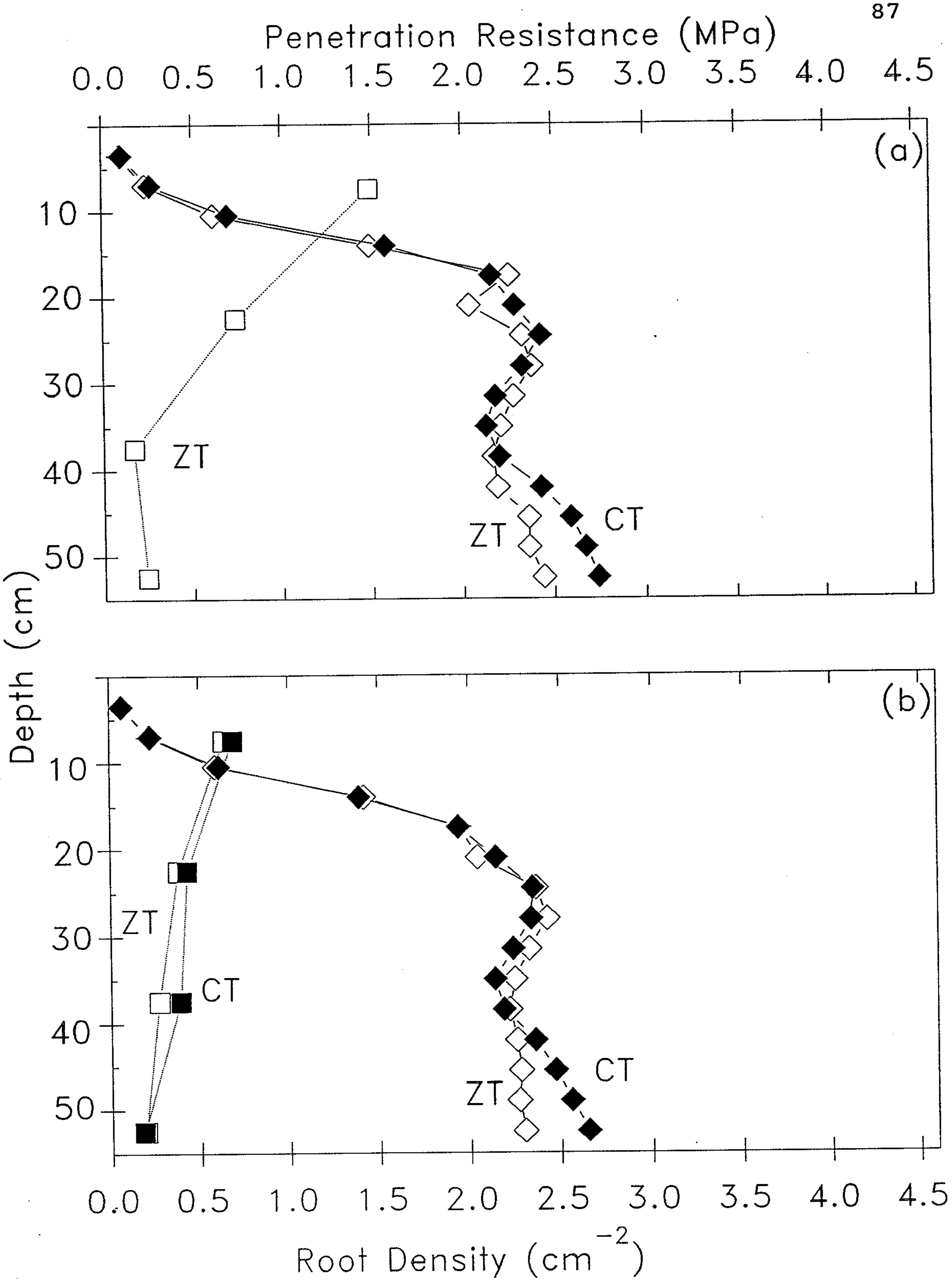


Figure 14. Penetrometer resistance at the four-leaf stage and root density profiles at Souris. (a) 1989. (b) 1990.

mechanical stress than wheat (Goss 1977), and this could be the main reason for the observed difference.

There were no differences between tillage treatments in 1990, which was in agreement with the lack of effects on the various soil physical properties evaluated. In general, root density measured at this site was measureably lower than at the other two sites, probably because of the higher mechanical impedance observed at this soil. However, this would not be the only reason, since other factors such as moisture availability and nutrient status may have been important as well.

3.6 Crop Yield

Some parameters related to crop productivity were measured only in 1989. The establishment of the wheat crop was better under ZT (Table 20), giving a higher plant density. This would have been the reason for the superior above-ground dry matter production at heading, and the trend to give a higher spike density under ZT. However, grain yields were not different between treatments. Yields were much lower than at Fortier, reflecting the poor fertility of Souris soil.

