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SPATIAL DISTRIBUTION AND WATER UPTAKE OF ROOTS IN STRUCTURED GROWTH MEDIA

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SPATIAL DISTRIBUTION AND WATER UPTAKE OF ROOTS IN STRUCTURED GROWTH MEDIA

By

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ABSTRACT

SPATIAL DISTRIBUTION AND WATER UPTAKE OF ROOTS IN STRUCTURED GROWTH MEDIA

By

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Root water uptake has classically been modeled based on the assumption that roots are distributed evenly within soil layers. In many instances, though, root distribution is more likely to be clustered than regular or random, and the distance water has to travel from bulk soil to root is larger than average distance between roots. This can imply limitations to water uptake in soil regions far from the root cluster. A study is presented that characterizes root clustering and water uptake in relation to soil structural status.

To measure small scale variability in volumetric water content, 21 mm long probes were designed for a time-domain reflectometer. Water content values higher than 0.07 cm^3 cm^{-3} were reliably measured in a sandy-clay and in a clay-loam soil. In the clay-loam, at water content higher than 0.29 cm^3 cm^{-3}, a few excessively high values of dielectric constant were measured, yielding excessively high values of θ_v.

In a greenhouse experiment, maize (Zea mays L.) was planted in soils of different structural status and grown on

stored water. Growth and water uptake were affected by soil structure; roots grew into sieved sandy-clay soil or shrinkage cracks but did not penetrate clay-loam peds beyond 2 cm from the surface, unless biopores were present. Unextracted water was left in peds, even after plants had lost practically all green leaf area, and large gradients in θ_v were measured as a consequence of root clustering. In a treatment with uniformly compacted clay-loam soil, very little root and plant growth was measured, and no wilting occurred although water extraction was small.

Water outflow from peds was modeled assuming that a ped could be simplified by a cylinder, and that flow was radially symmetrical. Experimentally measured water gradients in peds could be reproduced by assuming that soil water diffusivity in peds ranged from $4.29*10^{-2}$ to 10 cm^2 day^{-1}.

In a field experiment maize was grown in a swelling soil with three structural treatments corresponding to minimum tillage, tillage to 50 cm, and loosening of the profile up to 100 cm. Plant growth and yield, as well as root and water uptake patterns were related to soil structure.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

WATER UPTAKE FROM ROOT SYSTEMS

Water uptake by plant root systems has been described by numerous models, classically ascribed to two main approaches:

- a microscopic approach

in which radial flow to a single root is described, and microscale processes that lead to water flow towards the root are taken into account.

The idealizations of the earlier models (Philip,J. R.,1957; Gardner, 1960, Cowan 1965) were that the root be considered as an infinitely long cylinder, of uniform radius and water absorbing characteristics. Water flow towards such a root was therefore imagined to be radial, and was expressed as a function of water potential gradients and hydraulic conductivity of the soil:

$$\frac{\delta\theta}{\delta t} = \frac{\delta}{r\delta r}\,(rk_s\ \delta\psi/\delta r) \qquad (1)$$

where θ = volumetric soil water content

t = time
r = radial distance across which water moves
k_s = soil hydraulic conductivity
ψ = soil matric water potential[1]

Various assumptions on the type of flow and boundary conditions have yielded different equations for flow calculation. Under the assumption of steady-state conditions, Philip (1957), suggested the expression:

$$q_r = \frac{-2\pi k_s \, (\psi_{rs} - \psi_s)}{\ln \, (r_{cyl} \, / \, r_r)} \qquad (2)$$

where q_r is the water uptake rate per unit root length
k_s is the soil hydraulic conductivity
ψ_{rs} is the water potential at the root surface
ψ_s is the water potential of the soil at a distance
r_{cyl} is the radius of the cylinder from which water moves to the root. Gardner (1960) calculates it as half the distance between adjacent roots.
r_r is the root external radius.

The value of k_s was often considered constant, and approximated by that of the bulk soil, when the resistance to flow within the rhizosphere was considered to be low (Arya et al., 1975 c)), or it was expressed by the more general relation :

$$k_s = \left[\int_{\psi_{rs}}^{\psi_r} k(\psi) d\psi \right] \, / \, (\psi_s - \psi_{rs}) \qquad (3)$$

(Whisler et al., 1970).

[1]in most cases, the formalism ψ = matric potential is used in the literature, rather than the more general φ = total potential, for practical reasons.

The difficulties in measuring potential at the root-soil interface,and the questions about the role that resistances to flow within the root play in determining water uptake in the soil-root system (Newman 1969 a,b,; Hansen 1974) led to flow calculations that included radial water movement within the root, from the surface to the xylem, so that the system was redefined (Taylor and Klepper 1975) and the radial flow equation used was :

$$q_r = \frac{-2\pi k_{sys} (\psi_{rx} - \psi_s)}{\ln (r_{cyl} / r_{stele})} \qquad (4)$$

where k_{sys} is the hydraulic conductivity of the soil-root system
ψ_{rx} is the water potential at the xylem
r_{stele} is the radius of the root stele.

Much research was stimulated by this approach, on the calculation of the water potential distributions around and across the root, and on establishing which of the soil and root resistances to water flow were most important in determining the water uptake rates in different situations (Gardner,1964, Molz,1971, Taylor and Klepper, 1975, Passioura, 1988, Newman, 1969 a and b, Boyer, 1971, Miller et al, 1971, Barrs and Klepper, 1968, Begg and Turner, 1970, Reicosky and Ritchie, 1976, So et al. 1976 a, Samui and Kar,1981). Several solutions of the cylindrical diffusion equation have also been devised, for different purposes and applications.

The extension of the model to the whole root system is

based on the simplifying hypothesis that each root draws water exclusively from a soil region. The complete root system is then viewed as a summation of single roots, since no overlapping between extraction zones is considered, nor is any other interaction between roots. The watershed of each root is calculated as a cylinder whose radius is half the average distance between roots (Gardner 1960, Tinker 1976).

Criticisms have been made of this approach (Molz 1981, Passioura 1988,Klepper and Taylor, 1978), mainly of its application to the whole root system, and for theoretical and practical reasons. Problems in application include difficulties in defining the boundary conditions, and in measuring the parameters involved, inaccuracies in determining the whole root length of a plant at each time, and more important the problems in establishing the relative contribution of each part of the total root length to active water uptake.

Furthermore, ignoring physical (overlapping) and physiological interactions between single roots is a cause of error. The model has,in many cases, proved inadequate to describe accurately the water uptake of root systems (Brenner et al, 1986; Faiz and Weatherley, 1977; Faiz and Weatherley, 1978; Miller, 1985; Herkelrath et al, 1977; Zur et al, 1982), although the behavior of single roots has been shown to be modeled fairly accurately in some cases (Hainsworth and Aylmore, 1986; Passioura, 1980; Taylor and Klepper, 1975).

This type of approach has stimulated a number of experimental and theoretical works on the processes related to water uptake (So et al.,1976 b),1978,).

- a macroscopic approach

in which the root is characterized as a water sink in its totality.

Many types of model can be listed under this category. Early work (Wadleigh 1946) proposed an integrated soil water value to represent the entire root water status. Based on thermodynamics, Wadleigh's view was that the root system adjusts water absorption so that the soil water potential is constant throughout the root zone.

Subsequent research (Taylor 1952) used the concept of integrated soil water stress but pointed out the fact that the soil dries in the top parts first and then in deeper layers. Models that followed (Whisler et al, 1968; Molz and Remson, 1970,1971, Nimah and Hanks, 1973, Hillel et al, 1976) viewed the root system as a whole and characterized it as a diffuse sink throughout the soil, though its strength was not necessarily regarded as uniform within the root zone, so that different parts of the root were recognized to experience different water status. In particular, some models recognize non-uniformity in the vertical dimension for soil and rooting patterns that affect water extraction.

Early macroscopic models (Rose and Stern,1967; Whisler

et al., 1968, van Bavel et al.,1968, Molz and Remson,1971; Feddes and Rijtema,1972) have been criticized for being too general and not considering physiological parameters with sufficient detail (Klepper and Taylor, 1987), and therefore being of limited use in interpreting experimental data or in predicting plant water use.

In an attempt to overcome some of these limitations, more recent macroscale models include a mechanistic treatment of soil and plant behavior, showing more attention to water uptake processes (Nimah and Hanks,1973; Rose et al,1976; van Bavel and Ahmed,1976, Hillel et al.,1976, Taylor and Klepper, 1978). Those models are sometimes regarded as microscopic or 'hybrid' models and have some of the problems microscale approaches encounter in describing and quantifying water withdrawal mechanisms.

In general, the sink effect of plant roots is represented by an extraction function that combined with the Darcy-Richards equation quantifies root water uptake. For a given volume of soil :

$$\frac{d\theta}{dt} = \frac{d(k(d\psi/dz))}{dz} - S(z,t) \qquad (5)$$

where z is depth

S(z,t) is the root water extraction - or 'sink' - term (volume of water extracted per unit soil volume per unit time) that is considered variable with depth and time. Only few authors (Cavazza, 1985) use the more general formalism S(x,y,z,t), taking explicitly

into account spatial variations in sink strength.

Several empirical functions have been used for the S term (see review in Molz, 1981; Perrochet, 1987). Some of them are not easy to compare and evaluate since they are part of more complex models (Nimah and Hanks 1973, Feddes et al,1974,1976,1978; Rowse et al,1978), and were not directly and independently tested. Rather soil and root characters included in the formulas were chosen as the ones that gave the best fit of the overall model when field data were used for calibration (Molz 1981) . Others are rather simple and include soil hydraulic properties alone, ignoring root resistance to water flow, and have therefore been criticized from a conceptual (Molz 1981, Reicosky and Ritchie 1972) and practical (Klepper and Taylor 1978) point of view. Others regard root-soil hydraulics with more detail(see in Molz, 1981 and Klepper and Taylor, 1978). Several of them include root density measurements per unit volume. Advantages, theoretical problems, practical disadvantages and inability to accurately describe experimental data have been reviewed (Molz 1981, Klepper and Taylor 1978, Passioura 1988) for the various approaches. Some of the problems, common to most of them need to be addressed for a better understanding of the processes of water transport and uptake and accurate quantification and modeling .

SPATIAL DISTRIBUTION OF ABSORBING ROOTS

Most water uptake models calculate extraction based on root density per unit volume of soil. Such density is either measured or estimated in the volume considered, and is generally considered to vary with soil depth. The explicit or underlying assumption is that roots are uniformly or regularly distributed in each soil layer or soil volume considered. In fact the single root model and its extension to the entire root system (Tinker, 1976) assume that the radius of the soil cylinder from which each root absorbs water is 1/2 the average distance between roots. Such distance is calculated with different formulas, based on different assumptions of root arrangement (random or regular with different geometry) as reviewed by Tardieu and Manichon (1986 a). One of the most used formulas is:

$$b = (\pi L)^{-1/2} \qquad \text{(Tinker, 1976)} \qquad (6)$$

where L is the average root length density in the soil volume considered. Such an approach is valid if L is above a certain threshold level, and is justified by the hypothesis that roots are parallel to one another, and that average distance and effective distance between roots coincide. This last condition is true if roots are uniformly distributed in the soil, and it is a reasonable approximation if the distribution varies

randomly (calculations based on random or regular distributions give similar results -Tardieu and Manichon 1986 a-). In such conditions, overlapping between water absorption zones of adjacent roots is not considered, and regions where soil water is not extracted are not accounted for.

In reality, the root is a coordinated system with complex interrelations so that single roots cannot be considered parallel nor independent of each other. Also, the soil environment shows heterogeneity in the physico-chemical and biological properties that affect root density. Therefore, the assumption of randomness or regularity in root distribution is not justified.

Testing of several water extraction models has been made in the laboratory,in artificial or often disturbed growth media, where conditions in the root environment were likely much more uniform than what generally happens in the field. However, a well defined relation between root length density and water uptake is not always found in water uptake studies. In field situations even greater differences between calculated and measured uptake are found. Root spatial variability in the horizontal (xy or areal according to Hamblin, 1985) dimension can account for a part of the discrepancies found between measurements and calculations.

CONSEQUENCES FOR WATER UPTAKE

The characterization of the root system as a water sink has involved the measurement and/or calculation of root density, water potential gradients and hydraulic resistances along the flow path. Most calculations were made following the hypothesis of uniform root distribution.

Tardieu and Manichon (1986 a) argue that the assumption of root uniformity leads to computation of distances between roots smaller than they actually are if root clustering exists. They show how,in case of structurally heterogeneous soil, the real distance between some adjacent roots is remarkably larger than the average distance (Tardieu and Manichon, 1986 c, Tardieu, 1988 b).

Overlooking of this phenomenon would lead to a series of errors: if the water flow trajectories from the bulk soil to the roots are longer, the importance of soil resistance to water flow is probably greater, and if it becomes limiting, larger gradients in water content and potential will exist in the root zone, between perirhizal and 'bulk' soil, than the ones resulting from average distance calculations. Roots water status will be affected, in that roots will experience water shortage even in a soil whose average water content is not low. Cavazza (1985), using data from Gardner, shows how the distance at which a root can draw water from the soil is of the order of a few mm or cm, depending on the initial soil

water conditions and the velocity of water uptake. He argues that if the root system does not permeate the whole soil, it may not have access to all of the water in the bulk soil. Passioura (1985) suggests that if roots are clustered, i.e. constrained in wormholes, each cluster should be considered like a single root, having access to a cylinder of soil of radius:

$$B = (\pi\ L^*)^{-1/2} \qquad (7)$$

where L* is the length of occupied pore per unit soil volume, and replaces the root length density of the single root model (equation 6). This way, water extraction is no longer a function of the actual root density. Rather, it becomes dependent on the geometry of soil pores accessible by the roots, and of the actual presence of roots in such pores. The values for B would be considerably higher than those of b (equation 6) based on average root length density. The author calculates a time constant that describes the rate of water uptake when flow through the soil is entirely limiting. Such a constant is proportional to b^2 if equation 6 is used, and to B^2 if equation 7 applies. Therefore, in case of clustered roots, the time constant may become quite large, and possibly limiting the access of the roots to soil water in a time useful for crop survival or stress relief. A more general treatment of a clustered root distribution (for roots growing

along planes or soil prisms) is formalized as the clumped root model :

$$Q = \frac{2n}{B^2} \int_{\theta_B}^{\theta o} D(\theta)\, d\theta \qquad (8)$$

(Passioura, 1985)

where θo is θ at the center of the prism or between planes;
B is the radius of the cylinder approximating the prism or half distance between planes;
n is 1, 2 or 3 according to the geometry of clusters.
$D(\theta)$ is soil water diffusivity[2]

Such an approach implies the need for changing the type of features that need to be measured in order to quantify root water uptake. Namely the geometry of soil regions accessible to roots, and the effective presence of roots in such regions would have to be determined instead of the average root length density in a given layer of soil. Root length density determinations would still be necessary if roots were sparse enough that the planes of root growth could not be considered diffuse water sinks. In that case a cylindrical or sub-cylindrical geometry should be assumed.

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[2] soil water diffusivity is used instead of soil water conductivity k for simplifications in the mathematical treatment of transient flow. The relations between D and k are: $D = k * \delta\psi/\delta\theta$. This approach implies therefore the use of gradients in water content instead of gradients in soil matric potential, and is formally identical to Fick's law of diffusion, therefore it is referred to as diffusion equation. Physically, though, it is not diffusion (random motion) but mass flow under pressure gradients. In order for the relation $\delta\psi/\delta\theta$ to hold, the soil must be uniform in texture and structure.

THE ROOT AS A SPATIALLY VARIABLE WATER SINK

It is well-known that plant roots present a highly non-uniform distribution in the soil. Such heterogeneity is generally recognized to have a structured component in the vertical dimension, but in the xy plane it is generally only described by a high coefficient of variation of the root character measured, since most of the root and soil sampling strategies used so far are not designed to study its spatial patterns.

Data in the literature exist, that document horizontal non-uniformity of root density or of water content and water potential distributions around plants (Nelson and Allmaras, 1969; Mengel and Barber,1974, Arya et al., 1975 b and c, Boehm et al., 1977, Kilic, 1973), but often the authors do not explicitly use the information on spatial arrangement for their calculations and comments. Only recently, attempts have been made to document root clumping (Ehlers et al,1983; Taylor,1983; Wang et al, 1986), to quantify it (Tardieu and Manichon, 1986 a and b, 1987 b, Tardieu 1988 b, Pettygrove et al., 1989) and to explicitly take it into account for its effects on nutrients (Sanders et al. 1970, Baldwin et al., 1972, Dunham and Nye, 1973; Pettygrove et al., 1989) and water (Tardieu and Manichon,1987,c; Tardieu, 1988,b and c) extraction.

One consequence of such an approach is that part

of the variability in root density is no longer viewed as random , so that it can no longer be considered part of the 'error' in statistical analysis. This should result in a reduction of the coefficient of variability. Tardieu (1988 b) reports a reduction of the coefficient of variability of root length density in the soil, if the calculations are made in non-compacted soil areas only (c.v. 30%) as opposed to pooling the data taken from compacted and non-compacted regions of the same soil layer (c.v. 80-90%).

The problem of characterizing roots as a spatially variable water sink is complicated by the presence of two dimensions relative to the geometry of the absorbing system:

a) roots distribution is generally not uniform or random in the soil, but different degrees of clustering are likely to occur. The consequences for water uptake are that on one side, extraction zones of roots in a cluster overlap, and on the other, soil regions relatively far from the roots exist in the rhizosphere, where water is not extracted because large potential gradients would be necessary to move a significant amount of water across several centimeters of soil, if the hydraulic conductivity is relatively small.

b) the ability to absorb water is not uniform throughout the root system.

It is due to both :

-i- physiological reasons : permeability to water varies with respect to position along the root. The Casparian strip

was identified as the main obstacle to water flow across the root, but other features play a role too, as suberin depositions on the epidermis, or the presence of least resistance paths like root hair insertion points and 'easy' symplastic ways (Clarkson, 1984; Drew,1979).

The assessment of which part of the root is to be considered actively absorbing was one of the first, and still is one of the main problems of a microscale-type approach, given the difficulties of the measurements involved.

Early works and a number of more recent ones (Boyer, 1985; Kramer,1983) identify the 1 to 10 cm of root behind the tip as the active region (young tissues), but the length of such zone has been reported to be dependent on various conditions, at least species (Sanderson, 1983; Drew,1979). It has also been argued that other parts of the root are likely to play a role (Passioura 1988), since uptake occurs in older parts of the root system as well, even though at a lower rate (Sanderson,1983). Kilic (1973) suggests that as the rate of transpiration increases, the zone of water absorption moves, extending to older zones of the root. Also, there is debate on whether the root resistances to water flow are constant or variable with flow rate. Conceptually, and also for many applications, it is likely more correct to speak of a gradient in absorbing properties rather than distinguishing between an active and an inactive zone.

Also, most of the data on water uptake by different

regions of the root come from experiments in nutrient solution. Passioura (1980) estimated from laboratory experiments on wheat seedlings grown in soil at ψ=-5 bar, that the effective length involved in water uptake was 1/3 of the total root length, but such a ratio should not be extended to other situations.

Kilic (1973) modified the root water extraction function (sink term of the water transfer equation) adding a term for the degree of suberization, defined as the required water potential gradient between soil and absorbing root surface to overcome the resistance of the suberized layer. With this correction he predicted that the rate of maximum water absorption occurs where the root density is optimum rather than maximum, due to suberization of the older roots.

Factors other than plant anatomical features play a role. An example is temperature that may vary considerably with soil depth, and that may affect root activity rate to a large extent (Allmaras et al., 1975). Small anaerobic soil areas, likely present in structured soils, will also change local root permeability (Everard and Drew 1987).

-ii- hydraulics of the root-soil interface: poor contact due to soil and/or root shrinkage (Faiz and Weatherley, 1982; Huck et al., 1970) during drying, interrupts the water flow continuity and water transfer may continue only through diffusion of vapor, orders of magnitude slower (Passioura,

1988).

Due to lack of soil-root contact , therefore, some root length may give a much lower contribution to water uptake than what would appear if extraction were considered proportional to root density.

The relevance of both classes of phenomena has not been clearly established, and the problem is complicated by the variations that they undergo in time and with changes in soil conditions, and by possible interactions. The result is that absorbing properties of the root system are distributed in space in a way even more complex than the physical spatial distribution of roots may suggest.

The composite spatial arrangement of the uptake properties of the root system, resulting from physical and physiological spatial variation, is what is relevant. Some of the existing models in the literature propose water extraction functions for the root sink term that are based on an 'effective ' root density, rather than on a physical one (Gardner,1964 ; Molz and Remson, 1970,1971; Molz, 1971; Feddes et al., 1976; Herkelrath et al, 1977; Passioura, 1980 and 1983). The concept was introduced for the purpose of accounting for the differences in permeability of different root parts (i.e. Passioura, 1983), or for the regions of poor soil-root contact (i.e. Herkelrath et al, 1977 b) and not for root spatial arrangement. The application of this concept encounters great difficulty in the actual determination of the

degree of 'effectiveness' of roots. Nonetheless, it is conceptually interesting in that it is a way of expressing root density in functional rather than physical units, attempting to model water absorption in a slightly more mechanistic way than just relating it to total root length.

Also, even if physical and physiological root spatial variations are conceptually separated, any testing of hypothesis on the effect of one of them on water extraction patterns will have to deal with the other.

In addition to the variability in space of the root absorbing characteristics, a temporal dimension is to be considered: roots grow and their absorbing surface moves in the soil. Phenological factors may imply that the roots found in deep soil have important time constraints for the extraction of the water present at the bottom of the root zone. Furthermore, water absorption often occurs in non-stationary conditions. Some of the dimensions of complexity introduced by these factors have been treated by Kilic (1973).

CAUSES OF XY (AREAL) SPATIAL VARIATION (that affect physical and functional spatial variation)

Research that treats of root horizontal spatial variability at the plant level (Tardieu and Manichon, 1986 and 1987, Pettygrove et al., 1989), generally discusses it in relation to heterogeneity of physical and chemical soil

properties.

As a matter of fact, the root is a coordinated system and single roots often are branches of the same individual, whose interactions are responsible for a part of the spatial distribution found. There is, then, also a physiological or plant component that determines root spatial arrangement.

The relative importance of the two components (within-plant interactions and soil variability) on the final root geometry is not easy to assess. Recent studies point out that some of the commonly accepted views on the dependence of root growth on local soil conditions probably underestimate the importance of plant coordination in determining the final plant form (Tardieu,1989). Even without hypothesizing central roles of coordination in the plant, it is reasonable to argue that interactions between roots, within and between individual plants, do play a considerable role in the final spatial arrangement.

In the following paragraph the sources of spatial variation of plant roots are treated with regard to both plant and soil factors that affect physical and functional distribution of the roots.

A) Plant

I- root geometry and branching.

i- geometrical relations between root parts (affects physical spatial variability)

Root geometry varies with genotype but two

common features, more or less represented, affect the form of its arrangement in space :

- one is the fact that the root is a branched system. Thus, a root in a certain soil region is not an independent entity, but rather comes from either continuation or branching of another root. Therefore the presence of a root in a given soil volume implies that the probability of finding another root in a neighboring region is higher than the probability of finding it in a far-away zone. Of course, this depends on the scale of measurement and on ramification patterns. Tardieu (1988 b)) reports a skewed distribution of maize root length density measured on a small scale, to be attributed to the branching pattern of the plant.

- another aspect is related to direction of root growth. Due to branching, structures growing in all the directions are present, so that parallelism between roots is not always a reasonable hypothesis.

In certain regions, though, growth has a preferred direction: more horizontal in top layers and vertical in lower layers. Where a preferred direction of growth exists, the probability of finding a root is not the same in each soil volume: for vertical growth, for instance, it is greater than average in the soil regions below an existing root, and lower than average in the areas around it.

Due to such features, therefore, single roots cannot be regarded as independently distributed in the soil.

ii- morphogenesis (affects physical spatial variability)

Laterals differentiation is known to be related to the vascular pattern of parent roots, and is thus thought of as radially symmetrical, while root disposition along the axis, has received little attention. Some research exists,from which a tendency toward lateral clumping emerges : pairs or groups of 3-5 roots are found in dicotyledons (Mallory et al., 1970; Charlton,1983), and larger groups in monocotyledons (mcCully, 1975) separated by a more or less large distance along the parent root's axis. The experimental conditions and the stages of laterals formation are different in the various works, but for at least a part of them it seems that the observed clustering is not due to local conditions of the growth medium. Little investigation has been made on the causes of clustering and spacing between clusters. Information from studies on the effects of existing lateral primordia on new ones is used to suggest that laterals inhibit the formation of other primordia (McCully,1975). Other evidence, though, suggests that mutual stimulation may exist. The effect of the apex (Mallory et al., 1970) in inhibiting laterals, and of root wounding on primordia initiation has also been object of study, and so has been the role of hormones in one or the other direction (McCully, 1975).

Also,questions have aroused about the evolutionary meaning of laterals clustering and the competitive advantages

it may involve .

According to what discussed in paragraphs i and ii, then, single roots distribution in soil would not likely be random, but rather show positive autocorrelation.

II competition and chemical interactions between roots (affect physical and functional spatial variability)

Roots belonging to the same or different individuals interact with one another in a way that affects not only their final arrangement in the soil, but also their functionality.

The net effect of competition for nutrients and water through depletion of certain soil areas, and of allelopathic communications between roots of the same plant or between plants developing at the same time is likely to result in regular arrangements of roots in space, since regular patterns allow to minimize total interactions.

Allelopathic interactions between roots and residues of previous crops, will have an effect on space occupation that is likely to result in complex patterns ("patches of occupation"). Such patterns will be dependent on the plant species, and variable in time, since new regions in the soil will become available for root colonization as soil metabolism of previous crop residues evolves towards humification eliminating phytotoxic compounds (Zucconi, personal communication).

One may view the factors listed under II as mainly

acting between roots on the same plane. The relations of roots along the same axis are likely to be more complex, regulated also, and more strongly, by the factors listed in I.

III growth relations and partitioning within the plant

Local soil conditions (like water and nutrient status, mechanical resistance, toxic or anoxic conditions) may affect the 'hospitability' of a soil region for root colonization. The presence and amount of roots in that particular area, though, are also due to whole plant effects, like general water status and nutrition (Tardieu,1989).
A plant growing in a soil partly affected by limiting conditions will under many circumstances have reduced growth and consequently its root will be smaller too. More complex growth pattern changes, like shifts in partitioning may play a role that can amplify or compensate for the effects of local soil conditions.

B) Soil

Soil variability at a scale that affects the single plant,is generally recognized in the vertical dimension, but not in the xy one.

Remarkable areal heterogeneity may exist in the soil, in one or more properties, so that it has been suggested that soil properties be described not with a single value, but with

a distribution function (Hewitt and Dexter, 1984 a).

Variability changes with the property considered and with the scale of measurement, so that if its relations with root growth are of interest:

a) it is important to measure on a scale relevant to root development and function

b) it may sometimes be difficult to determine the resultant of the different properties on root final distribution, although limiting conditions are likely to be one or few associated ones.

Physical, chemical and biological properties may be relevant for variability in root distribution. A major role is likely played by:

Physical properties : related to soil structural status
- pore system reduction
- penetration resistance
- oxygen diffusion rate-oxygen concentration
- hydraulic conductivity-water content
- temperature

Chemical and biochemical properties :
- nutrients distribution
- nutrients availability
- toxic compounds (reduced compounds due to anoxic conditions, Al,etc.)
- pH
- allelochemical conditions caused by residues decomposition

The variation of some of these features in structured soils will be discussed in the following sections.

C) Interactions

Interactions between plant and soil causes of spatial variability, and of vertical and areal heterogeneity complicate the task of modelling root distribution. An example of such interactions is the fact that where a preferential direction of root growth exists, an obstacle to root growth in a soil area will likely not only reduce root growth in that soil region, but also in the areas beyond the obstacle. Such an effect is documented by Tardieu (1988 b) and 1989) who reports that non-uniform compaction in a soil layer determines lower root density in the compacted zones, and in the areas below them as well ('shadow effect').

STATISTICAL METHODS AND INDEXES

Soil and root spatial arrangement, and water uptake patterns can be described using different methods, several of which have been reviewed by Grieg-Smith (1983) and Pielou (1969). Some of the reviewed indexes are used as a test for deviation from an expected distribution (random or regular), others may be simply adopted as a mean of detecting aggregation.

Not all of the indexes used in the literature have the same sensitivity for the different possible spatial arrangements (randomness, regularity, clustering, regular

clustering), so their choice deserves particular attention. Geostatistical techniques (Webster, 1985) can be used as well.

Pettygrove et al. (1989) characterized root arrangement using the square root of number of roots per sampling unit. This number is proportional to the half-distance between roots. They used the comparison between mean and median of the distribution of this number to quantify root aggregation. Other authors use the comparison between mean and variance of root counts per sampling unit, with small scale grid sampling strategy. This approach is based on the fact that mean and variance are equal in a Poisson distribution, which is the expected distribution in case of random arrangement on the whole sampling area. Deviations from Poisson-type distribution are reported to result in a mean/variance ratio different from 1, so this ratio is suggested as a means for studying clustering. But Pielou (1969) reports that even some cases of clustering may give a value of 1 for this index.

Tardieu and Manichon (1986) and Tardieu (1988 b)) used three methods : spatial autocorrelation, for aggregation analysis of root data collected on a small grid, the quadrat method for a larger grid study, and also the distribution function of the distance between each point of the plane and the nearest root impact. This last method proved more accurate than the average RLD for characterizing the root as a water

sink, but it is more time consuming.

Tardieu (1988 b)) analyzed the effect of sampling grid size on root clustering measurement; he discriminated between centimeter-scale variation, attributed to maize branching patterns, and decimeter-scale variation, attributed to the differences in soil compaction that he applied to the soil as experimental treatments.

Some of the above mentioned indices require sampling to be made on a grid, others are based on the distance between roots or between each point of the plane and the nearest root. In all cases information has to be geographically recorded and small scale sampling is needed. This type of study, then, requires particular sampling techniques and is rather time-consuming. One of the needs of plant modelling would be to predict degree of clustering in selected situations in order to avoid extensive measurements.

TECHNIQUES FOR MEASURING ON A RELEVANT SCALE

The description of spatial arrangement of roots requires small scale measurements. The actual scale depends on the study purpose, and so does the particular technique used. The study of the soil properties that affect, or come as a consequence of root clustering should be made on a relevant scale as well. The methods we use to characterize soil properties do not always describe these properties in a way

that can be put in relation to root growth and function. For instance, it is known that the soil penetration resistance values, measured on the same soil, vary with penetrometer size (Bradford, 1980), and a root tip, growing axially and radially and being surrounded by lubricating materials, will most likely experience a resistance to penetration even different from that recorded by a penetrometer of the right size (Greacen et al., 1986).

In other words, if an attempt has to be made to characterize the soil as the root sees it, particular attention has to paid in seeking appropriate scales and methods of measurement.

A) Root measurements

In order to describe clustering, the roots should be measured on a few millimeters or centimeters scale. Sampling schemes have to account for root position, therefore data have to be geographically recorded. For this purpose, regular sampling schemes can be used, as transects or grids, or mapping can be made based on each root's position with respect to a coordinate system.

As far as techniques, destructive ones have been used , i.e. mapping or collecting small samples from a pit wall (Boehm et al., 1977), or from selected horizontal planes (Tardieu et Manichon, 1986 and 1987) . Pettygrove et al (1989) used mini-rhizothrons to analyze root spatial arrangement on a transect. Nelson and Allmaras (1969) developed a

soil-monolith and pinboard method that approximately keeps the root spatial arrangement, although the scale used was quite large. A good potential for this type of study is presented by nondestructive three-dimensional techniques, like the Nuclear Magnetic Resonance imaging systems (Rogers and Bottomley, 1987).

B) Soil water content measurements

Water content of the soil can be measured on a small scale by destructive methods, like gravimetric samples. Nondestructive techniques, such as gamma rays attenuation or x-rays, or also Nuclear Magnetic Resonance can be of good use and provide the possibility of measurements on a suitably small scale. In order to obtain the three-dimensional information necessary to describe spatial arrangement,these techniques must be used with tomography. Therefore they cannot be used in situ, but in container-grown plants only. The development of Nuclear Magnetic Resonance imaging applications to soil studies would be a particularly appropriate technique, because of its interesting potential for showing both soil water content and root distribution on the same container.

A small scale in-situ technique that allows to take roots and water measurements on the same soil site would be necessary.

C) Measurement of soil properties

The measurement of soil properties related to root clustering should be made in a way that is relevant to root

behavior. The first problem is to measure on the right scale, as pointed out above for soil penetration resistance. The problem of scale brings up a second aspect : for several soil characters it is probably not correct to describe them with a single value in the soil, but rather they can be better represented with a distribution function. For instance, in a system made of aggregates, solid particles and voids (pores), like the soil, it is easy to imagine how the roots do not experience a single value of resistance to penetration, but rather a series of situations, different from site to site on a very small scale.

Thus, in order to obtain a relevant measurement it is necessary to use an appropriate conceptual model of the spatial scales and arrangements needed for sampling.

STRUCTURED GROWTH MEDIA

Both problems of mechanical impedance and low conductivity for water and oxygen are likely to cause root clustering in cracks of structured soils. Furthermore, the oxygen status of the soil is likely to interact with other causes of root clustering. For instance residues decomposition is likely to be greatly affected by the hypoxic zones that exist in a structured growth medium. Residue metabolism will then be slower, and reduced phytotoxic compounds will likely persist longer in those regions, creating inhospitable areas

for root growth. Also, anoxic conditions do not only affect root growth (Schumacher and Smucker,1984), but they reduce root activity as well (Everard and Drew, 1987). Furthermore, preferential ways for water movement (i.e. cracks) will cause a non-uniform movement and final distribution of water (Ritchie et al., 1972) and soluble nutrients.

In a structured soil, therefore:

a) Roots are rather likely to show clustering. The ability of roots to extract water may then be overestimated by average root density calculations, and the development of plant genotypes able to extract a higher amount of water may take advantage of root characterization methods that can describe root spatial distribution.

b) Clustering will occur as the resultant of several factors (physical, chemical, microbiological) that may be difficult to separate. But since a number of them are interrelated, and basically dependent on mechanical impedance and oxygen status, they are likely to be associated with structural status and result in patterns of root growth that are predictable from soil structure, at least to a certain extent.

If structural heterogeneities are due to the swelling properties of clays, they are likely to have a rather large systematic component and even a certain fractal dimension. Thus the system will be somewhat regular and root clustering will be relatively easy to describe and model.

In other cases heterogeneities can be considered not

regular on a plant scale (i.e. the heterogeneities created in fine-textured soils when tilled in bad conditions).

The two situations will probably cause different types of root patterns, and may be treated differently as far as description and quantification. The first kind of heterogeneities will be dependent on the clay type and therefore predictable to a certain extent.

The study of root clustering and its consequences in structured growth media may prove critical for the extension of crop models to such soils, as well as to field situations where the soil structural status and its effects on root geometry are modeled (i.e. soil tillage models).

Models exist on the behavior of roots in soils with discontinuous structural properties, but most of them are either prominently theoretical (Hasegawa and Sato, 1987) or based on experiments done in simplified conditions (Dexter and Hewitt, 1978; Hewitt and Dexter, 1979 and 1984 b; Whiteley and Dexter, 1984;).

Complications arise in modelling the influence of structured growth media on rooting pattern because soil strength, hydraulic conductivity and oxygen content, and related properties do change with time, essentially due to variations in water content. Furthermore, the effects of root clustering on plant water supply vary with water content too. The problem must be considered as a dynamic one. Thus, there is a need for studies based on field situations.

The present work studies some cases of root spatial variability in structured growth media, and the consequences of root clustering on water uptake in maize (Zea mays L.).

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9
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CHAPTER 1

SMALL SCALE SOIL WATER CONTENT MEASUREMENT WITH TIME-DOMAIN REFLECTOMETRY (TDR)

ABSTRACT

The suitability of Time-Domain Reflectometry (TDR) technique for volumetric soil water measurement at small scale was explored. Measurements were made on a clay-loam and on a sandy-clay soil with 21 mm long parallel balanced transmission lines and gravimetrically. Water content values ranged from oven-dry to saturation. In order to quantify the error in length measurement with TDR using short transmission lines, measurements in air of lengths ranging from 10 to 150 mm were also performed. At tracelengths lower than 0.03 m, corresponding to air-dry soil, the coefficient of variation of the measurements was quite high (2.8% to 7.3%), therefore the technique proved less reliable. For longer traces, corresponding to higher water contents, the coefficient of variation was lower than 2.8%. At water content higher than 0.29 cm3 cm-3 in the clay-loam soil a few samples showed excessively high values of dielectric constant . Care should

be taken in data interpretation at high θ_v for these media.

TDR proved effective in measuring soil volumetric water content with the tested transmission line at θ_v> about .07 cm3 cm-3.

INTRODUCTION

The characterization of spatial distribution of roots and water movement can provide important information to quantify plant water uptake and to explain discrepancies between plant-soil-water model predictions and field-scale water measurements (Tardieu and Manichon, 1986; Passioura, 1988). However, the description and prediction of soil water movement in a way relevant to field conditions requires a transition from relatively uniform and well-defined systems to the heterogeneity in space and time that occurs in the field (Hamblin, 1985).

The study of small scale soil water distribution has been limited by lack of suitable techniques operational at the required resolution. Dunham and Nye (1973), using a thin section (2 mm) technique, determined the gravimetric water content of soil layers as a function of distance from a plane of onion roots. Hsieh et al. (1972) studied the bidimensional water distribution around root hairs using a non-destructive gamma-ray technique. Hainsworth and Aylmore (1983) quantified small-scale soil water content using computer-assisted

tomography with x-ray, with 2 by 2 mm pixels on 5 mm thick planes. Each of these techniques was developed for laboratory measurements in containers. Small scale techniques have not been developed for field characterization of soil water content.

Time-domain reflectometry is a recent technique for the measurement of the volumetric soil water content that can be used in container studies as well as in the field. It is based on the determination of the soil relative dielectric constant ε, from the velocity of propagation of an electromagnetic signal (1MHz - 1GHz) in the soil. Since the relative dielectric constant of water (81.5 at 20 °C) is about 20 to 40 times larger than that of the dry soil (2-4), the measured values of ε are strongly related to the volumetric water content in soil. The EM signal travels in the soil along a transmission line, whose propagation characteristics (variations of impedance as a function of distance) are displayed on an oscilloscope screen as a trace with length units on the x-axis. The length of the wavetrace relative to the transmission line in the sample, is the basis for dielectric constant determination. Topp et al (1980) suggested an empirical equation to calculate the volumetric water content from ε in mineral soils. A number of works have contributed to define limitations, advantages and possible future developments of the technique. Among the limitations, it has been pointed out that the maximum length of the TDR

transmission line is dependent on the soil type, and that in soils with high clay content signal attenuation may limit the maximum length to less than 1 m, while lines up to 20 m long have been used in sandy soils (Topp and Davis, 1985). The use of short transmission lines for small scale measurements is limited by the instrument accuracy, and depends on the line geometry. Topp et al. (1984) reported consistently low values of TDR-determined versus gravimetrically-determined volumetric water content when measuring water content in the 0-5 cm soil layer, using 150 mm parallel balanced metal rods partly inserted in the soil. No other data have been reported on transmission lines shorter than 100 mm.

The aim of the present study is to test the performance of short transmission lines for TDR measurement of soil water content. Since TDR determinations are based on the determination of the wavetrace length, the error in tracelength measurement was determined for traces ranging from 10 to 150 mm. Then soil water content was measured in two soils with 21 mm long transmission lines.

MATERIALS AND METHODS

A Tektronics 1502 B cable-tester was used. The transmission lines were parallel balanced. A balun (impedance transformer Anzac TP 103) was used in order to minimize the impedance mismatch at the transition from coaxial to parallel

balanced geometry. The transformer was mounted on a fiberglass board, and it was connected to the transmission line through banana plugs (Figure 1.1).

In order to evaluate the error in length measurement using short waveguides, the following procedure was used: the velocity of propagation of the signal was set at 99% of the propagation velocity in air, so that tracelengths would be at the same scale as the lengths measured on a transmission line in air and could be compared directly. A 150 mm long parallel balanced transmission line was set in air, by inserting a couple of 200 mm stainless steel waveguides (diameter 5 mm; distance between rods: 50 mm) on a 50 mm styrofoam support so that 150 mm would be left in air. The Time-domain reflectometer was connected to the guides by inserting the balun banana plugs in the styrofoam until contact with the probes was reached. A zero spatial reference was set by short-circuiting the waveguides at one point with a thin blade, and recording its position on the wavetrace. The rods were marked with a razor blade in 10 mm increments up to 150 mm (measured with a caliper). Lengths were measured with TDR by shortcircuiting the waveguides at the marked points and determining on the oscilloscope the length of the trace relative to the chosen distance. Measurements were replicated five times.

Two soils were used for water content determination: a clay loam (sand 36.5%, silt 24.1%, and clay 39.4%.), and a

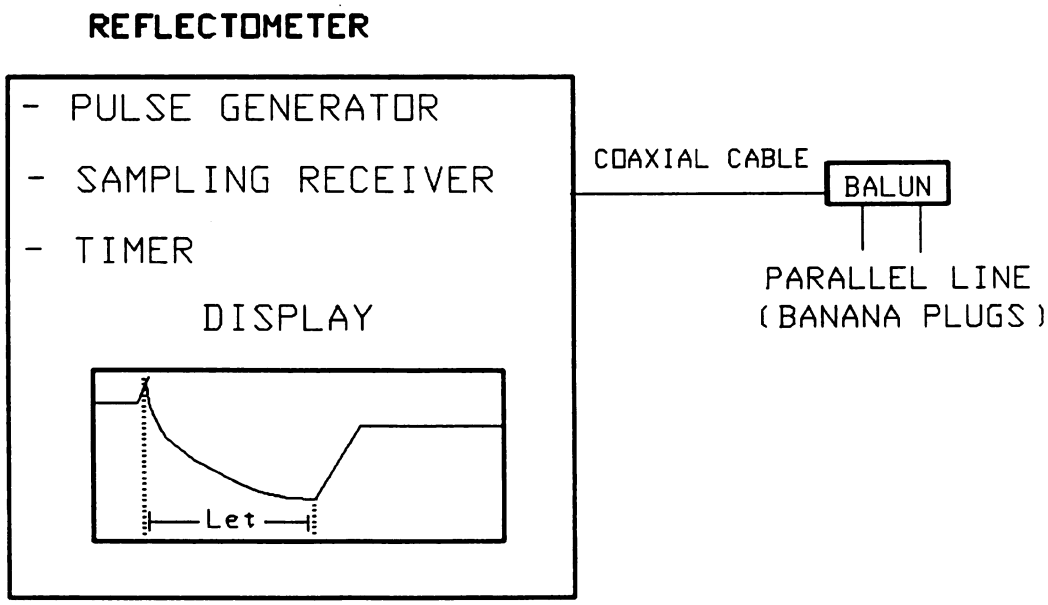

Figure 1.1. Time-domain reflectometer and connections for a parallel-balanced transmission line.

sandy clay (sand 52.3%, silt 10.6%, clay 37.1%)(ISSS classification: sand 2 - 0.02 mm, silt .02-.002 mm, clay <.002 mm). For each soil 101 measurements were made, comparing TDR-determined and gravimetrically determined volumetric soil water content on samples prepared as follows:

a 100 by 100 mm wooden frame, 21 mm high, was attached to a plastified cardboard bottom. The box was filled with sieved soil and carefully leveled to 21 mm, and covered with plastic wrap to prevent evaporation during the measurements. The transmission line for soil water content determinations consisted of a couple of stainless steel syringe needles truncated at 21 mm, inserted on a rubber support at a distance of 14 mm (Figure 1.2). The needle plastic sockets were used for connection with the balun-board banana plugs.

Two TDR measurements of soil water were made in each box, with the described transmission lines.

The relative dielectric constant ε of the samples was calculated from wavetrace length according to Topp et al. (1980):

$$\varepsilon = \left(\frac{c \cdot L_{et}}{v_p \cdot L_r} \right)^2$$

where: c = propagation velocity of an electromagnetic signal in void = $3*10^8$ m sec^{-1}
v_p = propagation velocity of the electromagnetic signal in the transmission line (m sec^{-1}). vp can be set on the instrument by the user.
L_r = transmission line length (m)
L_{et} length of the wavetrace (m)

and the volumetric water fraction of the soil was calculated

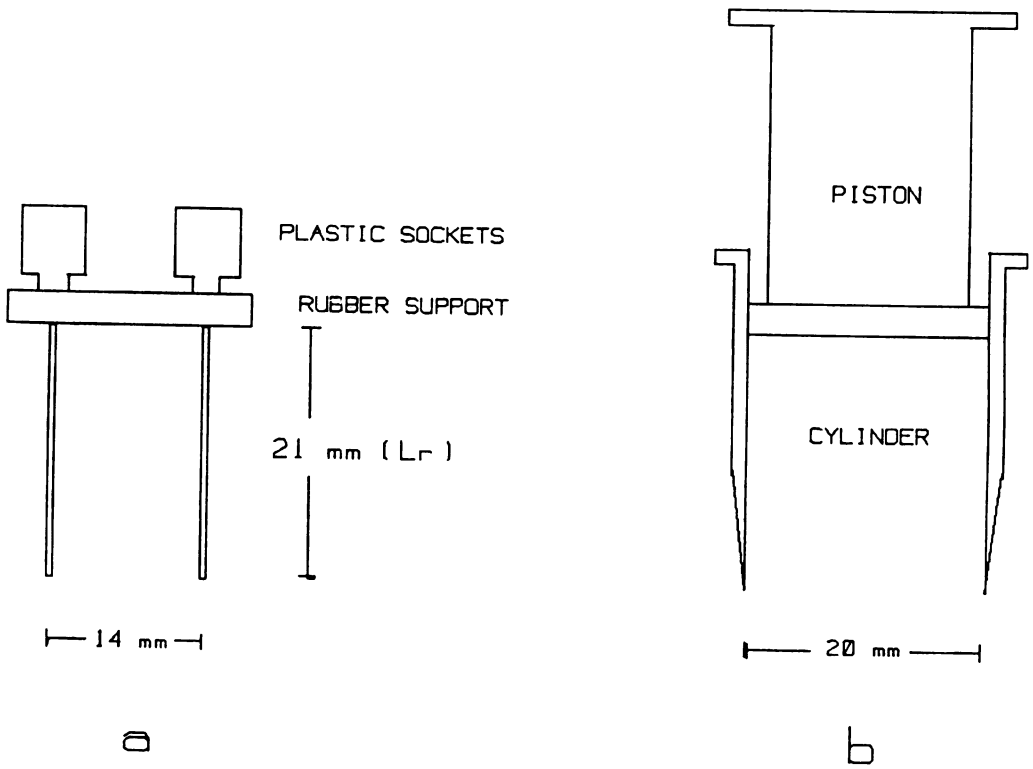

Figure 1.2. a) Transmission line for small-scale TDR water content measurements in soil; b) Soil sampler for gravimetric determinations.

with the equation:

$$\theta_{v(TDR)} = -5.3*10^{-2}+2.92*10^{-2}*\varepsilon-5.5*10^{-4}*\varepsilon^2+4.3*10^{-6}*\varepsilon^3$$

(Topp et al., 1980)

where $\theta_{v(TDR)}$ = TDR-determined volumetric soil water content
ε = relative dielectric constant.