Table 20. Plant density, above-ground dry matter at heading, final spike density, grain yield per spike and grain yield for the conventional (CT) and zero (ZT) tillage treatments. Souris, 1989.

	Plant Density $pl.m^{-2}$	Shoot Yield $Mg.ha^{-1}$	Spike Density $sp.m^{-2}$	Spike Yield $g.sp^{-1}$	Grain Yield $Mg.ha^{-1}$
ZT	343 a†	5.3 b	379 a	0.45 a	1.69 a
CT	316 b	6.1 a	405 a	0.44 a	1.79 a

† Means followed by the same letter within each column did not differ significantly ($p<0.05$)

4. Relationship between Mechanical Impedance and Soil Moisture

Data from experiments at the Fortier and Souris soils suggested that variations in time of soil mechanical impedance are much larger than those due to treatment effects. Such variations were demonstrated to be associated with changes in the soil moisture content, with mechanical impedance decreasing as the soil water content increases. Since bulk density varied very little during the crop cycle, it was assumed that all variations in penetration resistance were due to differences in the soil water content. Data from all six samplings at each site (Fortier and Souris) were pooled and linear regression coefficients of penetration resistance on gravimetric water content determined (Table 21). This may have been an oversimplification since in some cases the relationship was clearly not linear. However, the linear

Table 21. Linear regression coefficients for the regression of Penetration Resistance (MPa) on gravimetric soil moisture content (%) at Souris and Fortier, and estimated Penetration Resistances at the moisture content corresponding to 10% air-filled porosity (AFP_{10}).

Depth	$\delta PR/\delta\theta_w$		Moisture content at AFP_{10} (%)	PR at AFP_{10} (MPa)	
(cm)	CT	ZT		CT	ZT
			FORTIER		
7.5	-0.03	-0.05	46	<0.5	<0.5
15.0	-0.11	-0.04	37	0.9	1.4
22.5	-0.06	-0.04	33	1.5	1.3
30.0	-0.06	-0.04	29	1.6	1.5
37.5	-0.06	-0.04	27	1.8	1.8
45.0	-0.08	-0.08	26	2.0	2.0
52.5	-0.09	-0.09	25	2.1	2.1
			SOURIS		
7.5	0	-0.01	23	<0.3	<0.3
15.0	-0.04	-0.04	20	<1.5	<1.5
22.5	-0.25	-0.20	17	<2.2	<2.2
30.0	-0.29	-0.23	15	<2.3	<2.3
37.5	-0.28	-0.24	14	<2.2	<2.2
45.0	-0.26	-0.22	14	<2.4	<2.4
52.5	-0.24	-0.17	13	<2.3	2.7

regression coefficients provide a reasonable means of comparing treatments and soil horizons, in order to assess the extent to which mechanical stresses can be alleviated by an increase in the moisture content.

The stress induced by the penetrating probe is complemented by the pore water pressure (in saturated soils) or by a fraction of it (unsaturated soils) in causing the soil to fail (Barley and Greacen 1967). In a sandy soil, because of its relatively low porosity, that fraction increases very rapidly as the soil is wetted, and this markedly reduces the force necessary to penetrate the soil. This, along with a reduction in the frictional component of penetration resistance as soil water content increases, would be the reasons why the coefficients at Souris (loamy sand) were much higher in absolute value than those at Fortier (silty clay loam). The same principle would apply to soil layers where porosity was reduced by loading processes such as the action of tillage implements (CT at 15 cm at Fortier), machinery traffic (surface layer under ZT) or slumping (deep horizons of soil).

In a similar analysis on a clay soil, Ehlers et al (1983) calculated slopes of -0.12, -0.17 and -0.24 for bulk densities of 1.28, 1.39 and 1.55 $g.cm^{-3}$, respectively. These values are large in absolute magnitude compared to the ones obtained at the Fortier soil, probably because the bulk densities in this soil (Table 10) were lower than those in the mentioned study.

Even though increasing soil moisture reduces the mechanical resistance, a point is reached where the oxygen diffusion to the roots may become restricted. A rough approximation to this point is provided by the water content corresponding to 10% air-filled porosity (Grable 1971). This calculation (Table 21) suggests that aeration was not a limitation in the Souris loamy sand, since the values of θ_w calculated were never reached. On the other hand, in the Fortier soil, the reduction in mechanical impedance by increased moisture would not have resulted in improved conditions for root growth, since at a given point, aeration would have started to be the limiting factor. Table 21 shows that at AFP_{10}, penetration resistance values are still relatively large, although not so large as to completely supress root growth (Camp and Lund 1968, Gerard et al 1982, Taylor and Gardner 1963, Taylor et al 1966).