This equation was found to satisfactorily express the relationship between volumetric water content and relative dielectric constant for a range of mineral soils (Topp et al, 1980), and was tested by Amato et al. (unpublished, b) for the same clay-loam soil used in this experiment, with 150 mm transmission lines.

According to Topp and Davis (1985) the area of soil explored by a transmission line with the geometry described is a cylinder having length of 21 mm and diameter of about 20 mm. In order to provide a comparison for $\theta_{v(TDR)}$, after each measurement the soil around each transmission line was sampled with a plastic sampler (cylinder + piston, see Figure 1.2) with inner diameter of 20 mm. After inserting the sampler, the area around it was cleared from the soil and the cardboard bottom was cut so that the soil cylinder sampled could be ejected by pressing the piston. The water content was then determined by weight difference on the sampled volume. Gravimetrically-determined volumetric soil water will be indicated as $\theta_{v(g)}$ in the rest of the chapter.

Measurements were made at water content levels ranging from oven-dry to saturated soil. Samples for which the

gravimetric sampling procedure visibly caused problems in volume sampling (loss of soil, excessive compaction) were discarded. A total of 101 values for each soil was obtained.

RESULTS AND DISCUSSION

The results for length measurements in air are summarized in Figure 1.3. The standard deviation of trace length measurements increased with the mean, ranging from 0.84 mm to 3 mm. The coefficient of variation of the length measurements was quite high for 10 and 20 mm measurements (7.5% and 4.6% respectively), and decreased with length increase. In the range 30 - 90 mm, which corresponds to the range of airdry to saturated soil (see below), the coefficient of variation was <= 2.8% Figure 1.4 reports the calculated error for trace length determination, based on the instrument's horizontal accuracy (redrawn from Amato et al., unpublished, a). The accuracy reported on the data sheet is+-(0.6mm+2% of the reading), therefore the absolute error increases with tracelength (0.8 to 3.6 mm for tracelengths of 10 to 150 mm), while the percent error decreases, tending to an asymptotic value of 2% (Amato et al., unpublished a). Comparing Figure 1.3 and 1.4 it can be seen that in a few cases the standard deviation values from actual measurements were slightly lower than the calculated absolute error. The reason for it could be that the theoretical error was based on the instrument's

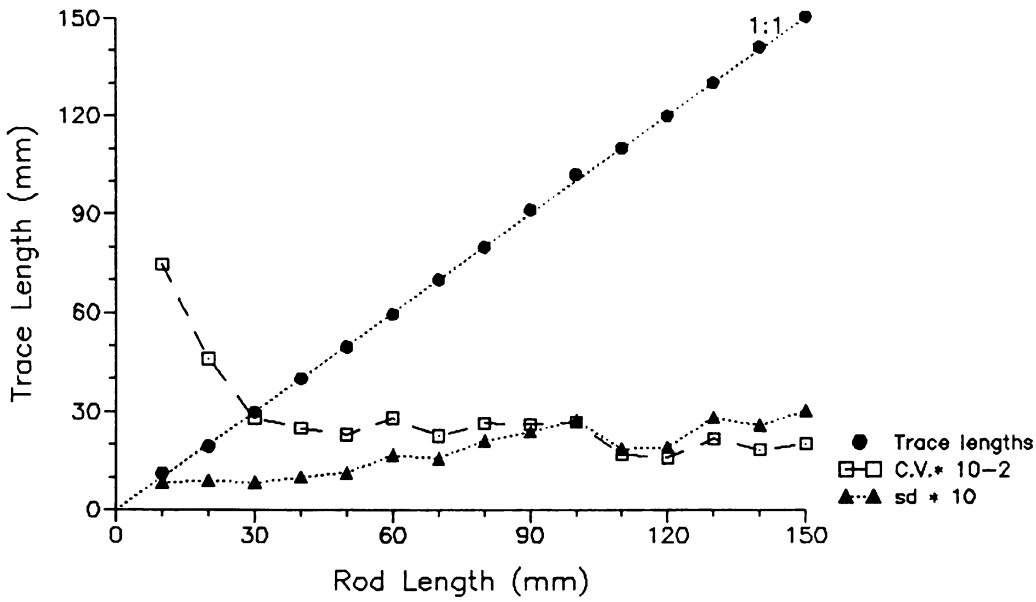

Figure 1.3. Comparison between length of transmission line in air and TDR trace length.CV = coefficient of variation (%). sd=standard deviation (mm).

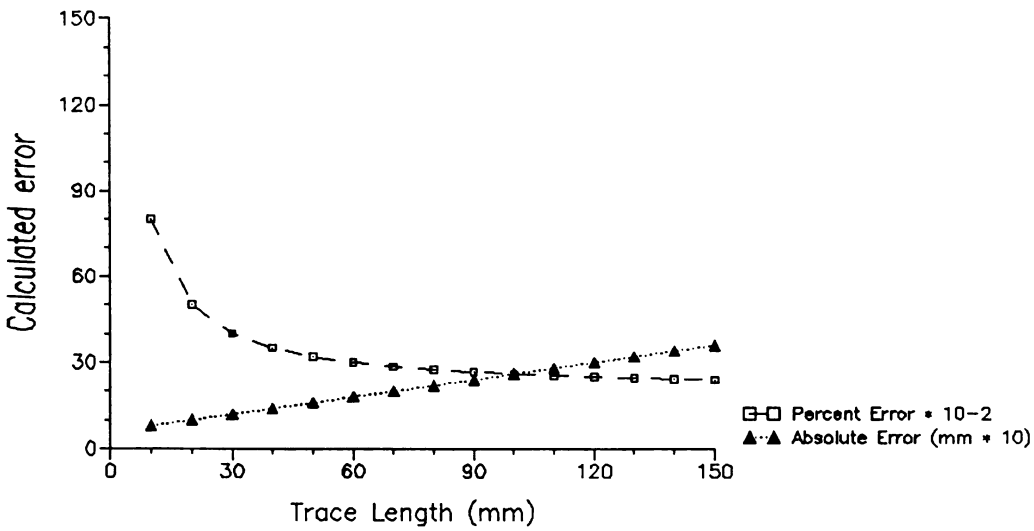

Figure 1.4. Absolute and percent error for trace length determination, calculated from data sheet specifications of the Tektronics 1502 B cable-tester.

specifications. The actual performance may be better in case of quite short transmission lines.

The comparison between measured values of $\theta_{v(TDR)}$ and $\theta_{v(g)}$ is reported in Figures 1.5 and 1.6 for the clay loam and the sandy clay soil respectively. The differences $\theta v_{(g)}-\theta v_{(TDR)}$ were analyzed with a paired-t test, the results of which are presented in Table 1.1. For the clay loam soil there was a good agreement between the two methods. The overall standard deviation was about 0.023 cm^3 cm^{-3}, but in some cases the deviation between methods reached values up to about 0.05 cm^3 cm^{-3}. The differences found were not significant for P = 0.01 and P = 0.05. For samples at $\theta v_{(g)} < 0.07$ cm^3 cm^{-3} the standard deviation was higher than the overall, probably due to the higher percent error in trace-length determination, especially for the oven-dry samples. For these, the tracelength was between 0.020 and 0.025 m, and thus it was subjected to a percent error of 3.0 to 4.6%, as discussed above. For dry samples the errors in gravimetric determination may have had a higher relative importance than at high water content. Besides, with dry samples being quite loose, small volume sampling may have implied relatively high soil losses. The latter source of error would explain the underestimation of θv with the gravimetric method observed for many samples at the dry end of the curve. In moist samples ($\theta_{v(g)} > 0.29$ cm^3 cm^{-3}), about 30% of the $\theta_{v(TDR)}$ values were excessively high (0.14 to 0.40 cm_3 cm^{-3} higher than $\theta_{v(g)}$). Such discrepancies can only

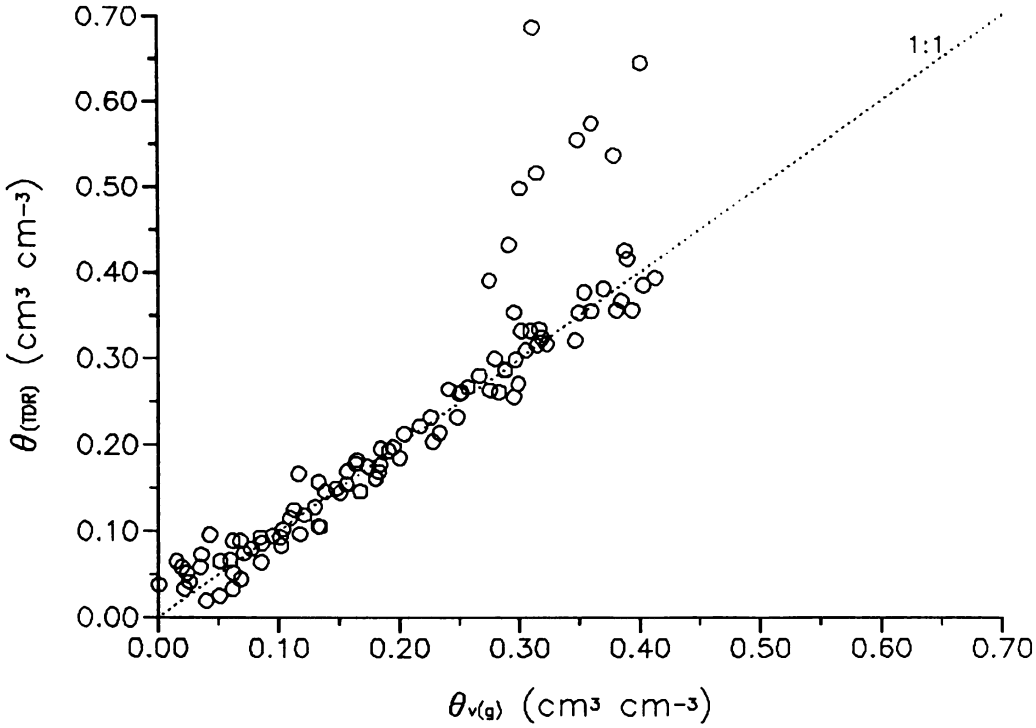

Figure 1.5. Comparison between TDR-determined ($\theta_{v(TDR)}$) and gravimetrically-determined ($\theta_{v(g)}$) volumetric water content in clay loam soil.

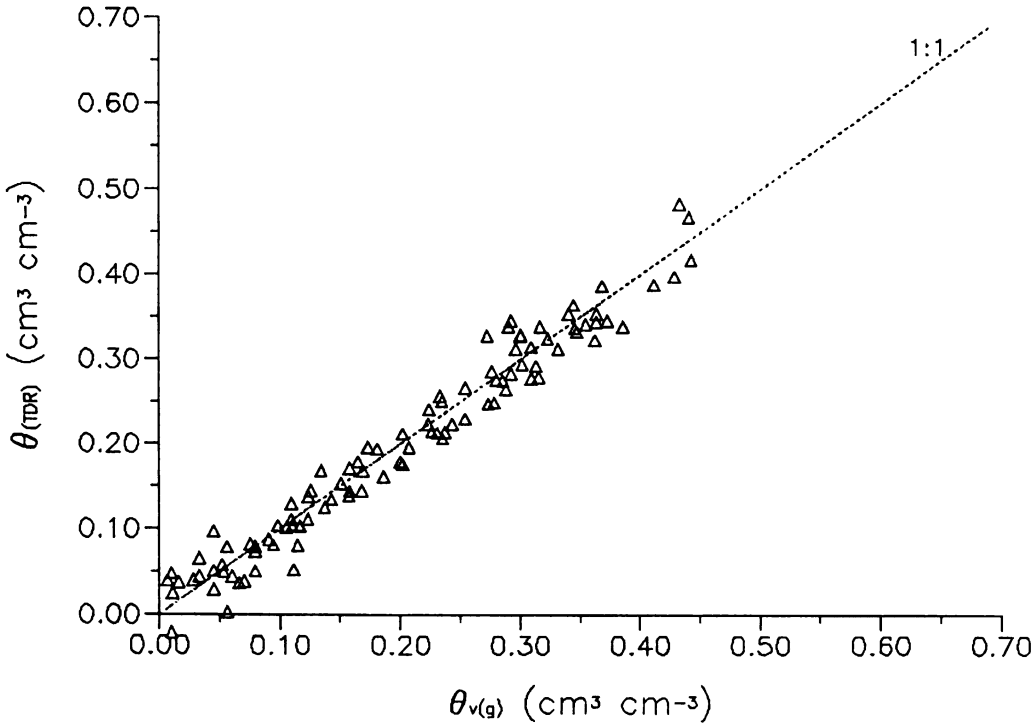

Figure 1.6. Comparison between TDR-determined ($\theta_{v(TDR)}$) and gravimetrically-determined ($\theta_{v(g)}$) volumetric water content in sandy clay soil.

Table 1.1. Pairwise t-test for the comparison between θv(g) and θv(TDR).

	θv(g)-θv(TDR)	
	clay loam soil #	sandy clay soil
mean	-0.004	0.002
sd	0.024	0.023
sdm	0.00241	0.00241
t	0.973	1.582
d.f.	100	92
	n.s.	n.s.

# for the clay loam soil the 8 points with θv(g)-θv(TDR) > 0.14 cm3 cm-3 were excluded from analysis.
sd = standard deviation of differences
sdm = standard error
d.f. = degrees of freedom

partly be explained by sampling problems that occur in swelling soils at high water content levels. Small volume sampling may cause considerable compaction. For the rest of the samples at $\theta_{v(g)} > 0.29$ cm^3 cm^{-3}, the standard deviation of the difference $\theta_{v(g)}-\theta_{v(TDR)}$ was comparable with the overall. No excessively high values were reported by Amato et al. (unpublished, b) for the same soil with 150 mm transmission lines.

For the sandy clay soil, the overall standard deviation of the difference $\theta_{v(g)}-\theta_{v(TDR)}$ was 0.024 cm^3 cm^{-3}, and it was higher for both the dry and the wet end of the range. The excessively high values of $\theta_{v(TDR)}$ recorded for the other soil at high water content were not found. Therefore, it is probably safe to attribute the errors to problems in sampling and length determination. Also, for all samples, volume sampling for the gravimetric determination was made on the assumption that the region explored by the TDR technique was a cylinder with diameter 1.4 times the distance between waveguides, as reported by Topp and Davis (1985) on an empirical basis, but the actual distribution of the EM field around the transmission line would be more complex, and Baker and Lascano (1989) report a region of lower sensitivity larger than that described above. This would be source of discrepancies between $\theta_{v(TDR)}$ and $\theta_{v(g)}$ in case of heterogeneous water distribution, because the two measures would refer to different soil volumes. Although the boxes for this experiment

were prepared so to have uniform water content, some spatial variation may have occurred, especially in the degree of soil compaction, that may have had some influence on the spatial heterogeneity of volumetric water content.

There are not many data reported in the literature on centimeter-scale water content determination with TDR. Topp et al (1984), obtained consistently low readings using Time Domain Reflectometry with probes inserted in the soil for 50 mm only. Their error is discussed in relation to travel time accuracy with short tracelength, although the consistent bias would suggest a problem of calibration at small scale, possibly due to the transmission lines used: the TDR probes used for the small scale measurements were long, only partly inserted in soil, and tapered, which can cause a higher error in end-of-trace determination. The probes used in the present experiment are parallel, of constant diameter and less spaced, which contributes to a higher resolution in the measurements (Topp and Davis, 1985).

CONCLUSIONS

Time-domain reflectometry can be used for the determination of soil water content at small scale with the probes described. The measurements in air and in dry soil proved that in case of tracelength lower than about 0.03 m (ovendry to airdry soil for the transmission lines used) the

percent error is quite high (4.7% and up), so the technique is less reliable. For water content higher than 0.07 cm3 cm-3 (tracelength higher than 0.03 m) the percent error in length determination was below 2.8% . In the clay-loam soil, at $\theta_{v(g)}$>0.29 cm^3 cm^{-3} some of the θv(TDR) values were excessively high, more than expected from errors in length determination or sampling problems, possibly due to problems of signal transmission in conductive soils. This can cause problems for high water content determination with small probes in such soils, although some of the values found were so high that they could be eliminated by a visual screening.

ACKNOWLEDGMENTS

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CHAPTER 2

PLANT GROWTH AND WATER UPTAKE IN STRUCTURED GROWTH MEDIA. I: MAIZE (ZEA MAYS L.) TOP GROWTH AND WATER USE.

ABSTRACT

A study on maize (Zea mays L.) growth and water uptake in structured soil material was conducted with the objective of quantifying the effect of soil structure on water availability for plants. Five treatments were compared in 100 cm deep containers: C (clay-loam soil), S (sandy-clay soil) S+LA (sandy clay with large clay-loam peds embedded), S+SA (sandy clay with small clay-loam peds embedded), CC (compacted clay-loam soil). The plants were grown on stored water until near total loss of green leaf area. An irrigated control was established for treatments C, S, and S+LA. Plant height, leaf area, and leaf number were determined weekly. Plant dry matter was determined at the end of the experiment. The total water uptake was determined by weight difference of the containers. Plant growth was initially faster in the S treatment, but ended rapidly when the water supply was exhausted. In the CC treatment, plant growth was slow, and water uptake minimal,

resulting in a quasi-stationary situation with no signs of wilting. In the other treatments, water deficiency affected growth, leaf rolling and the rate of leaf appearance. In the C, CC, and S+LA treatments the total water extracted was relatively small, suggesting that unextracted water was left in the soil. The root/shoot ratio ranged from about 0.16 to about 0.20 in the dry treatments and from 0.12 to 0.14 in the irrigated ones. Irrigation increased the plant top and root size, and decreased the root/shoot ratio in all treatments, but the growth rates for C were smaller than those for S and S+LA even after irrigation, indicating that possibly factors other than water deficiency affected plant growth in the clay-loam soil.

INTRODUCTION

The effect of soil structural status on plant water uptake has been studied mainly in relation to the influence of tillage on plant water relations. Soil compaction is believed to cause a reduction in water uptake due to limited penetration of roots (Hamblin, 1985). More recently the effect of soil compaction on root clustering has been taken into account to explain limited water extraction within layers colonized by roots (Tardieu, 1977). Such experimental evidence could be the result of complex soil-plant interactions, including effects of hypoxic soil conditions associated with

compaction (Blackwell et al., 1985) on root growth (Schumacher and Smucker, 1984; Vorhees et al., 1975), and root activity (Everard and Drew, 1987), as well as direct effects of soil compaction on plant growth. It has been reported (Masle and Passioura, 1987) that high soil strength has an effect on plant growth that is independent of water and oxygen availability in the soil, and that root hypoxia can reduce shoot growth (Smit et al., 1989). In that case, a reduced water uptake may be partly a consequence and partly a cause of limited plant size in compacted soils. The present work aims to compare plant growth and water use in different types of structured soil materials in order to study the effects of soil structure on root spatial distribution, water uptake, and plant behavior in water-limited conditions. The first article presents total water uptake and shoot growth. The spatial distribution of roots and water is discussed in the second article (Chapter 3).

MATERIALS AND METHODS

A greenhouse experiment was conducted at Potenza (Italy) in which maize (*Zea mays* L.) Dekalb Vitrex 200L was grown in PVC cylindrical tubes. The tubes, 100 cm high and 25 cm in diameter, were split in half longitudinally and then reassembled with tape so that at the end of the experiment they could be taken apart for soil sampling. Plastic fabric

was attached to the bottom and 3 cm of fritted clay were packed on the bottom to allow drainage. Five growth media were tested. They are as follows: 1) C : clay-loam soil (sand 36.5%, silt 24.1%, clay 39.4%)[1] taken from a vertisol in four 25 cm layers; the soil was packed in the tube in 25 cm layers, and each layer was allowed to settle by two wetting-drying cycles to an average bulk density of 1.2 g cm^{-3};

2) CC : compacted clay-loam soil. The same soil as in C, wet-compacted to a bulk density of 1.5 g cm^{-3};

3) S : sandy-clay soil (sand 52.3%; silt 10.6%; clay 37.1%)[1] taken from the field in four 25 cm layers, sieved and packed to a bulk density of 1.0 g cm^{-3};

4) S+LA : sandy clay embedded with large clay-loam peds. Three sub-prismatic peds per tube, of 14-18 cm smaller side, were used. The average bulk density of the final mixture was 1.1 g cm^{-3};

5) S+SA : sandy clay embedded with small clay loam peds. Eight kg of sub-prismatic peds, of 6-10 cm smaller side were used per tube. The average bulk density of the final mixture was 1.1 g cm^{-3}.

The containers were filled with water, covered with plastic and allowed to drain for four weeks. One maize plant was transplanted in each container at the 4-leaf stage, and fertilized with 2.3 g NH_4NO_3. Each soil treatment had an

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[1] Percentages in weight. ISSS classification: sand 0.02-2.00 mm; silt 0.002-0.02 mm; clay < 0.002 mm.

unirrigated water treatment in which plants were grown on stored water. Treatments C, S, and S+LA had an irrigated control in which plants were irrigated every other day from 20 days after transplanting with 15 mm of water. Each treatment was replicated six times. On each plant the following measurements were taken weekly starting at 13 days after transplanting: plant height to the top ligule, leaf length from tip to ligule, and the number of fully expanded leaves. For 10 plants grown out of the experiment, the area of each leaf and the length from the leaf tip to the ligule was measured, and a power regression equation was chosen, based on R^2 maximization, to express the allometric relation between the two leaf characters:

$$\text{Log}_{10}\ \text{Area} = -1.217 + 2.09 * \text{Log}_{10}\ \text{Length} \qquad R^2=0.95.$$

Based on the obtained relationship, green leaf area was calculated for each sampling date. The experiment was terminated when the green leaf area of the plants was reduced to less than 20 cm^2 per plant for the treatments C, S, S+LA, and S+SA. Treatment CC was ended on day 41 from transplanting, due to cessation of growth, although no signs of wilting were shown by the plants. Plant dry matter was determined at the end of the experiment. Above ground biomass was determined for each plant, and root biomass was determined on three replicate tubes, using two 100 cm^3 cores per soil layer. The number of layers was three for treatment S+LA (0-33, 33-66, 66-100 cm from the soil surface) and four for all other treatments (0-

25, 25-50, 50-75, and 75-100 cm from soil surface) The total water uptake in the unirrigated treatments over the period of the experiment was determined by weight difference.

The daily air temperatures in the greenhouse for the period of the experiment are reported in Figure 2.1.

RESULTS AND DISCUSSION

Figure 2.2.a reports the initial and final volumetric water content of the soil for the five unirrigated treatments. Since the actual soil volume in the tubes changed during the course of the experiment due to shrinking, mostly in the clay-loam soil, the amounts reported are corrected for the volume variations. The water extracted by plants and evaporated from the soil surface is reported in Figure 2.2.b. It was calculated as the difference between initial and final volumetric water content, to which the shrinkage volume was added. The initial volumetric water content that was held in the tubes against gravity ranged from 0.25 cm^3 cm^{-3} in the sandy-clay, to 0.43 cm^3 cm^{-3} in the compacted clay-loam. At the end of the experiment most of the initial water was still present in the CC treatment, while the water content of the S treatment was reduced to about 15 cm^3 cm^{-3}. Perniola (unpublished) reports that this water content corresponds to a suction of about -1.5 MPa. The total extracted water from the S treatment was about 0.11 cm^3 cm^{-3}. In the S+LA and S+SA

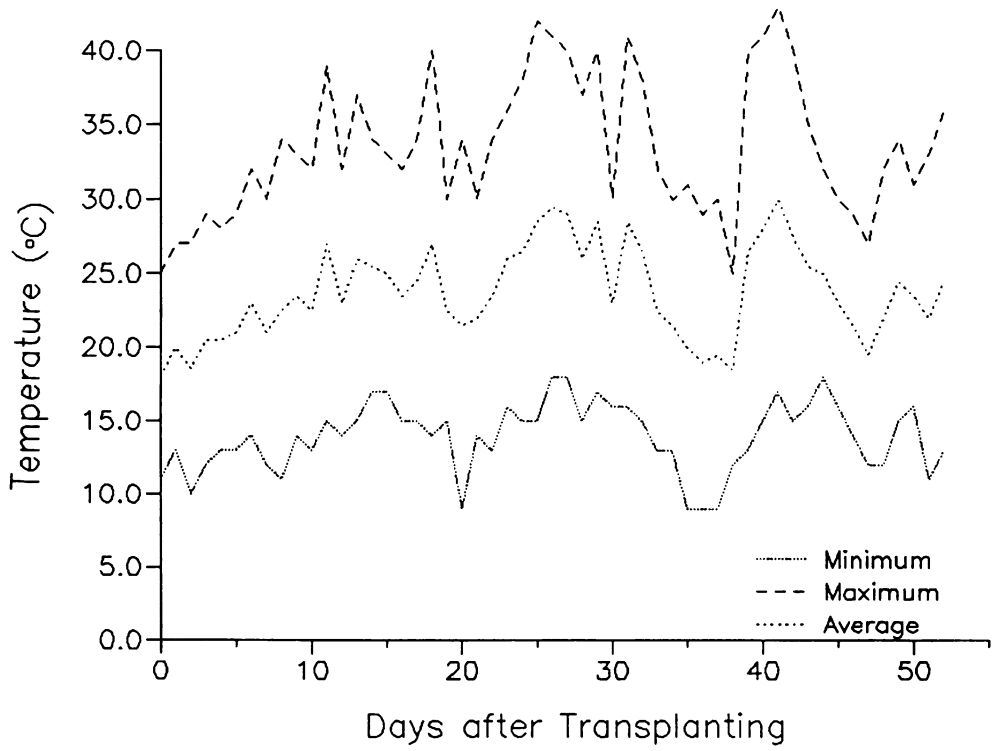

Figure 2.1. Daily maximum, minimum and average temperatures from transplanting to termination of the experiment.

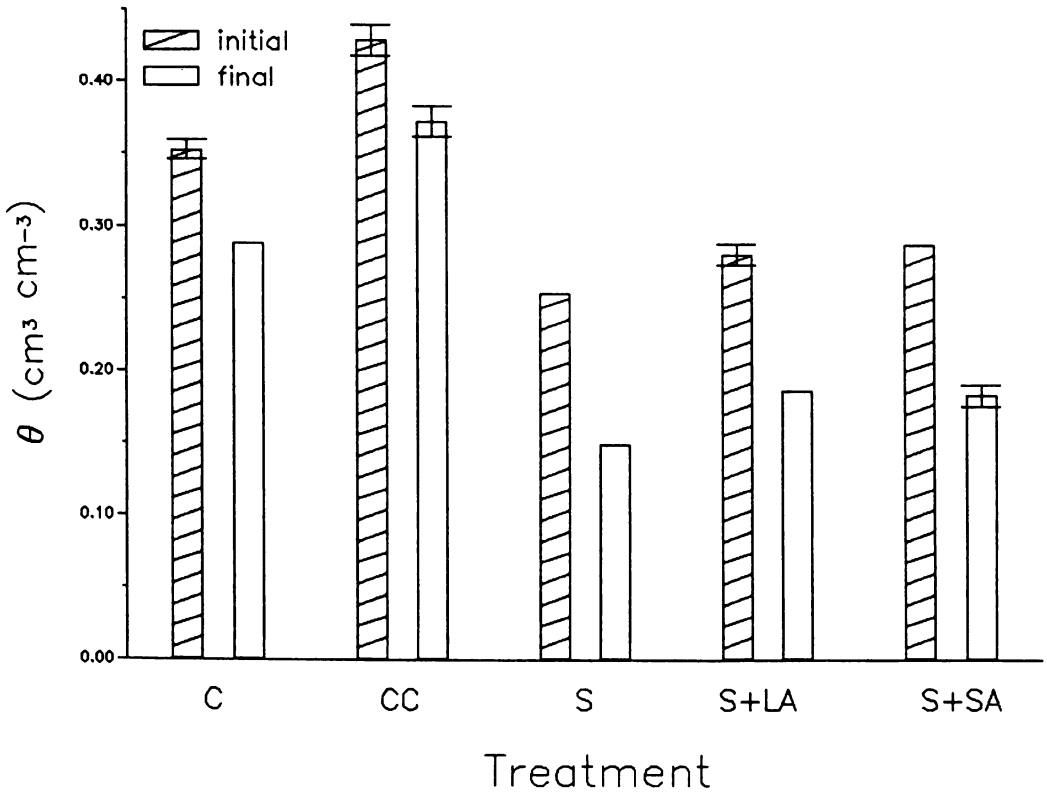

Figure 2.2.a. Initial and final water content in the containers. Vertical bars represent twice the standard deviation.Where vertical bars are not present, the standard deviation is < 0.05 cm^3 cm^{-3}.

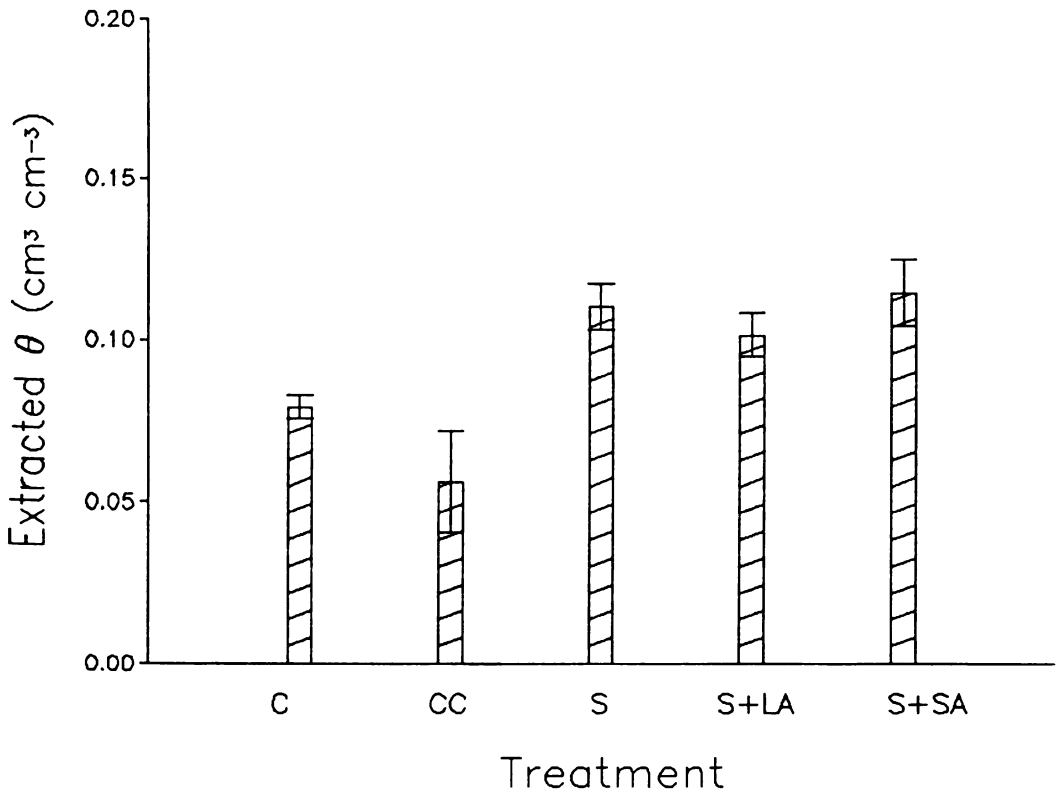

Figure 2.2.b. Extracted water from planting to termination of the experiment. Vertical bars represent twice the standard deviation.

treatments, the contribution of the clay-loam peds was responsible for an initial water content higher than that of the S tubes. The total water extracted, though, was equal or less than what measured in S. For the C treatment the total amount of water extracted was even smaller, and at the end of the experiment the soil had not been dried to the calculated lower limit of plant available water: Comegna et al., 1990, report for the same clay-loam soil, that a volumetric water content of about 0.28 cm^3 cm^{-3}, as found in the C treatment at the end of the experiment, corresponds, in laboratory determinations, to a pressure head of about - 0.5 Mpa, that is likely well above the roots ability to lower their potential.

Figure 2.3 reports the time-course of plant height for the five treatments under study. Initial plant height was quite uniform, around 6 cm, and it increased rapidly in the S treatment, reaching 15.5 cm at 27 days after transplanting, but it thereafter decreased quite rapidly, while in the S+LA and S+SA treatments it reached a maximum at 34 days. The highest values were found in S+SA. The clay loam soil (C) showed lower values, and a slower decrease after day 34 of transplanting. Plant height in the CC treatment showed a small increase after transplanting (7.8 cm at 13 days), and remained quite constant thereafter. A very similar trend was shown in leaf area time-course, as shown in Figure 2.4. Green leaf area fell to less than 20 cm^2 after 34 days from transplanting for the S treatment, and after 41 days for S+LA, S+SA and C. Table

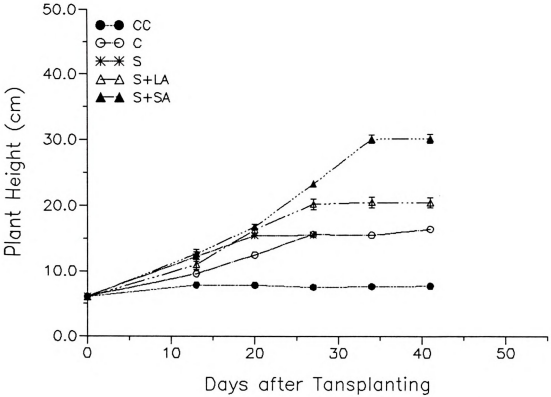

Figure 2.3. Plant height to the uppermost leaf collar in the unirrigated treatments. Vertical bars represent twice the standard deviation. Where vertical bars are not present, they are smaller than symbols.

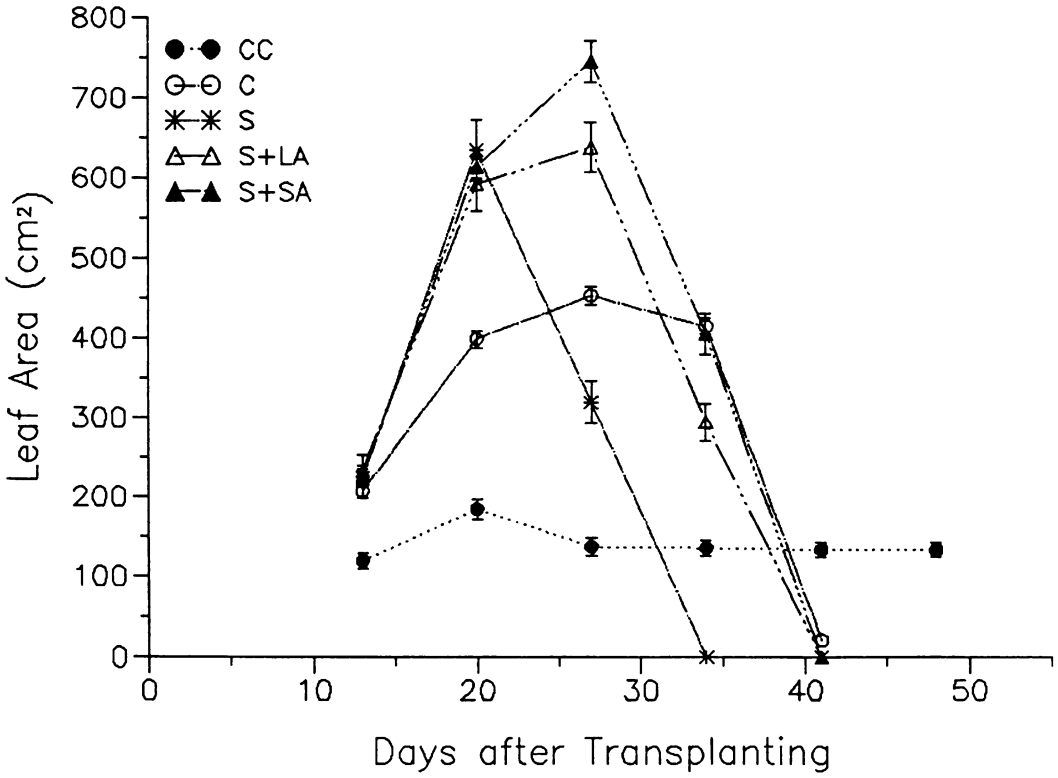

Figure 2.4. Green leaf area per plant in the unirrigated treatments. Vertical bars represent twice the standard deviation. Where vertical bars are not present, they are smaller than symbols.

2.1 indicates the time at which plants visually started showing signs of wilting (beginning leaf rolling), and the time at which severe leaf rolling was recorded.

Table 2.1. Time at which beginning and severe leaf rolling were observed (days from transplanting). Horizontal bars indicate treatments for which the phenomenon was not observed.

Treatment	Beginning Leaf rolling	Severe Leaf rolling
S	—	20
S+SA	17	22
S+LA	13	20
C	13	27
CC	—	—

and S+LA were the first to show some leaf rolling at 13 days after transplanting, and the S+LA showed severe leaf rolling 1 week later. Leaves of the C treatment did not roll until 27 days after transplanting, showing a slower development of water deficit. In the S treatment leaf rolling was not perceivable at 13 days, but at 20 days it was already severe. The S+SA treatment started leaf rolling at 17 days. The only treatment in which leaves maintained turgor was the compacted clay loam in which plants kept their green leaf area after terminal stress in the other treatments. Plants in soil S lost

their leaves earlier than those in other soils.

As regards the number of leaves (Figure 2.5), it was not dissimilar in treatments S, S+LA and S+SA at 13 days of transplanting; after that time, development in the S tubes slowed down until plant death, and it proceeded at the same pace for S+SA and S+LA up to 27 days, after which date the soil with small aggregates (S+SA) produced 0.5 leaves more than the other, on average. This differentiation corresponds with the reported superiority of the S+SA treatment for height and leaf area, and can be related to the higher amount of water actually extracted by S+SA plants. Differences in development between treatments, though, occurred at a later time than what shown for growth. The C plants had a slower development than those in the above treatments, and ended with only 7 to 8 leaves having appeared at 40 days, about 1.0 and 1.5 less than S+LA and S+SA respectively. Plants in the CC tubes had the lowest number of leaves at each date and apparently growth was reduced such that new leaves did not appear out of the whorl after 27 days from transplanting, about 7 days after height and leaf area had reached a stationary point for this treatment.

The final above and below-ground plant dry matter for each treatment is shown in Figure 2.6. It was highest for the S, S+SA, and S+LA treatments, and lowest for the CC, in which treatment roots were not found in the 75-100 cm layer. The root/shoot ratio was highest for the sandy-clay soil (around

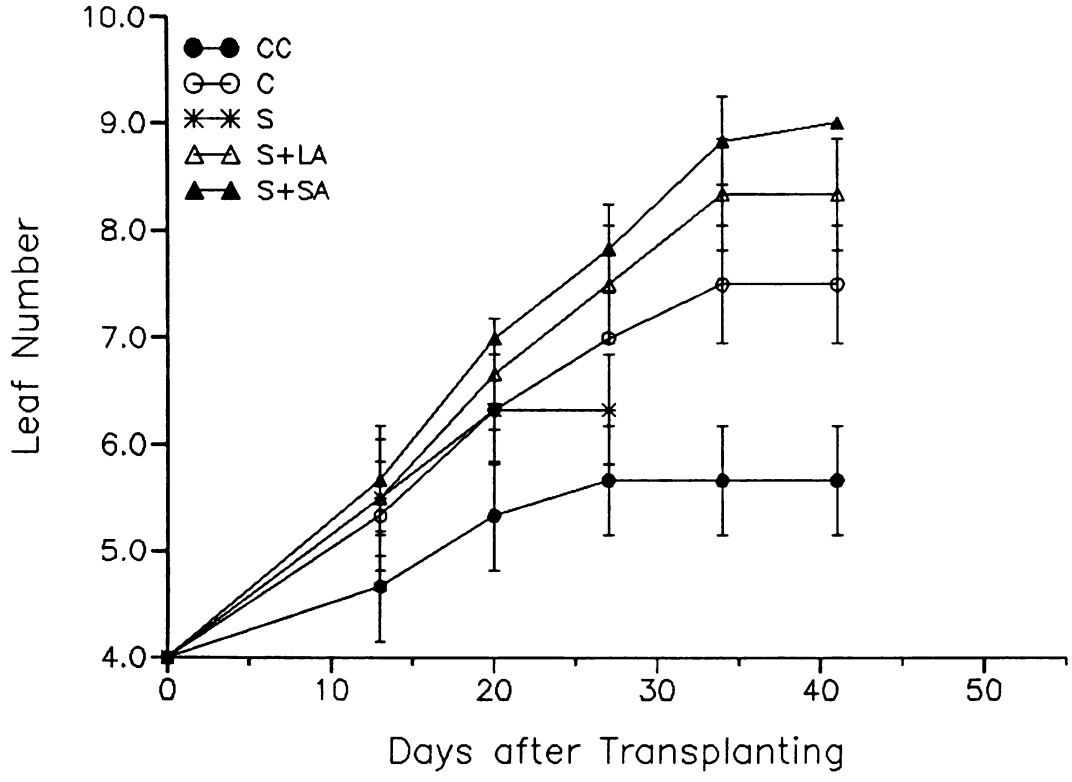

Figure 2.5. Leaf number in the unirrigated treatments. Vertical bars represent twice the standard deviation. Where vertical bars are not present, they are smaller than symbols.

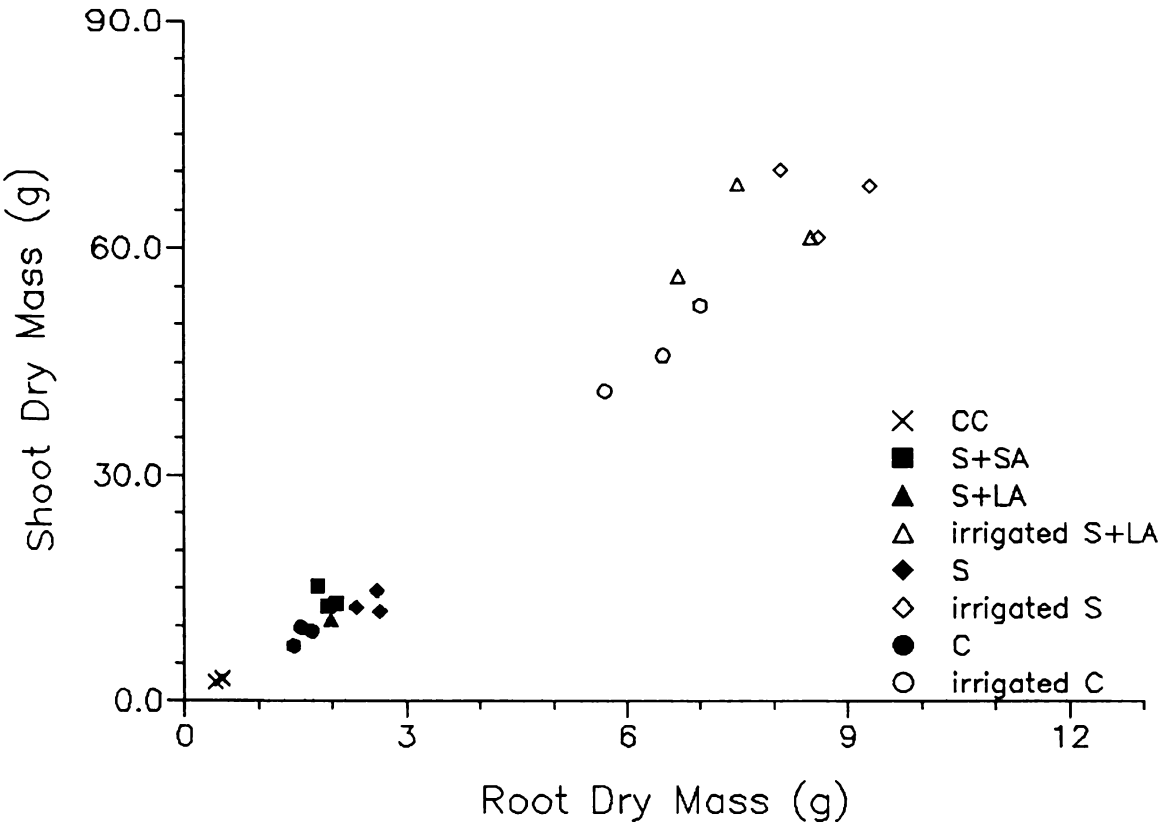

Figure 2.6. Shoot and root dry mass at experiment termination for irrigated and unirrigated plants.

19) and lowest for S+SA (around 0.14). Some developmental ctors confounded this result, since the S plants died and ere collected 7 days earlier than the others, and this may ave affected the root relative contribution to dry mass in oung plants.