5. Penetration Resistance and Root Density

Because mechanical impedance at all the soils included in this study varied widely both in time and position, it is difficult to assess how plants in the field integrated such variations in their response. The final root density does not provide an indication of the timing of root growth in response to short-term variations in mechanical impedance and aeration status. On the other hand, averaging penetration resistance and root density values obtained for a given treatment could mask important spatial variations characteristic of these variables.

The lack of a clear relationship between root density and cone index when analyzing treatment averages (Figs. 3, 11 and 14) may well be due to the use of the unappropriate scale of comparison. Since the location of all samples taken in 1990 was recorded, this relationship could be studied at a more reduced scale. For every depth increment and site sampled in the field, the ratio between root density at a given depth and

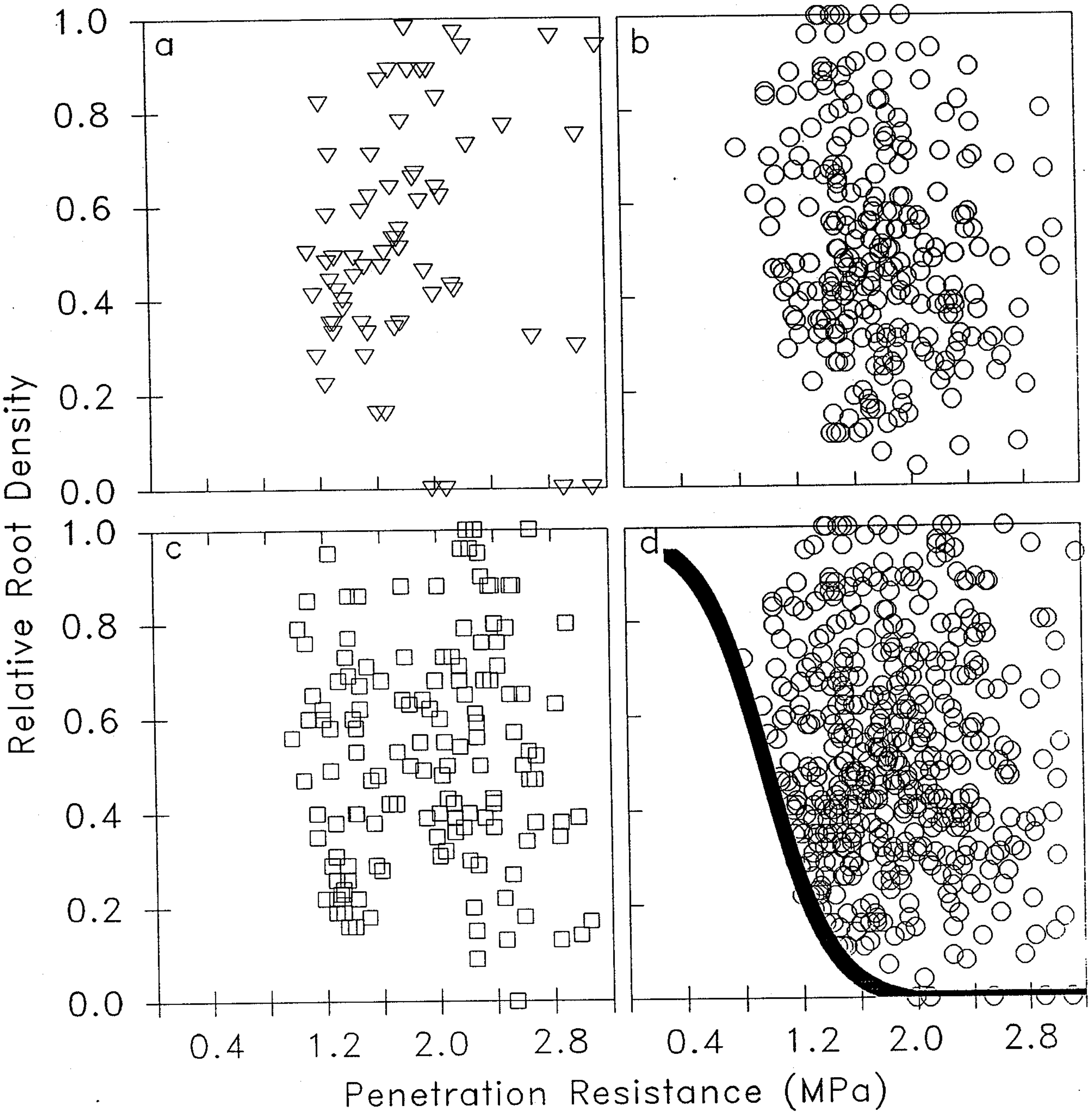


Figure 15. Relative root density (root density at a given depth over that at the depth immediately above), as a function of the cone index between both depths.(a) Marquette.(b) Fortier.(c) Souris.(d) All sites