The effect of irrigation from day 20 on plant growth and development is shown in Figures 2.7-2.9. The results show that all measured characters were higher with irrigation, and that the S and S+LA treatments had similar trends and final values, while in the clay loam soil both growth (leaf area and height) and development (leaf number) were lower than in the other treatments. This was the result of both the initially lower values of the C treatment at day 20, when irrigation was applied, and of a slower rate of growth and development after the application of irrigation. Plant behavior after irrigation indicated that the unirrigated treatments were water-limited and the loss of green leaf area could be attributed to water deficit, but growth and development limitations found in the C treatment were probably due to non water-related causes as well. The root/shoot ratio of the irrigated treatments was lower than that of the dry ones, and ranged from 0.12 in the S+LA to 0.14 in C, but the absolute values of root dry matter were higher than those of the dry treatments. A larger contribution of the root to the total plant dry matter in water-deficient plants has been reported by many authors, and lately by Mayaki et al. (1976) for soybeans and maize, Blum

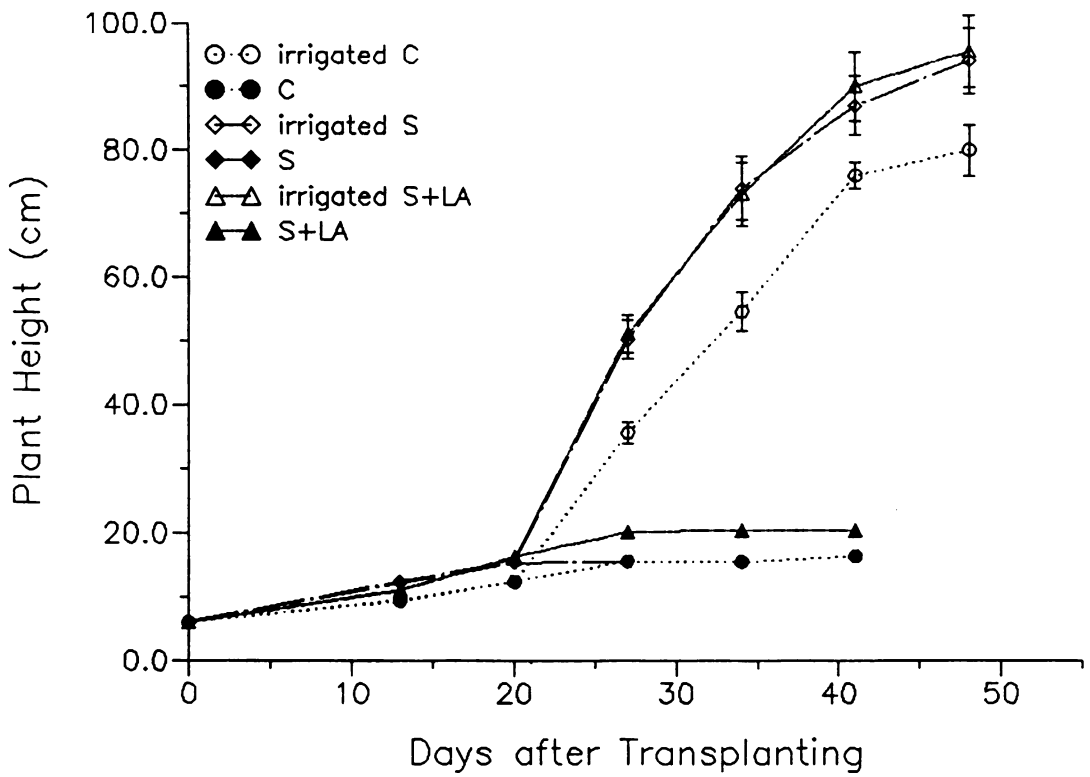

Figure 2.7. Plant height to the uppermost leaf collar in the irrigated treatments, compared with unirrigated ones. Vertical bars represent twice the standard deviation. Where vertical bars are not present, they are smaller than symbols.

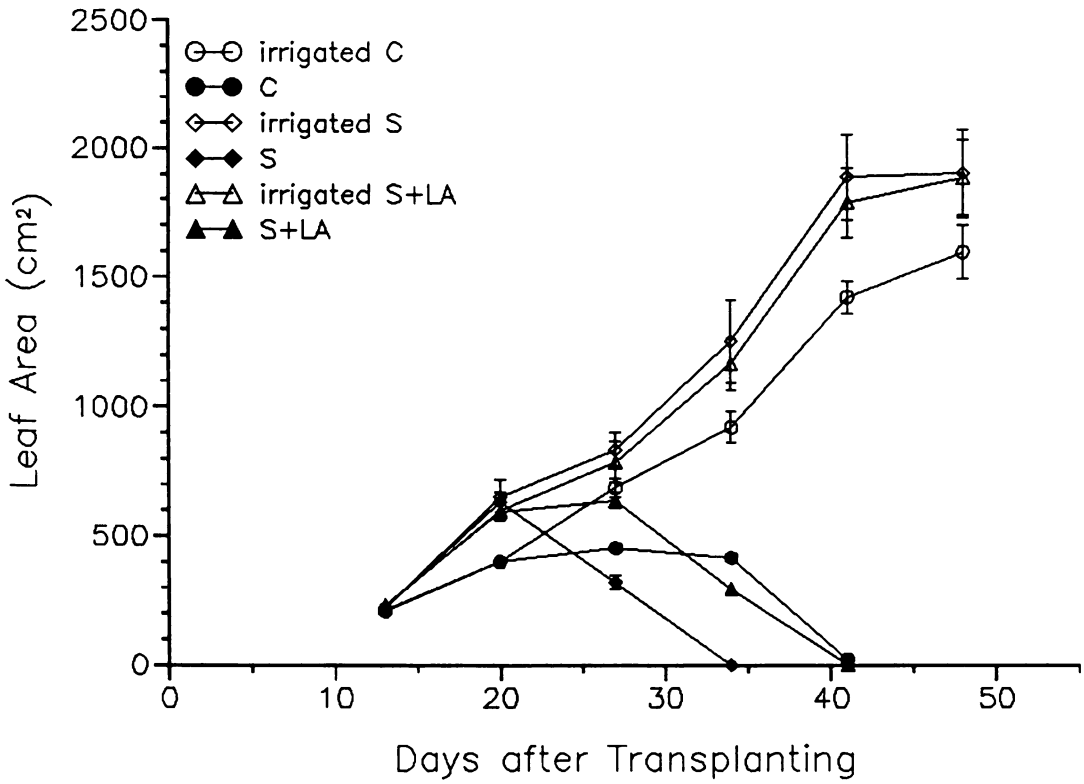

Figure 2.8. Green leaf area per plant in the irrigated treatments, compared with unirrigated ones. Vertical bars represent twice the standard deviation. Where vertical bars are not present, they are smaller than symbols.

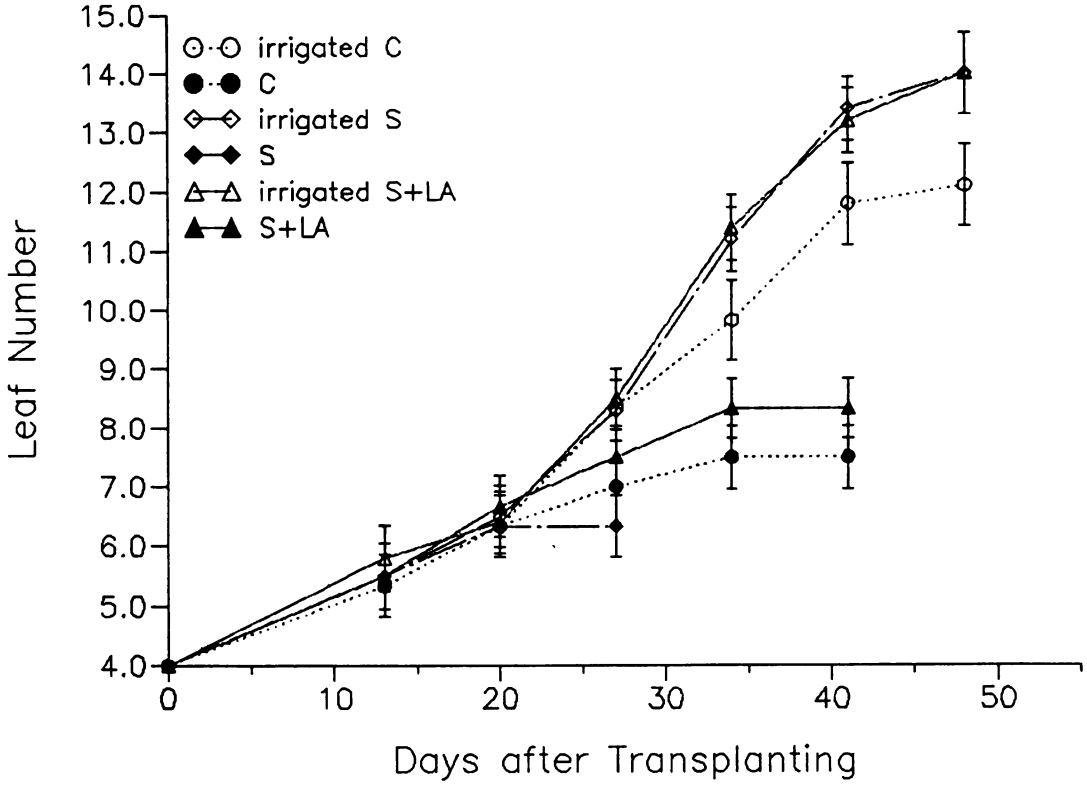

Figure 2.9. Leaf number in the irrigated treatments, compared with unirrigated ones. Vertical bars represent twice the standard deviation. Where vertical bars are not present, they are smaller than symbols.

and Ritchie (1984) for sorghum, Hamblin et al. (1990) for wheat. Differences in root distribution between irrigated and dry treatments will be presented in chapter 3.

The overall behavior of plants in treatments C, S, S+LA, and S+SA indicates that water deficit limited plant growth, slowed their development, and finally led to almost total loss of green leaf area. The faster initial growth and more rapid plant water deficit reported for the S treatment was presumably due to faster access to the soil water, and consequently more rapid depletion. The clay loam contribution in the different growth media was to increase the amount of water held, and to make it more slowly accessible. For the CC treatment the plants had not died, nor did they show signs of wilting at the end of the experiment, but their size and rate of development were remarkably reduced. There is evidence in the literature (Masle and Passioura, Smit et al, 1989) suggesting that in compacted soils there is a direct effect of soil strength on plant growth. Also, the air-filled porosity of the treatment was low, and poor aeration is likely to have contributed to the reduced growth rate. In this treatment little water was extracted by small but turgid plants, suggesting that factors other than water availability itself were limiting and, in that case, incomplete water extraction may be more correctly seen as a consequence rather than a cause of limited plant growth. Another possibility is that early-developed severe water deficiency reduced growth and led

to sufficient osmotic adjustments to maintain leaf turgor. In the other treatments where water extraction was less than expected (C, S+LA), the plants were apparently near death, and little if any green leaf area was left after severe wilting. This indicates that water availability had been a limiting factor, in spite of the average water content of the tubes being above the limits of root water extraction. In the second article, root length density, root clustering and water content spatial variability within the tube will be examined as possible causes of incomplete extraction in growth media where root penetration in soil peds or compacted soil was limited.

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CHAPTER 3

PLANT GROWTH AND WATER UPTAKE IN STRUCTURED GROWTH MEDIA. II: CLUSTERING OF MAIZE (ZEA MAYS L.) ROOTS AND SPATIAL DISTRIBUTION OF WATER.

ABSTRACT

The spatial arrangement of maize (Zea mays L.) roots and of residual water at plant death were studied in structured soil materials in order to quantify the effect of root clustering on water uptake in water-limited plants. Five treatments were compared in 100 cm-high containers: C (clay-loam soil), S (sandy-clay soil) S+LA (sandy clay embedded with large clay-loam peds), S+SA (sandy clay embedded with small clay-loam peds), CC (compacted clay-loam soil). The plants were grown on stored water until extreme wilting. The structure of the growth media was characterized by structural mapping on five horizontal planes, and by bulk density determinations. Maps of root and water content at the end of the experiment were made on 2 x 2 cm grids, on the same planes used for structural mapping, and across peds. Volumetric water content was measured with time-domain reflectometry. Root length density was also determined at the end of the

experiment with the technique of Newman (1969), separately for the peds and the bulk soil. Root growth was highest and quite uniform in the S treatment, while in the others root growth was restricted due to little penetration in the peds, particularly beyond the 2 cm outer layer. Water uptake was limited in the large peds not penetrated by roots. This caused pockets of unextracted water in the C and S+LA treatments, and to a lesser extent in S+SA. Limited root growth and water uptake was measured in the CC treatment, and were likely due to direct and indirect effects of compaction.

INTRODUCTION

Root water uptake has classically been described based on average root length density in a soil layer. Such an approach implies that roots are parallel and distributed randomly or regularly in each layer of the soil, so that each root exclusively draws water from a cylindrical region whose diameter is the mean distance between roots (Gardner, 1960, Newman, 1969). Based on such calculations, the distance water has to travel from the bulk soil to the root is often of the order of millimeters (Tardieu and Manichon, 1986a). In many instances, though, the root horizontal distribution is more likely to be clustered than regular or random. In that case, the distance water has to travel in order to reach the root can be relatively high, and certainly larger than the mean

distance between roots. Depending on the soil characteristics, such a path length can be limiting for water movement within a time-frame useful for the plant to overcome water deficiency stress.

Although the most common root sampling techniques do not allow for root clumping to be measured, the phenomenon has sometimes been documented by root mapping studies, and recently quantified by a few authors (Tardieu and Manichon ,1987; Tardieu, 1988a; Pettygrove et al., 1989). In those studies where soil water content was measured, a lower uptake was found in case of clustering (Tardieu, 1987; Tardieu, 1988b) but the distribution of water around roots was not reported. One of the reasons is to be found in the lack of adequate experimental techniques.

The present work is aimed to quantify root growth and clustering in maize plants grown in structured growth media, and its relation with water uptake patterns under water-limited conditions.

MATERIALS AND METHODS

A greenhouse experiment was conducted in which maize (*Zea mays* L.) plants were grown on media with different structural characteristics. The experimental design is described in the first article of this series (Chapter 2). The treatments were: C (clay-loam soil), S (sandy-clay soil) S+LA (sandy clay

embedded with large clay-loam peds), S+SA (sandy clay embedded with small clay-loam peds), CC (compacted clay-loam soil).

Mapping of roots, water content and soil structure were made at the end of the experiment, which corresponded to nearly total loss of green leaf area for the treatments C, S, S+LA, S+SA, and to the cessation of plant growth in treatment CC.

Access for taking samples in each layer was obtained by separating the two longitudinal halves of each tube.

On three replications (tubes) per treatment, two 100 cm^3 soil cores were taken in each of the layers: 0-25, 25-50, 50-75, and 75-100 cm. The soil in the cores was dried at 110 °C and weighed in order to obtain the bulk density, and was then used to determine the root length density (RLD, cm^{-3}) using the technique of Newman (1969). The root dry mass was determined after oven drying at 60 °C. The bulk density of the peds was also determined for treatment S+LA on 3 peds per tube, and for treatment S+SA on 8 peds per tube, by water displacement after coating the aggregates with liquid paraffin. Root length density and root dry mass were determined for the peds as described above. For treatments C and S the number of 100 cm^3 cores sampled was four per layer, and bulk density was also determined on two 200 cm^3 cores per layer, and on four 8 cm^3 samples per layer in order to characterize the soil structural status at different scales.

Small-scale characterization of root and water spatial

variation was made on the remaining three replication tubes per treatment. Measurements of volumetric water content and root length density were made according to the following sampling scheme:

- For the S treatment, measurements were made on three 10 cm transects for each of the 0-25, 25-50, 50-75, and 75-100 cm layers. Volumetric water content was measured with time-domain reflectometry (TDR) every 2 cm, using small probes 20 mm long, and with a distance between rods of 14 mm (see chapter 1 for more details). During the measurements, the soil was covered with plastic film to minimize evaporation. After TDR readings, the transect soil was sampled with the sampler pictured in Figure 3.1, designed to collect five contiguous 2 x 2 x 2 cm soil cubes, on which RLD was determined according to Newman (1969).
- For the other treatments, the sampling scheme was modified to suit the structural status: in the S+LA treatment water content measured by TDR, and RLD were determined in the bulk soil (sandy-clay) on three replicates for each of the three layers: 0-33, 33-66, 66-100 cm. In each layer a large clay-loam ped was present, and it was extracted from the soil, and sliced along the central horizontal plane. The surface obtained was covered with plastic film and divided into concentric rings by tracing lines parallel to the ped surface every 2 cm on the film. For each ring, three TDR readings were made with the probes described above. The ped was then

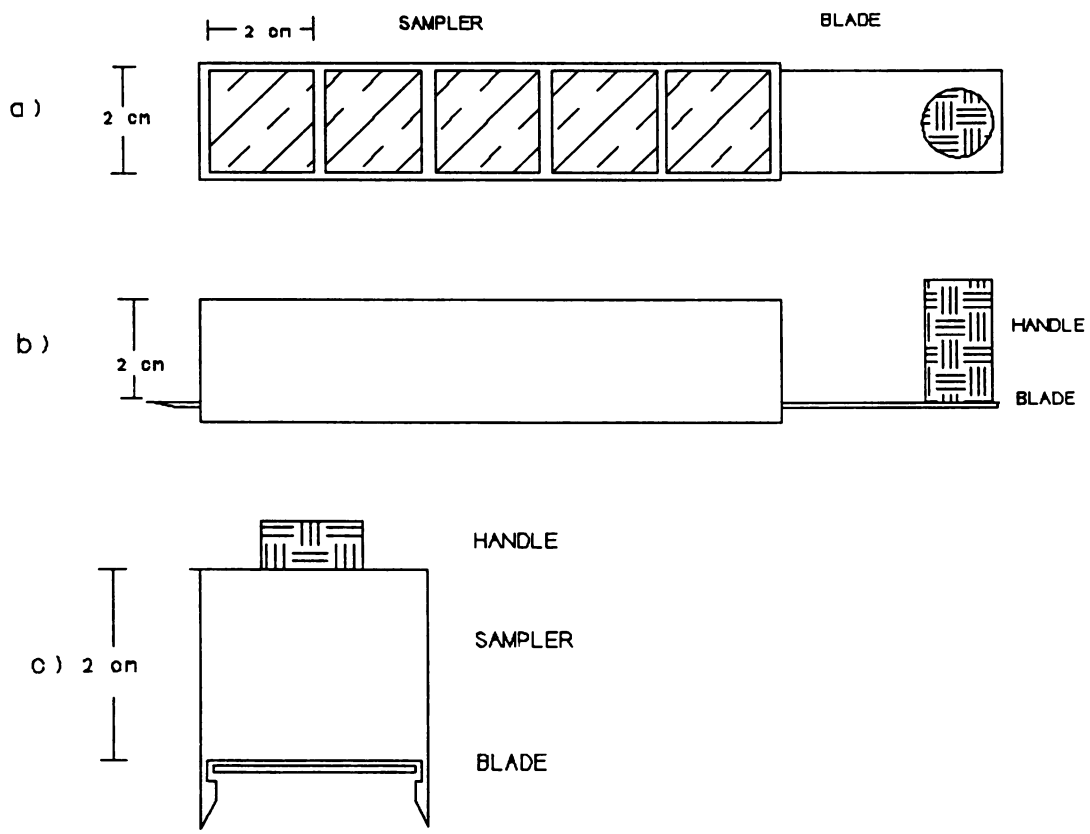


Figure 3.1. Small-scale soil sampler. a) top view; b) side view; c) front view.

sliced again 2 cm below the surface used for measurement, and the 2 cm thick slice obtained was cut into concentric rings following the lines previously drawn on the plastic. The soil from each ring was divided into three subsamples on which RLD was determined. This way, volumetric water content and root length density were measured as a function of distance from the surface of the ped. The internal layers of the peds were often too small to allow triplicate measurements. In those cases the number of samples was reduced to two or one.

In the S+SA treatment, sampling was as described for S+LA, but the layers in each tube were 0-25, 25-50, 50-75, and 75-100 cm, and for each layer three small peds were sliced and measured as described for S+LA.

In the C treatment shrinkage cracks had formed due to soil drying in the 0-25 and 25-50 cm layers. For these layers root length density and TDR water content were measured on three peds per layer as described above.

Small scale measurements were not made in the CC treatment, due to problems in soil sampling and TDR probe insertion in the compacted soil.

On one tube per treatment mapping of water content and roots was made on five horizontal planes: at 3, 25, 50, 75, and 95 cm, on a 2 x 2 cm grid. Water content was determined by TDR with the probes described above. Determinations were not made for two single sampling grid points, because the dielectric constant values obtained were excessively high (see

discussion in chapter 1). Roots were characterized using the notation described by Tardieu and Manichon (1986b). On the same planes mapping of structural status was also made, using three categories: crack, ped, bulk soil.

RESULTS AND DISCUSSION

Bulk density

The bulk density values measured in the 8, 100, and 200 cm^3 samples for the C and S treatments are reported in Table 3.1. In both soils, the bulk density at the end of the experiment increased with soil depth. The measured values as well as their variability (coefficient of variation, CV) increased as the sample size decreased, especially in the clay-loam soil. This was partly due to the higher incidence of sampling compaction in the small samples, and partly also to the less likely presence of structural discontinuities (cracks, biopores) in small volumes of soil. Similar results are reported by Fies and Stengel (1981) who argue that bulk density values at small volumes represent the textural density of soil, since they are less likely to include non texture related features like macropores.

Results for bulk density measurements in the CC, S+LA, and S+LA treatments are summarized in Table 3.2. Bulk density of the compacted clay-loam treatment was quite high, increasing slightly with depth. Its high CV (ranging from 5.8

Table 3.1. Bulk density (g cm^{-3}) and coefficient of variation (CV, %) as a function of soil depth and sample size in the clay loam and sandy clay treatments.

sample size (cm^3)		200	100	8
number of samples		(2)	(4)	(4)
		Clay-loam (C)		
Layer (cm)				
0-25	mean	1.37	1.59	1.63
	CV	3.4	7.9	7.4
25-50	mean	1.45	1.63	1.65
	CV	4.5	4.6	11.6
50-75	mean	1.55	1.69	1.83
	CV	5.2	4.6	7.7
75-100	mean	1.57	1.69	1.84
	CV	4.9	3.5	6.6
		Sandy-clay (S)		
Layer (cm)				
0-25	mean	1.13	1.19	1.29
	CV	7.5	5.8	14.8
25-50	mean	1.14	1.22	1.26
	CV	5.2	3.5	6.6
50-75	mean	1.20	1.29	1.31
	CV	5.2	7.0	11.1
75-100	mean	1.21	1.28	1.38
	CV	4.1	6.3	7.1

Table 3.2. Bulk density (g cm^{-3}) and coefficient of variation (CV, %) from 100 cm^3 cores for the soil matrix and from soil peds as a function of soil depth.

Treatment		CC	S+LA	S+SA
Layer (cm)				
0-25	mean	1.74	1.18	1.17
	CV	10.4	4.7	3.9
25-50	mean	1.75	1.27	1.24
	CV	11.2	4.4	5.8
50-75	mean	1.87	1.29	1.32
	CV	5.8	6.4	4.9
75-100	mean	1.84	1.39	1.35
	CV	7.8	5.3	4.7
Peds	mean	____	1.48	1.63
	CV	____	4.8	4.4

to 11.2 %) were due to problems in core insertion in the compacted soil. Densities for the bulk (sandy-clay) soil were quite similar between treatments S, S+SA, and S+LA. The bulk density of the peds was higher than that of the bulk soil, and its values were larger in the small peds compared to the large ones. Two main factors are likely to be the cause of the difference between the bulk density of the small and large peds. Firstly, the bulk density of the peds was calculated on the volume as sampled at the end of the experiment. As will be shown in the following paragraphs, the water content of the inner layers of the large peds was at that time higher than that of the outer layers, while the small peds were more uniformly dry. Therefore, while the density of the small peds corresponded to a lower water content, the density of large peds was an average from layers of different water content, and therefore at an intermediate density between wet and dry. Secondly, large peds are more likely to enclose structural cracks or biopores, that would also explain a lower density.