the root density at the depth immediately above (relative root density) was plotted against the average cone index between both depths (Fig. 15). This resulted in a random distribution of points with a well defined boundary to the left, which became very evident when all three sites were pooled in the same plot, giving a sample of over 500 points (Fig. 15d). The shape of this border resembles very closely the curve obtained by Taylor et al (1966) for the relationship between penetration resistance and the proportion of cotton roots that passed through cores from a wide range of soils. According to Fig. 15d, the relative root density would have been a sigmoidal function of penetration resistances, with the maximum effect occurring between 0.9 and 1.1 MPa. The critical soil strength, defined as the cone index that completely supressed root growth was about 2 MPa, which is in close agreement with other findings (Camp and Lund 1968, Cockroft et al 1968, Taylor and Gardner 1963, Taylor et al 1966). Other authors (Ehlers et al 1983, Gerard et al 1982, Grimes et al 1975, Vepraskas and Wagger 1989, Yapa et al 1988) have reported higher values, but all of these studies were performed in field conditions, and the higher critical strength was usually attributed to the presence of biopores through which roots penetrated, despite the high soil matrix strength.

The points scattered above the curve represent situations where the roots could overcome the mechanical stress. Several mechanisms would have been used, all of them based on temporal and/or spatial variability in the soil physical properties: a) growth through biochannels and cracks which, because of their tortuosity, are not detected by the penetrometer; b) lateral growth from immediately adjacent soil regions of low strength; and c) by using temporal decreases in soil strength, i.e., immediately after a rain.

An attempt was made to assess whether different tillage systems or soil depths differed in the degree of dispersion from the curve, but no clear pattern was found, probably because: a) the resulting number of points in each class was too low as to detect any effect; and b) it was shown that the effects of tillage systems on the soil physical properties were relatively unimportant, and likely less important than the spatial variability within the treatments. Also, the data could not be related to pore size distribution measurements, because the exact location of samples for this determination in the field was not recorded.

The ability of roots to penetrate the soil against a mechanical stress was observed in all three soils (figs. 15a, 15b and 15c), although the analysis of the dispersion of points reveals some slight differences. At Souris, the points tended to be more concentrated towards low relative root density values, while at Fortier the maximum concentration occurred in the region of medium root densities. This difference could be related to the observed occurrence of biochannels in both soils. On the other hand, a relatively large proportion of points in the high root density region was observed at Marquette, probably reflecting the effect of shrinkage cracks in this soil.

SUMMARY AND CONCLUSIONS

In contrast to most literature reports, the present study has shown that the effect of the tillage systems on the soil physical condition was generally small and, in some cases, negligible. The large number of freezing and thawing cycles that occur during the spring and fall in Manitoba, would be one factor attenuating the effects of tillage, by accelerating natural aggregation processes.

Space and time variability of soil physical properties within a given tillage treatment was generally larger than between treatments in a particular soil.

In two of the three soils studied (Marquette and Fortier), the top 10 cm layer was found to have higher mechanical impedance, as measured by a cone penetrometer, under zero tillage than conventional or minimum tillage. The reverse tended to occur below that depth, possibly because of improved pore systems under zero tillage. No effect was observed at the sandy soil (Souris), presumably because of its poor structure and the slow rates of natural aggregation and biopore formation in this soil.

All three soils presented layers with penetrometer resistance levels that would have been restrictive for root growth. The presence of cracks, biochannels and a continuous system of macropores would have been essential to allow the roots to pass through those layers.

Zero tillage tended to produce higher proportion of macropores (>100 μm in diameter) at 10 cm depth than conventional or minimum tillage in all three soils studied. This would be the consequence of the preservation of root and earthworm pores under no-tillage conditions, against the action of compacting forces (wheel traffic, slumping and wetting-drying cycles) typical of ZT systems.

The levels of oxygen diffusion rate at mid-tillering were above the critical levels for root growth in all three sites. No differences between treatments were observed. However, as suggested by air-filled porosity measurements, root aeration may have been impaired at the beginning of the growing season at the two finer-textured soils (Marquette and Fortier), particularly under zero tillage.

Changes in soil moisture had the greatest influence on penetration resistance. The effect was largest in the sandy soil (Souris) and in the compacted soil layers (topsoil under zero tillage, and subsurface under conventional tillage). Temporal variations in penetration resistance, caused by changes in the soil moisture content, constitute one mechanism for roots to penetrate soil regions with relatively high mechanical impedance.

This study showed that cone index can not be used as an exclusive parameter in predicting mechanical constraints for root growth. In most situations, roots were able to use spatial and temporal soil heterogeneity to overcome high mechanical impedances. This produced large deviations from the basic relationship between root growth and cone index. These deviations could not be explained by differences in pore size distribution, suggesting the need for better methods to describe the root physical environment. The development of mathematical models that simulate time and space changes in soil structure would provide a better understanding of the interrelations between the four basic soil physical parameters that affect root growth.

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