The characterization of soil mechanical impedance in a way relevant to root growth has been discussed in relation to bulk density and resistance to penetrometer insertion, and both features present a high variability, depending on the specific methods used. Their relationship with root growth is also variable (Cockroff et al., 1969). The relations between soil bulk density and root growth have recently been discussed by Jones et al. (1991), who used the soil sand percent by

weight to predict the moist bulk density at which rooting is severely impaired (BDX) and that at which there is no inhibition of rooting (BDO). The bulk density values reported for the S treatment, and for the sandy clay soil in the other treatments, were in all cases lower or around BDO. In these soils, therefore, no large effect of strength on root growth is predicted. Bulk densities for the peds and the C and CC treatments were higher than BDO. This would indicate inhospitability for root growth in these soils. Values in the CC soil were higher than BDX; this would imply severe impairment of root growth (Jones et al., 1991). Values of BDX, though, were developed for bulk densities at water content near field capacity, while the ones reported in this paper were measured in drier conditions (except for the CC treatment) at the end of the experiment, this indicating that at initial (wetter) conditions the soil density was less limiting for root growth. Characterizing soil strength with a single parameter, does not allow to account for soil structure or macroporosity that may provide ways for root penetration, even where the bulk soil strength is high. In this study, the reported decrease in density values with increasing soil volume, especially in the clay loam soil, suggests that cracks were present, in which localized root growth could take place. It should also be pointed out that local soil conditions (like strength in a soil layer) may affect the hospitability of a particular soil region for root colonization, but the actual

presence of roots in that area will also depend on whole plant effects, like general water status or nutrition (Tardieu, 1989) and the time-course of stress development. The conditions in adjacent soil regions will also play a role. Tardieu (1988a, 1989) reports that a soil region where soil strength is not limiting per-se, may have low root density because of local compaction directly above ('shadow effect').In the following paragraphs root density will be shown to be higher in the peds of the clay-loam treatment compared to peds in the other treatments. The observation will be discussed in terms of compensatory growth (since in C roots did not have more hospitable soil to grow into), rather than in relation to differences in local peds conditions.

Root length density

A summary of the results for the root length density measurements on 100 cm^3 cores and on peds is shown in Table 3.3. RLD was highest in the sandy clay soil, and decreased relatively little with depth. It was quite similar in the S+LA and S+LA treatments, and lowest in the compacted clay-loam soil, in which it declined markedly below 50 cm. No roots were found in the CC samples below 75 cm. Variability was quite high in all treatments, especially so in the C, S+LA, and S+SA tubes, if all samples were pooled to calculate mean values for each layer. If samples taken from the bulk soil and from the aggregates were considered separately, for the S+LA and S+SA

Table 3.3. Root length density (RLD), root weight, and root weight per unit length in unirrigated treatments. sd=standard deviation.

Soil layer (cm)		Treatment CC	C	S	S+LA	S+SA
				RLD (cm cm^{-3})		
0-25	mean	0.56	0.84	1.56	1.20	1.15
	sd	0.21	0.46	0.40	0.96	0.85
25-50	mean	0.40	0.77	1.28	1.02	1.10
	sd	0.14	0.45	0.29	0.87	0.80
50-75	mean	0.02	0.48	1.04	0.75	0.67
	sd	0.02	0.30	0.28	0.56	0.43
5-100	mean	0.00	0.36	0.68	0.39	0.42
	sd	/	0.25	0.27	0.22	0.29
				Root weight (g cm^{-3})		
0-25	mean	0.0058	0.0113	0.0173	0.0132	0.0129
	sd	0.0020	0.0075	0.0052	0.0113	0.0106
25-50	mean	0.0019	0.0097	0.0127	0.0113	0.0116
	sd	0.0007	0.0068	0.0029	0.0102	0.0095
50-75	mean	0.0000	0.0035	0.0077	0.0059	0.0049
	sd	0.0001	0.0026	0.0019	0.0046	0.0037
5-100	mean	0.0000	0.0021	0.0045	0.0028	0.0027
	sd	/	0.0015	0.0022	0.0017	0.0023
				Root weight per unit length (g cm^{-1})		
0-25	mean	0.000106	0.000127	0.000111	0.000101	0.000104
	sd	0.000006	0.000022	0.000016	0.000014	0.000015
25-50	mean	0.000048	0.000117	0.000100	0.000103	0.000097
	sd	0.000005	0.000024	0.000010	0.000012	0.000017
50-75	mean	0.000040	0.000070	0.000075	0.000079	0.000071
	sd	0.000009	0.000016	0.000009	0.000014	0.000015
5-100	mean	0.000000	0.000056	0.000066	0.000068	0.000062
	sd	/	0.000012	0.000013	0.000010	0.000008

tubes, the distribution became bimodal and the variability decreased (Figure 3.2). In the 0-33 cm layer of the S+LA treatment, for instance, the coefficient of variability was reduced from 79% for the pooled samples, to 40% for roots growing in peds only.

This result shows how some of the variation in root sampling can be eliminated if a structured (non random) component is identified, and separated from the total variability. This treatment requires that appropriate sampling schemes are used. Similar treatment was shown by Tardieu (1988 a) to reduce the coefficient of variation for length density of maize roots grown in soil with compacted inter-rows.

Root weight is reported in Table 3.3 The separation of samples from bulk soil and aggregates for the S+LA, and S+SA treatments is shown in Figure 3.3. This treatment of data allowed the reduction of sample variability, as reported for the RLD.

Table 3.3 reports the calculated root weight per unit length for the same samples. Values were of the order of 10^{-4} for the 0-25 layer, and decreased with depth, likely the result of a lower incidence of primary and secondary structures. Unlike root length and weight, weight per unit length was similar between peds and bulk soil, although the values measured in peds tended to be a little lower. For this reason, the separation of samples from bulk soil and aggregates had a relatively little effect on reducing

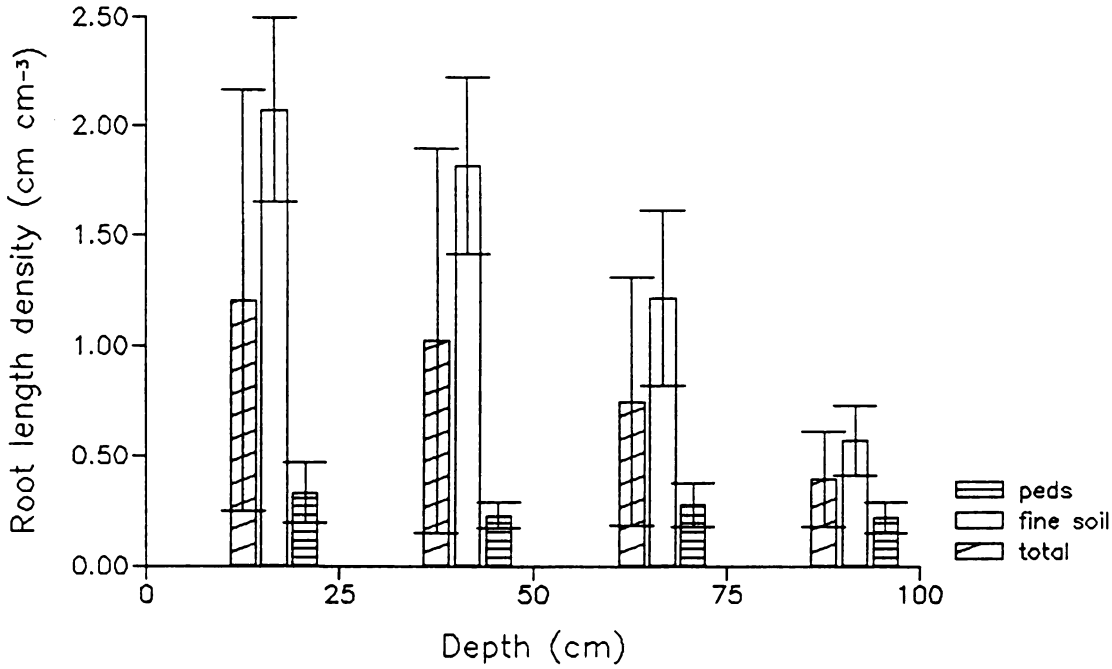


Figure 3.2. Root length density in peds and fine soil. Vertical bars represent the standard deviation. a) treatment S+LA.

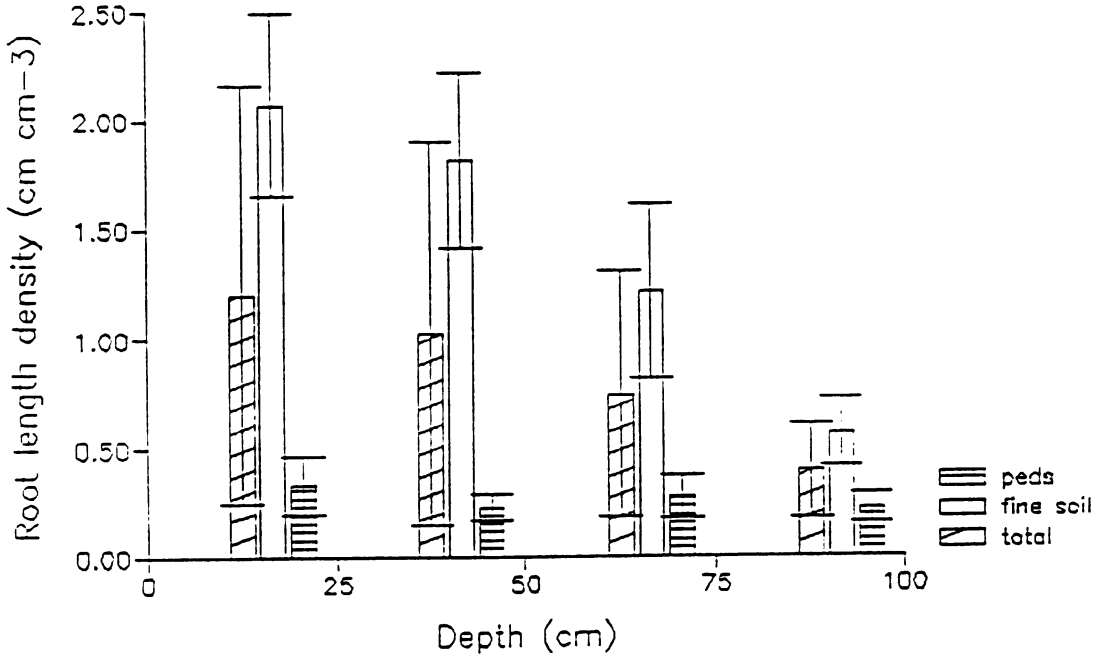
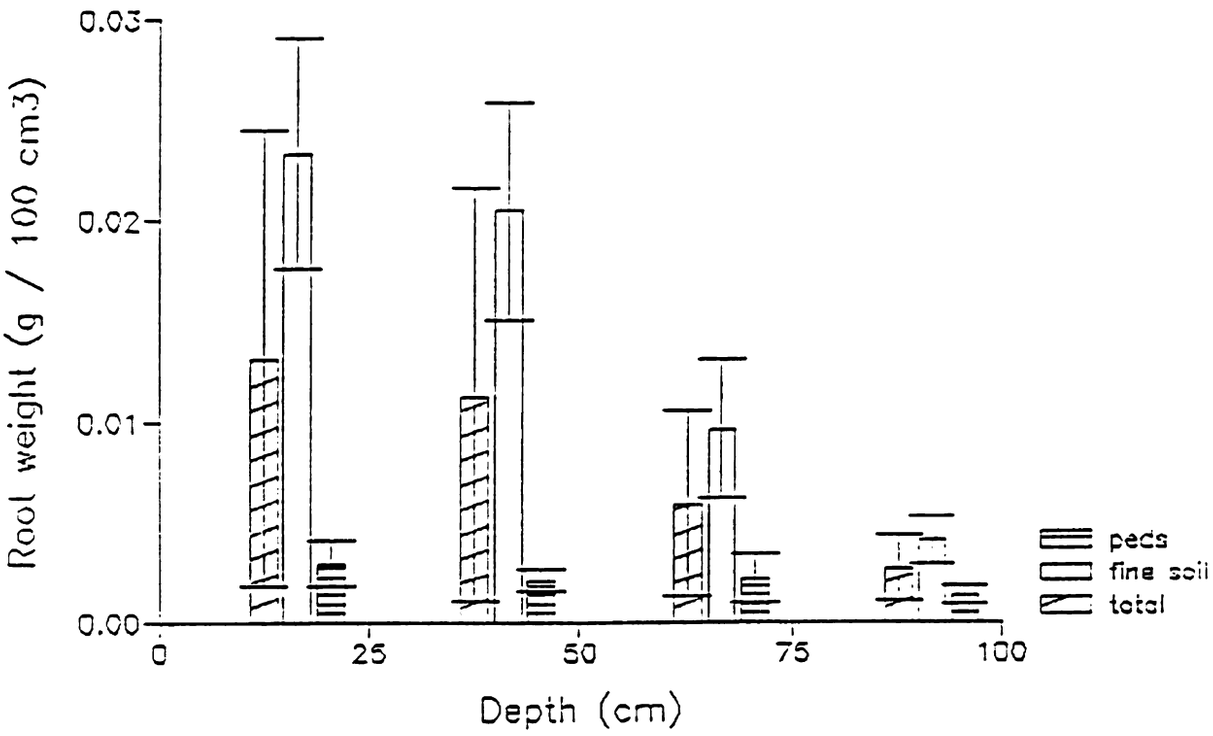
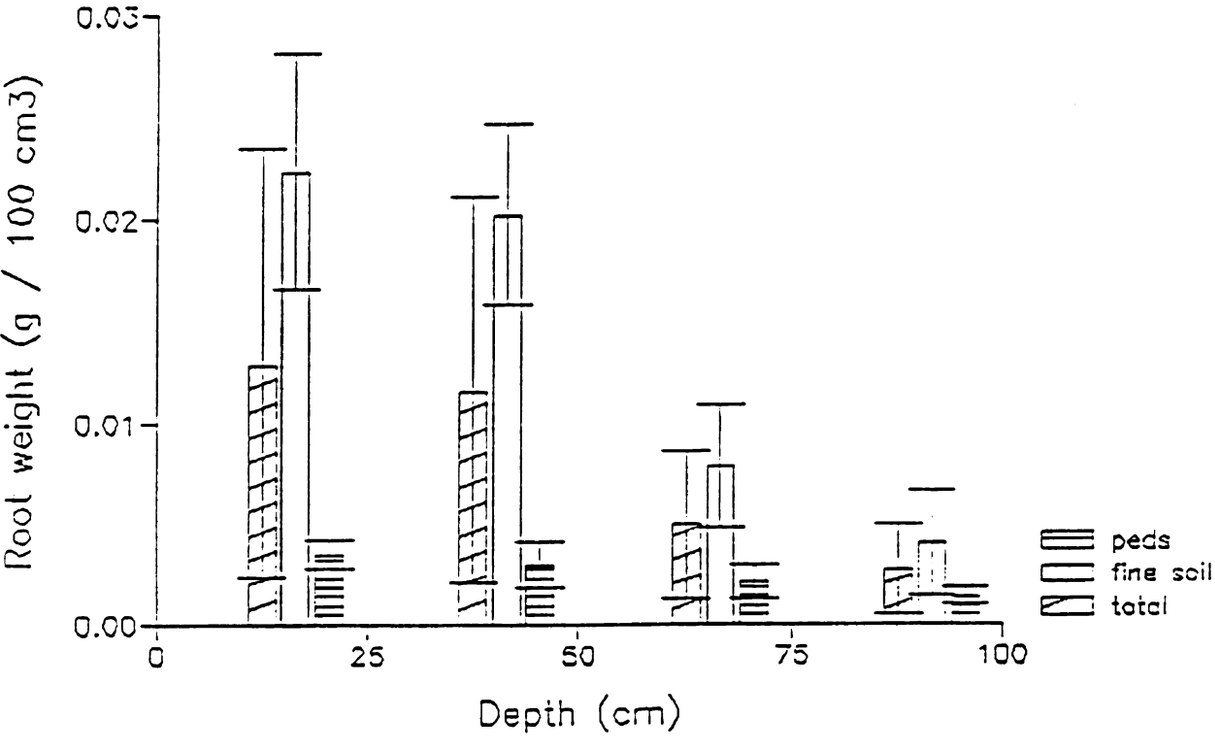


Figure 3.2. Root length density in peds and fine soil. Vertical bars represent the standard deviation. b) treatment S+SA.



.gure 3.3. Root weight in peds and fine soil. Vertical bars
epresent twice the standard deviation. a) treatment S+LA



igure 3.3. Root weight in peds and fine soil. Vertical bars epresent twice the standard deviation. b) treatment S+SA.

variability (Figure 3.4). Root weight per unit length was also similar between treatments, with the exception of CC, in which lower values were found. Values of root weight per unit lengthwere slightly higher in the first 50 cm of the C treatment, probably because of the large structures growing on the face of peds, while the roots growing into peds looked similar in thickness to those found in peds in the other treatments. The results indicate that roots growing into compacted soil were thinner than the others. One reason may be the presence of only lower order branches in the peds. It has been reported (Schuurman, 1965; Vorhees et al., 1975), that a contrasting interface enhances root branching in the soil so that the ratio of laterals to primary roots increases. Large roots have a lower probability of penetrating the narrow pores of compacted soil unless they can exert radial pressure to enlarge them (Hamblin, 1985). There are contrasting reports in the literature: roots growing in compacted soils are sometimes found to be thicker and other times thinner than those growing in soils of lower strength. Eavis (1972) tried to separate mechanical strength from aeration effects to explain the discrepancy. From a visual analysis of roots in this study, large root structures were limited to the bulk soil and ped surfaces, while only the finer roots penetrated peds.

Table 3.4 summarizes root data collected from the irrigated tubes. Root length density was higher after irrigation, and decreased with depth more than in the dry

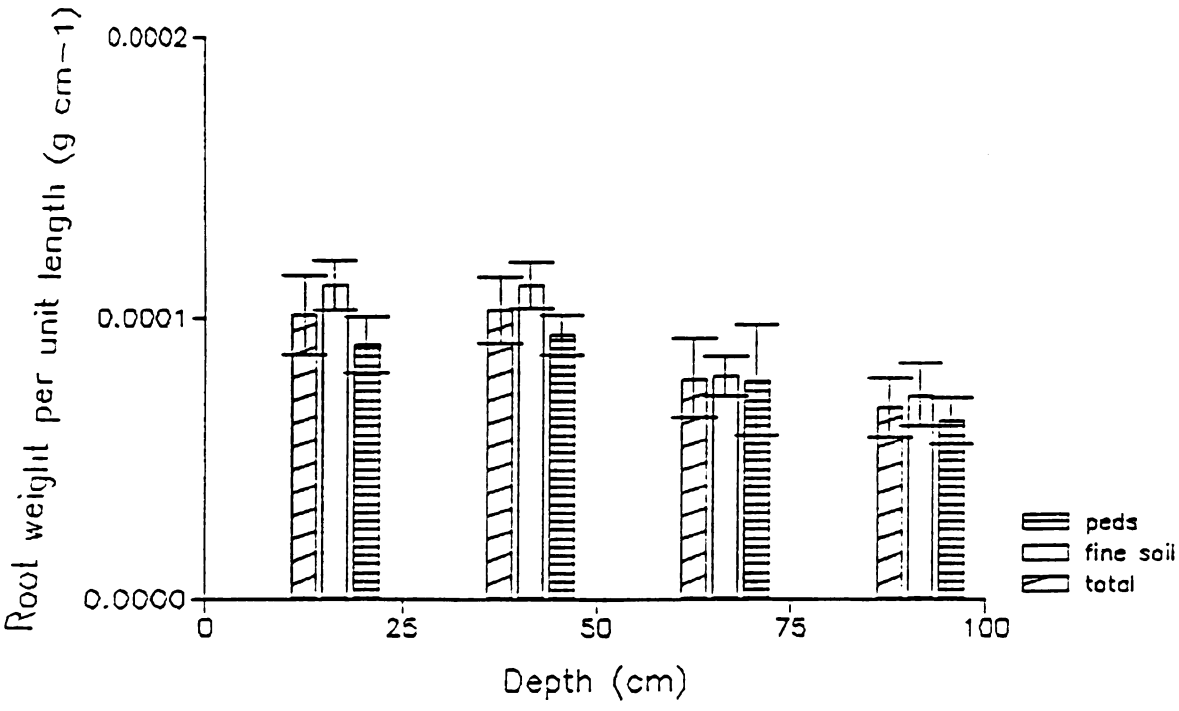
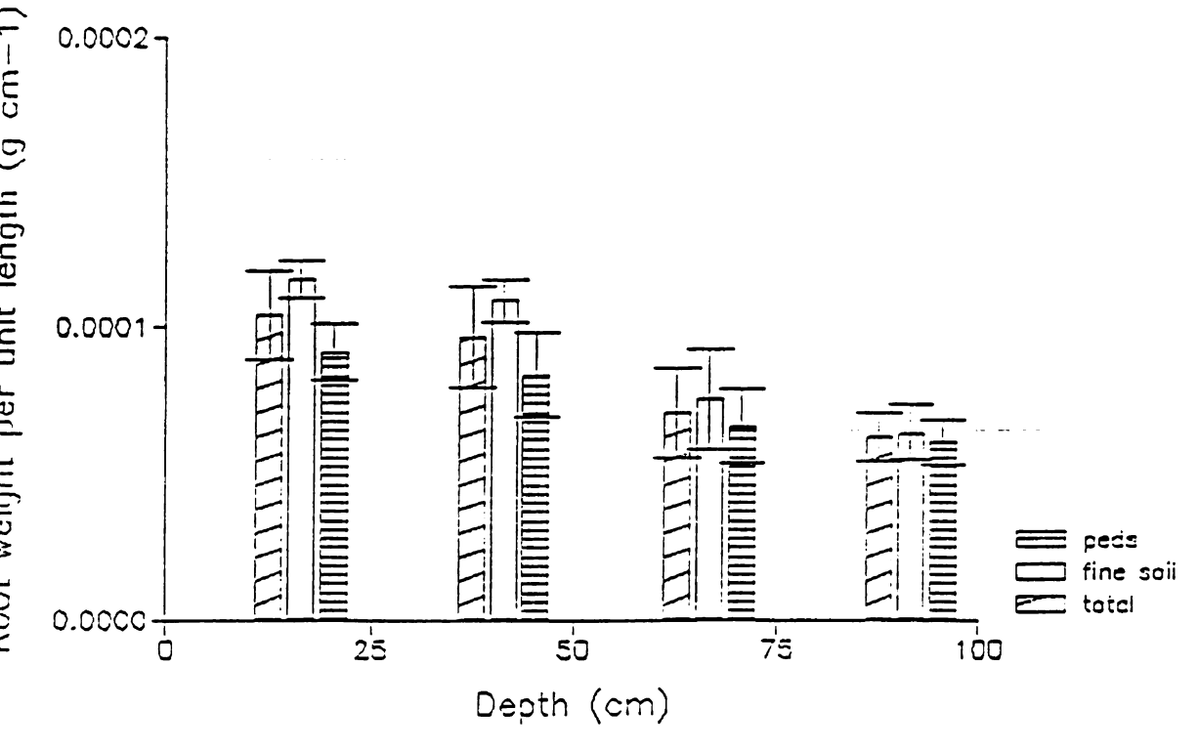


Figure 3.4. Root weight per unit length in peds and fine soil. Vertical bars represent twice the standard deviation. a) treatment S+LA



igure 3.4. Root weight per unit length in peds and fine soil. ertical bars represent twice the standard deviation.b) reatment S+SA.

able 3.4. Root length density (RLD), root weight, and root eight per unit length in irrigated treatments. sd= standard eviation.

+LA		treatment irrigated C	irrigated S	irrigated
oil layer (cm)				
		RLD (cm cm^{-3})		
-25	mean	4.47	5.57	5.10
	sd	1.59	1.38	3.85
5-50	mean	2.46	3.68	3.25
	sd	1.28	0.82	2.69
0-75	mean	1.47	2.21	1.37
	sd	1.00	0.59	1.07
5-100	mean	0.36	0.54	0.39
	sd	0.25	0.26	0.23
		Root weight (g cm^{-3})		
-25	mean	0.0666	0.0796	0.0694
	sd	0.0444	0.0242	0.0597
5-50	mean	0.0290	0.0481	0.0415
	sd	0.0202	0.0109	0.0375
0-75	mean	0.0058	0.0124	0.0074
	sd	0.0043	0.0031	0.0057
5-100	mean	0.0064	0.0058	0.0072
	sd	0.0048	0.0028	0.0044
		Root weight per unit length (g cm^{-1})		
-25	mean	0.000149	0.000143	0.000136
	sd	0.000026	0.000020	0.000019
5-50	mean	0.000118	0.000131	0.000128
	sd	0.000024	0.000013	0.000015
0-75	mean	0.000039	0.000056	0.000055
	sd	0.000009	0.000007	0.000010
5-100	mean	0.000181	0.000107	0.000186
	sd	0.000040	0.000021	0.000028

treatments. Values were higher in the S and S+LA treatments, compared to C. Root weight showed a similar pattern, and root weight per unit length was not very different between irrigated and dry tubes In irrigated treatments root weight was greater in the top layers and smaller in the bottom ones, compared to unirrigated treatments. The standard deviation values reported in the table were higher than those of the dry tubes, but the CV, independent of the treatment mean, were of the same order. The comparison of root data between dry and irrigated treatments confirms reports that the root of droughted plants deviates from the classical exponential distribution found in well-watered plants (Merrill and Rawlins, 1979) because of a lower proportion of roots in the dry superficial soil layers. The higher density of roots in deep layers of drying profiles has been discussed in terms of compensatory growth (Jordan et al., 1979), and Sharp and Davies (1985) speculated about the fine mechanisms of root proliferation in depth, suggesting that aeration effects and abscisic acid may play an important role.

Small scale root and water characterization

Figure 3.5 reports the values for RLD and TDR-determined volumetric water content in the 25-50 cm layer, across a 10 cm transect in the S treatment. Values of RLD across transects ranged from 0.94 to 1.43 cm^{-3}, and volumetric water content ranged from 0.126 to 0.133 cm^3 cm^{-3}. No clear trend in space

was detected for either RLD or θ_v.

Figure 3.6 summarizes the results for RLD and θ_v measured outside and across peds in the S+LA treatment in the 33-66 cm layer. Root length density in the bulk soil averaged 1.58 cm cm^{-3}. In the ped, roots were found in the 0-2 cm (superficial) layer, where the average RLD was lower than in the bulk soil (0.74 cm cm^{-3}), whereas in the internal layers of the peds roots were found only occasionally, probably growing in biopores. The corresponding θ_v values show a water content gradient within peds, with values ranging from 0.246 cm^3 cm^{-3} in the external layer (0-2 cm) to .350 cm^3 cm^{-3} and higher in the layers beyond 4 cm from the ped surface. Values for volumetric water content of the sandy-clay soil outside the peds were lower than those of the ped superficial layer, but in this case the discrepancy is to be attributed to the different texture and density of the two soils. The soil water potential values were likely much closer than the values of θ_v.

The corresponding figure for the 25-50 cm layer of the C treatment (Figure 3.7) shows very similar trends to that in treatment S+LA, although the actual values for RLD at the ped surface are higher, probably as a result of some compensatory growth, since in the C treatment roots could not grow in fine soil. A large proportion of the roots measured in the 0-2 cm were in fact located on the face of the peds. The root spatial distribution across peds was similar for the S+SA treatment

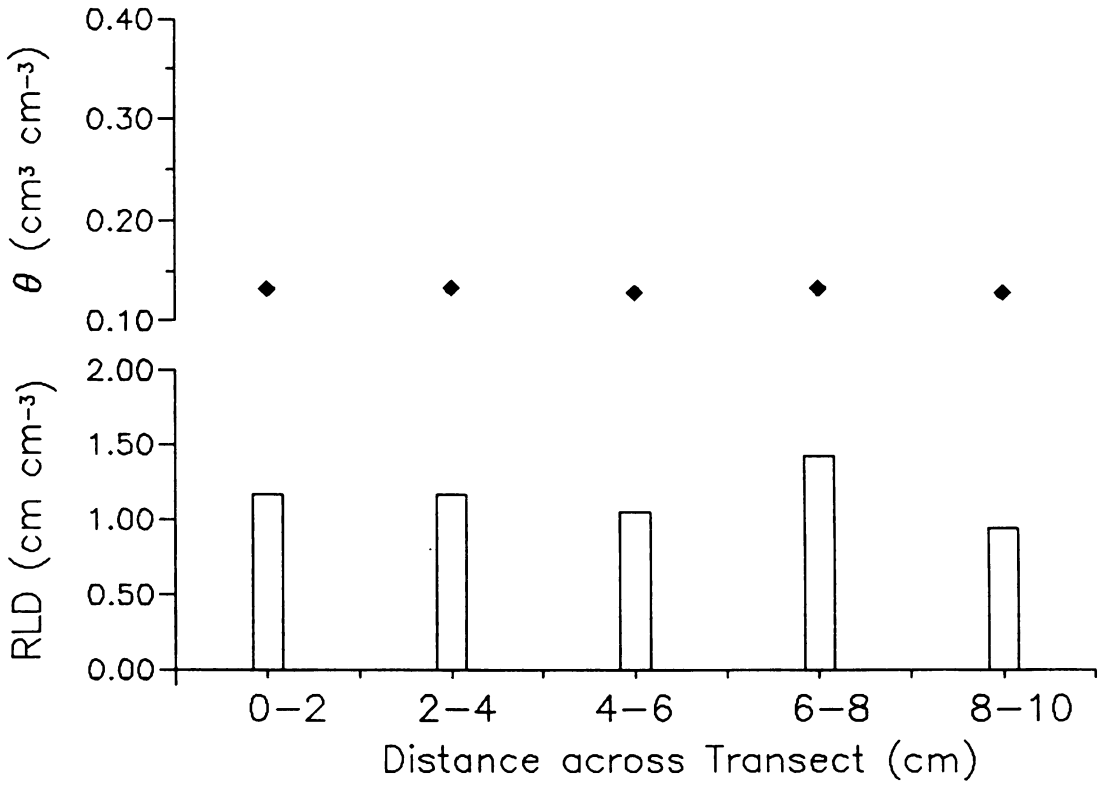


Figure 3.5. TDR-determined volumetric water content, and root length density across a 10-cm soil transects in the 25-50 cm layer of treatment S.

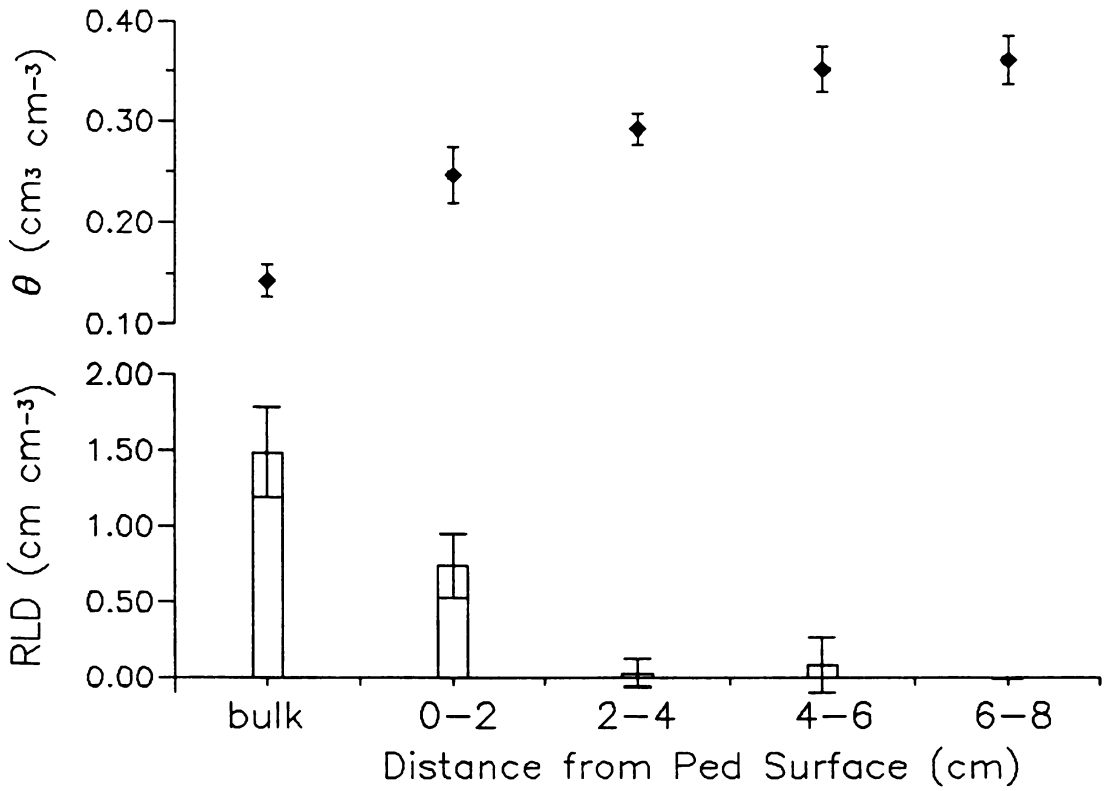


Figure 3.6. TDR-determined volumetric water content, and root length density in the bulk soil and across peds in the S+LA treatment. Vertical bars represent twice the standard deviation.

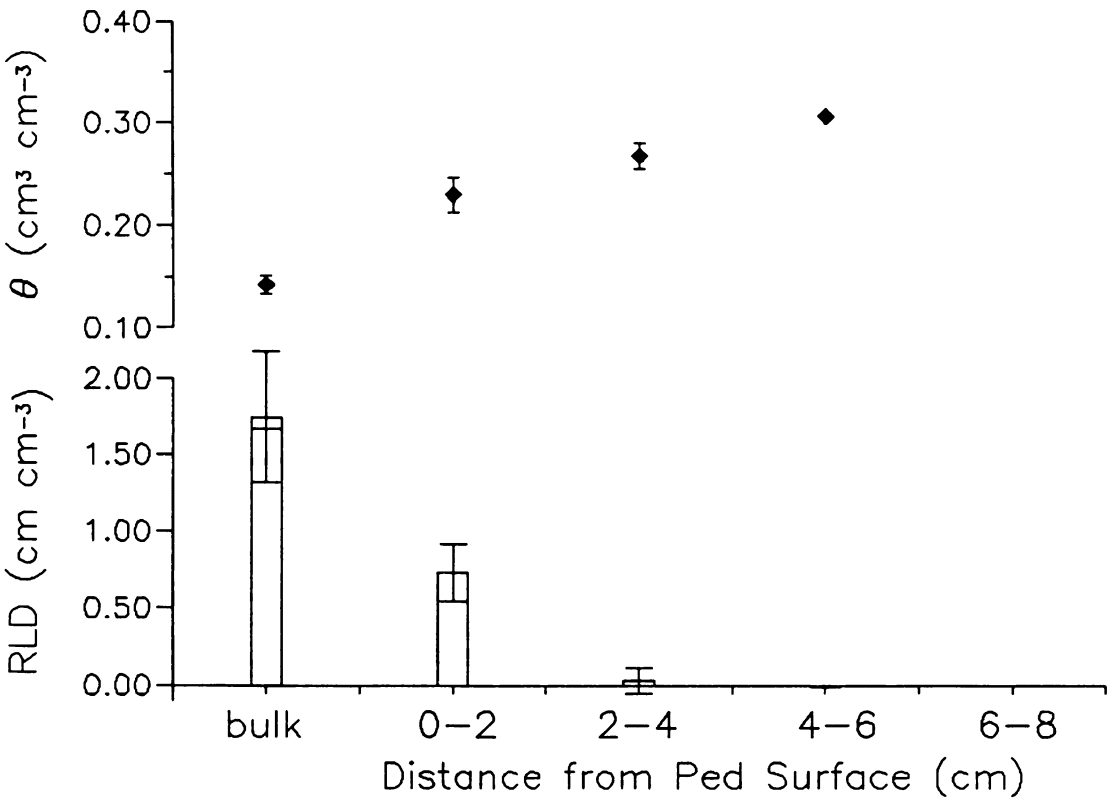


Figure 3.7. TDR-determined volumetric water content, and root length density in the bulk soil and across peds in the C treatment. Vertical bars represent twice the standard deviation.

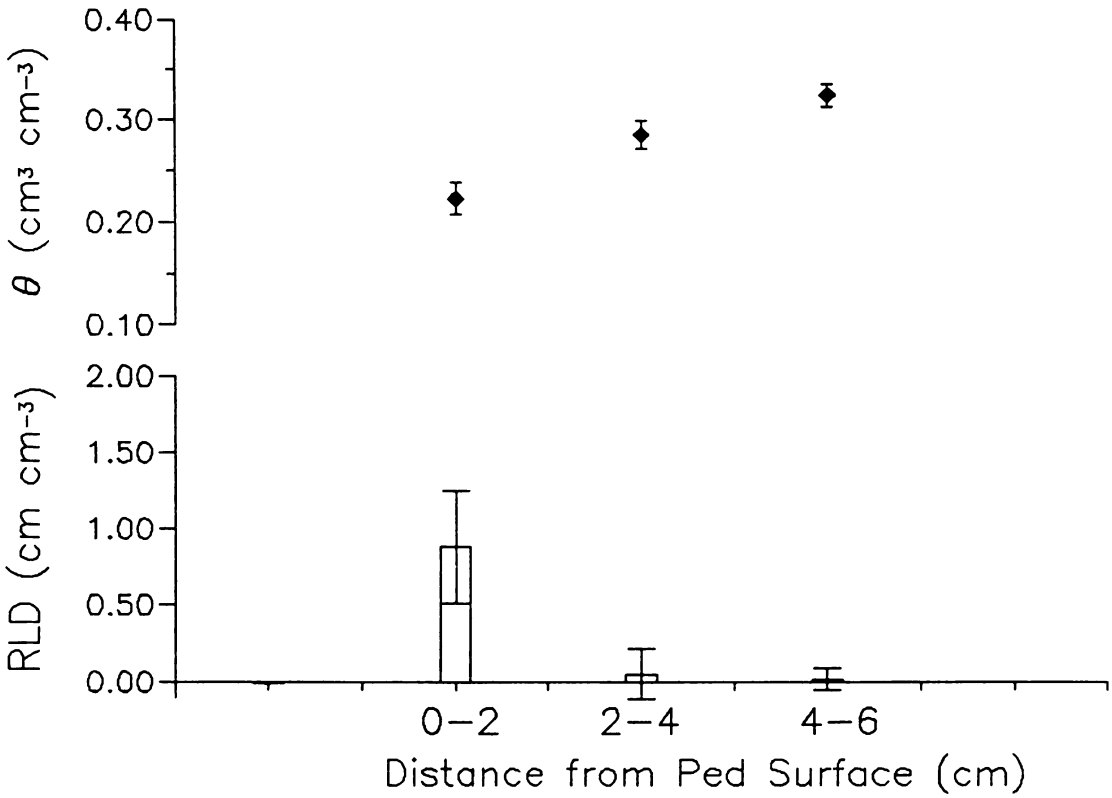


Figure 3.8. TDR-determined volumetric water content, and root length density in the bulk soil and across peds in the S+SA treatment. Vertical bars represent twice the standard deviation.

(Figure 3.8), for which little if any roots were found beyond the superficial layer of the aggregates. For both C and S+SA treatments, the measured gradient in θ_v across peds was smaller than that found in S+LA.

Values of TDR-determined θ_v for the bulk soil and across peds for all layers are reported in Tables 3.5 to 3.8 for each treatment. Bulk soil volumetric water content was quite low in some of the samples in the top layer of the tubes due to soil evaporation at the surface. Gradients across aggregates for all soil layers were of the order of magnitude of those reported in Figures 3.5 to 3.8. In the clay-loam soil below 50 cm shrinking cracks were not clearly detected, therefore sampling across structural units was not possible. The values of standard deviation associated with θ_v measurements were lower than 0.028 cm^3 cm^{-3}, except for the internal layers in the S+SA treatment, in which the standard deviation was higher. The reason for a higher variability in those layers is that peds in the S+SA treatment ranged from 8 to 10 cm in size, therefore the internal layer was actually at different distances from the ped surface in the different peds. No excessively high dielectric constant values were found, as the ones reported for the clay-loam soil in 21 mm-high layers in chapter 1, and the consistency of the measurements, even at high θ_v, suggests that none of the measured values was an artifact of the TDR technique.

Values of RLD for the bulk soil and across peds for all

Table 3.5. TDR-determined θ_v (cm^3 cm^{-3}) across peds and in bulk soil for the S+LA treatment. n= number of samples. sd=standard deviation. CV = coefficient of variation.

	bulk soil	ped layer (cm)			
Soil layer (cm)		0-2	2-4	4-6	6-8
0-33					
n.	24	24	18	8	2
mean	0.088	0.240	0.288	0.342	0.353
sd	0.010	0.019	0.028	0.019	0.010
CV	11.0	8.1	9.7	5.6	2.8
33-66					
n.	24	22	14	6	2
mean	0.143	0.246	0.292	0.351	0.363
sd	0.016	0.028	0.016	0.022	0.023
CV	11.2	11.4	5.6	6.3	6.2
66-100					
n.	24	21	12	6	1
mean	0.154	0.233	0.276	0.353	0.318
sd	0.010	0.025	0.016	0.021	/
CV	6.7	10.6	5.8	6.1	/

Table 3.6. TDR-determined θ_v ($cm^3\ cm^{-3}$) across peds and in for the C treatment. n= number of samples. sd=standard deviation. CV = coefficient of variation.

	bulk soil	ped layer (cm)		
Soil layer (cm)		0-2	2-4	4-6
0-25				
n.		9	9	9
mean		0.212	0.277	0.316
sd		0.020	0.022	0.007
CV		9.4	7.9	2.3
25-50				
n.		9	9	9
mean		0.223	0.285	0.324
sd		0.016	0.014	0.011
CV		7.2	4.8	3.4
50-75				
n.	9			
mean	0.345			
sd	0.030			
CV	8.8			
75-100				
n.	9			
mean	0.389			
sd	0.043			
CV	11.1			

Table 3.7. TDR-determined θ_v (cm^3 cm^{-3}) across peds and in bulk soil for the S+SA treatment. n= number of samples. sd=standard deviation. CV = coefficient of variation.

	bulk soil	ped layer (cm)		
Soil layer (cm)		0-2	2-4	4-6
0-25				
n.	9	25	12	3
mean	0.085	0.220	0.272	0.283
sd	0.016	0.014	0.014	0.033
CV	18.7	6.4	5.2	11.7
25-50				
n.	9	26	15	1
mean	0.142	0.229	0.267	0.306
sd	0.009	0.017	0.012	/
CV	6.2	7.4	4.6	/
50-75				
n.	9	26	15	2
mean	0.163	0.221	0.279	0.304
sd	0.011	0.015	0.015	0.051
CV	6.9	7.0	5.5	16.8
75-100				
n.	9	26	14	3
mean	0.175	0.223	0.280	0.324
sd	0.016	0.014	0.014	0.022
CV	9.1	6.2	4.9	6.9

Table 3.8. TDR-determined θ_v (cm^3 cm^{-3}) across 10 cm transects for the S treatment. n= number of samples. sd=standard deviation. CV = coefficient of variation.

	distance on transect (cm)				
Soil layer (cm)	0-2	2-4	4-6	6-8	8-10
0-25					
n.	9	9	9	9	9
mean	0.084	0.090	0.091	0.088	0.087
sd	0.012	0.008	0.010	0.010	0.010
CV	14.3	9.3	10.9	11.0	11.2
25-50					
n.	9	9	9	9	9
mean	0.132	0.133	0.128	0.133	0.125
sd	0.024	0.019	0.013	0.013	0.014
CV	18.0	14.6	10.0	9.5	10.9
50-75					
n.	9	9	9	9	9
mean	0.156	0.152	0.152	0.154	0.156
sd	0.019	0.018	0.016	0.020	0.020
CV	12.2	11.8	10.3	12.9	12.9
75-100					
n.	9	9	9	9	9
mean	0.196	0.194	0.187	0.184	0.191
sd	0.024	0.026	0.021	0.017	0.020
CV	12.3	13.2	11.1	9.3	10.6

Table 3.9. Root length density (cm cm^{-3}) across peds and in bulk soil for the S+LA treatment. n= number of samples. sd=standard deviation. CV = coefficient of variation.

	bulk soil	ped layer (cm)			
Soil layer (cm)		0-2	2-4	4-6	6-8
0-33					
n.	9	9	9	8	2
mean	1.93	0.76	0.05	0.00	0.35
sd	0.371	0.123	0.100	0.000	0.501
CV	19.2	16.2	212.1	0.0	141.4
33-66					
n.	9	9	9	7	1
mean	1.49	0.74	0.03	0.08	0.00
sd	0.298	0.210	0.094	0.184	0.000
CV	20.1	28.4	300.0	216.0	0.0
66-100					
n.	9	9	9	5	1
mean	0.68	0.65	0.11	0.08	0.42
sd	0.210	0.085	0.221	0.190	0.000
CV	31.0	13.0	201.0	223.6	0.0

Table 3.10. Root length density (cm cm^{-3}) across peds for the C treatment. n= number of samples. sd=standard deviation. CV = coefficient of variation.

	bulk soil	ped layer (cm)		
Soil layer (cm)		0-2	2-4	4-6
0-25				
n.		9	9	9
mean		0.91	0.05	0.04
sd		0.348	0.142	0.118
CV		38.3	300.0	300.0
25-50				
n.		9	9	9
mean		0.88	0.06	0.02
sd		0.366	0.165	0.071
CV		41.5	300.0	300.0
50-75				
n.	9			
mean	0.45			
sd	0.184			
CV	41.0			
75-100				
n.	9			
mean	0.28			
sd	0.265			
CV	93.5			

Table 3.11. Root length density (cm cm^{-3}) across peds and in bulk soil for the S+SA treatment. n= number of samples. sd=standard deviation. CV = coefficient of variation.

	bulk soil	ped layer (cm)		
Soil layer (cm)		0-2	2-4	4-6
0-25				
n.	9	25	16	3
mean	1.92	0.68	0.07	0.07
sd	0.444	0.145	0.150	0.123
CV	23.1	21.3	225.3	173.2
25-50				
n.	9	26	18	2
mean	1.75	0.73	0.04	0.00
sd	0.434	0.185	0.085	0.000
CV	24.8	25.4	240.1	0.0
50-75				
n.	9	26	15	2
mean	1.12	0.57	0.06	0.14
sd	0.229	0.170	0.162	0.200
CV	20.5	29.6	264.8	141.4
75-100				
n.	9	26	15	4
mean	0.68	0.49	0.03	0.11
sd	0.237	0.130	0.106	0.196
CV	34.7	26.5	400.9	184.8

Table 3.12. Root length density (cm cm^{-3}) across 10 cm transects for the S treatment. n= number of samples. sd=standard deviation. CV = coefficient of variation.

	distance on transect (cm)				
Soil layer (cm)	0-2	2-4	4-6	6-8	8-10
0-25					
n.	9	9	9	9	9
mean	1.49	1.30	1.43	1.60	1.89
sd	0.556	0.347	0.443	0.480	0.541
CV	37.4	26.7	31.0	29.9	28.7
25-50					
n.	9	9	9	9	9
mean	1.17	1.16	1.05	1.43	0.94
sd	0.410	0.391	0.273	0.424	0.300
CV	35.0	33.6	25.9	29.6	31.8
50-75					
n.	9	9	9	9	9
mean	0.94	0.94	0.92	1.05	0.83
sd	0.274	0.381	0.279	0.262	0.400
CV	29.2	40.7	30.3	25.0	48.5
75-100					
n.	9	9	9	9	9
mean	0.53	0.66	0.65	0.61	1.53
sd	0.151	0.253	0.125	0.283	2.807
CV	28.2	38.3	19.4	46.8	183.1

layers is reported in Table 3.9 to 3.12, for each treatment. Measured RLD in the bulk soil of treatments S+LA (Table 3.9) and S+SA (Table 3.11) was higher than in S (Table 3.11) probably as a result of compensatory growth, since growth in peds was limited in treatments S+LA and S+SA. Roots were found beyond the surface 2 cm in peds only in biopores or secondary cracks.

In all clay-loam structural units, the volumetric water content of the external layer ranged from about 0.220 to 0.246 cm^3 cm^{-3}. According to Comegna et al. (1990) this amount corresponds to a soil matric potential of about -0.8 to -1.0 MPa in this soil. This value is higher than that at which roots can lower their potential, but since it is an average value for the whole 0-2 cm of the external layer, the actual value around roots may be lower. Dunham and Nye (1973) and Hsieh et al. (1972) report large water content gradients across the first 5 mm from a root plane, and if measurements had been made over smaller space increments in this experiment, steeper gradients might have been found. A visual analysis of the samples suggested that roots in the superficial ped layer were actually not uniformly distributed in the 0-2 cm layer, but density was higher close to the surface of peds.

Soil mapping

Some of the results for soil mapping on horizontal planes are reported in Figures 3.9 to 3.12 for the C, S, S+LA, and S+SA treatments at various depths. Mapping showed that the distribution in space of roots and volumetric water content was strongly related to the structural status of soil: roots developed quite uniformly at the centimeter scale in the sandy-clay, and could not penetrate peds beyond the 0-2 cm layer, unless biopores or cracks were present. In the clay-loam treatment, up to 50 cm, where structural units were distinguishable, root growth was higher on ped surfaces and in the 0-2 cm superficial layer of peds, but some root growth was found within peds, in secondary cracks. Below 50 cm, root growth was quite variable spatially, but no structural unit was clearly distinguishable due to the higher water content of the layers. Root indexes determined within ped layers were quite uniform. The water content was quite uniform, within .02 $cm^3\ cm^{-3}$ in the sandy-clay soil, except for the areas close to the container walls in the 3 and 25 cm layers, where θ_v was lower than the layer average, presumably due to evaporation. Across peds, gradients of water were shown. In the sampling planes close to the tube surface (3 cm depth), root density was quite high in the center of the plane, close to the plant crown, due to the higher presence of structures departing from the plant. The water content was higher in that region, presumably because of protection from evaporation due to the

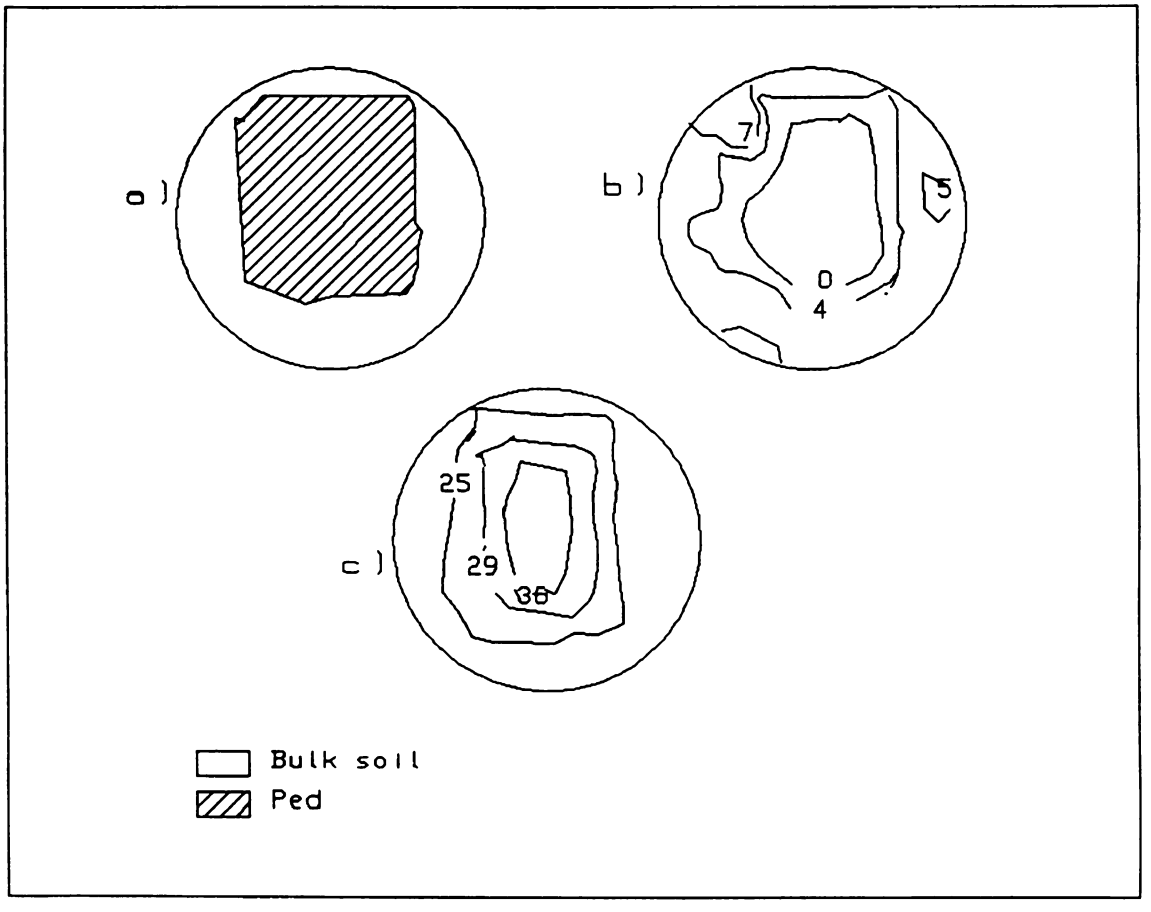


Figure 3.9. Map of the 75 cm layer in the S+LA treatment. a) structural features; b) root density index; c) TDR-determined volumetric water content.

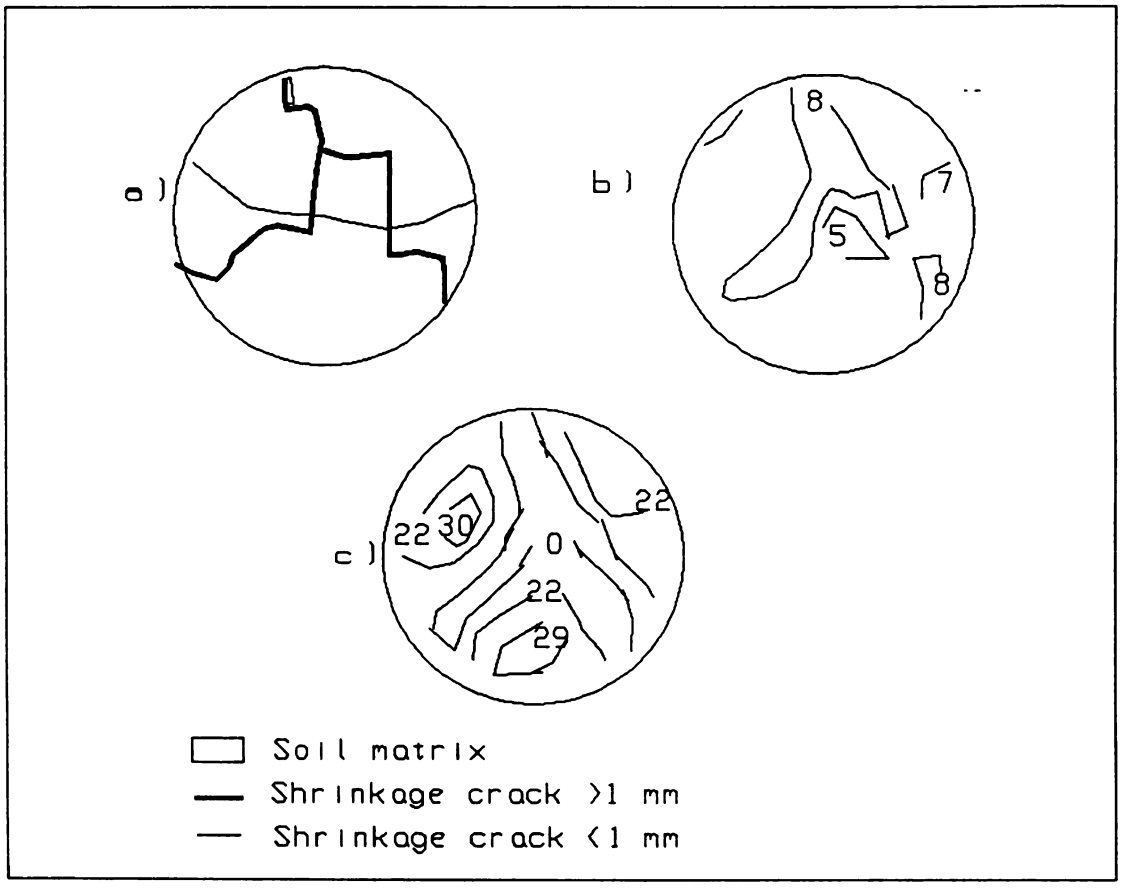


Figure 3.10. Map of the 25 cm layer in the C treatment. a) structural features; b) root density index; c) TDR-determined volumetric water content.

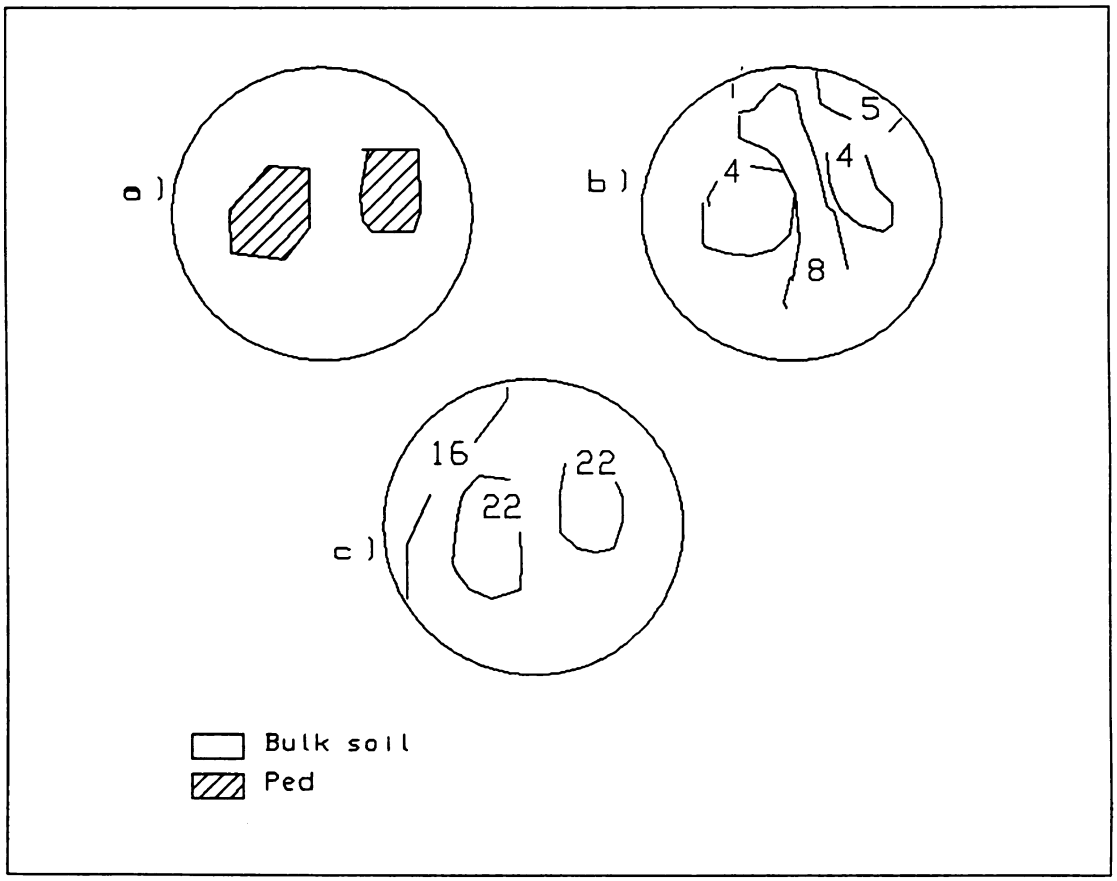


Figure 3.11. Map of the 50 cm layer in the S+SA treatment. a) structural features; b) root density index; c) TDR-determined volumetric water content.

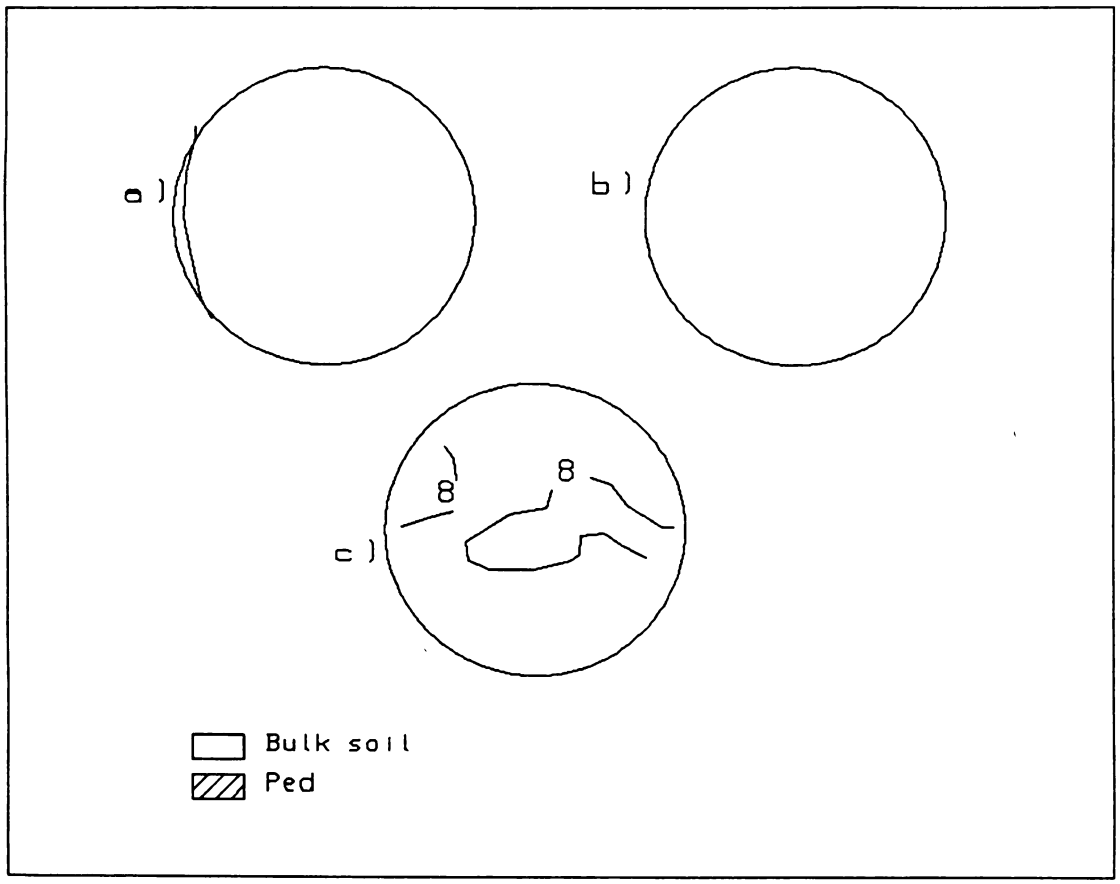


Figure 3.12. Map of the 75 cm layer in the S treatment. a) structural features; b) root density index; c) TDR-determined volumetric water content.

plant stem and root mass. Around that area, evaporation was responsible for a low water content in all treatments. Another possibility to explain the higher water content values found where roots were more dense in the top soil layer is that water loss from the root to the soil may have taken place during water transport from wet soil regions through dry layers. Flow of water from roots to dry soil was reported by Molz and Peterson (1976) and Caldwell and Richards (1989), although other experiments fail to show any (Nobel and Sanderson, 1984; Dirksen and Raats, 1985). It has been pointed out that roots may act as rectifiers (Nobel and Sanderson, 1984), and increase dramatically radial resistance by suberization and deposition of structural carbohydrates to block symplastic water pathways (Sharp and Davies, 1985), so that loss of water is prevented. Other mechanisms have been suggested (Passioura, 1988). In summary, effects of structural status on root clustering and water content were documented. Roots grew quite uniformly in the sandy-clay soil (S treatment), and in the bulk soil or shrinking cracks of the other treatments, but did not penetrate peds beyond 2 cm from the surface, unless biopores or secondary cracks were present. The limitations of root clustering to water extraction from the soil were large, especially 2 cm beyond the ped surface. Among structured growth media, the S+SA extracted the highest amount of water, from peds of 8-10 cm in diameter, while S+LA extracted less water from larger peds,

even though average RLD was comparable to that of S+SA. In all structured treatments (C, S+LA, and S+SA) water gradients across peds, away from roots, were detected.

The large gradients found across peds are responsible for the low water extraction reported for the S+LA and C treatment in Chapter 2, and to a smaller extent in treatment S+SA. The water left in peds was on average 69% of the initial water for the large peds (S+LA), 58% for the small ones,(S+SA), and 60% for the C treatment.

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Vorhees, W.B., Farrell, D.A., and Larson, W.E., 1975. Soil strength and aeration effects on root elongation. Soil Sci. Soc. Amer. Proc. 39:948-953Figure 3.1. Small-scale soil sampler. a) top view; b) side view; c) front view.

CHAPTER 4

PLANT GROWTH AND WATER UPTAKE IN STRUCTURED GROWTH MEDIA. III: SIMULATION OF WATER OUTFLOW FROM PEDS.

ABSTRACT

In a previous experiment unextracted water at plant wilting was found in soil peds where roots could not penetrate beyond 2 cm from the surface. In order to test if the water gradients measured across peds could be explained by classical modeling approaches, half the mean distance between roots (b) was calculated based on experimental data. The b values were used to derive a time constant τ as suggested by Passioura (1985) to predict the time of water withdrawal from soil assuming a uniform root distribution throughout a soil layer. The time constant was also calculated from b values obtained separately in peds and bulk soil, and for the assumption of roots clustered around peds. The calculated τ values predicted a faster water depletion than what measured experimentally, if a diffusivity (D) value of 1 cm^2 day^{-1} was used, and especially so for the assumption of uniform roots.

Water outflow from peds was also modeled by simulating radially symmetrical flow out of a cylinder, and the

dependence of water outflow from different values of $D(\theta)$ was tested. A slow water depletion at the cylinder center was obtained with low D values at high θ, or by assuming quite low values of D in dry soil around roots. Experimental results on water gradients across peds were reproduced using $D(\theta)$ values ranging from $4.19*10^{-2}$ at the dry end to 10 cm^2 day^{-1} at the wet end.

INTRODUCTION

Many models of root water uptake in the soil are based on the single-root approach (Gardner, 1960), and flux of water into the root system is considered to be proportional to the root length density in a layer. Experimental data do not always verify this assumption, and both larger and smaller water uptake than predicted by theory have been reported (Hamblin, 1985). Herkelrath et al. (1977) found in a container experiment that calculated water extraction rates were as much as 8 times larger than measured values. They suggested that incomplete root-soil contact could explain the lower uptake rates of roots in drying soil. Faiz and Weatherley (1977, 1978) calculated a four- to six-fold increase in resistance to water flow in the soil around roots, responsible for limitations in water uptake and the development of steep water gradients between perirhizal and pararhizal soil. Zur at al. (1982) found a decrease in

transpiration flux that could not be predicted by calculations of bulk soil resistance. Resistance to water flow obtained from experimental data were 6 orders of magnitude higher than the ones obtained from theory. They hypothesize that perirhizal resistance may be several orders of magnitude higher than the bulk soil value. Hamblin (1985) discusses reports of low water uptake in deep layers of fine-textured soils (i.e. Jordan and Miller, 1980), suggesting that the explanation is to be found in non-uniform root distribution rather than high axial resistance. A series of recent papers (Tardieu and Manichon, 1986; Tardieu, 1988) argues that in case of root clustering water uptake can be much smaller than that calculated by the single-root model. Passioura (1985) suggested that a time constant can be used to describe the rate of water uptake when flow through the soil is limiting. Such a constant depends on average distance between roots in the case of uniform distribution, and on distance between root clusters in the case of clumped distribution. In the latter case the time constant is larger, depending on the actual geometry of clusters, and may become limiting for access of roots to soil water in a time useful for relief from water deficits. Experimental results on root clustering and water uptake patterns around roots have not been used to test the model.

In a companion paper (chapter 3), incomplete water extraction was measured in peds where root penetration was

limited to the 2 cm outer layer. Gradients of water content as a function of distance from the ped surface were measured at plant wilting. These results are analyzed here with the time constant approach proposed by Passioura (1985), both for the classical assumptions of uniform roots and with the assumption of root clustering. A model of outflow from peds is also used, with the aim of testing the dependence of flow from the relation between soil water diffusivity and water content.

MATERIALS AND METHODS

In a greenhouse experiment maize (Zea mays L.) was grown in 100 cm long containers with the experimental design described in chapter 2. The treatments were: C (clay-loam soil), S (sandy-clay soil) S+LA (sandy clay with large clay-loam peds embedded), S+SA (sandy clay with small clay-loam peds embedded), CC (compacted clay-loam soil). Water uptake was low in the CC treatment where root length density (RLD) was low in the 50-75 cm layer and null in the 75-100 cm. In the other treatments water extraction was low in peds, where roots were found only in the 0-2 cm outer layer.

The measured water loss from peds was compared with calculated water losses according to two approaches:

1) Time-constant calculation.

Passioura's (1985) time constant was calculated to quantify the predicted time of water withdrawal from a soil region

according to two different models :

i) **the classical single-root approach** in which the time constant is:

$$\tau = 2b^2/D \qquad \text{(Passioura, 1985)}$$

where b is the half-mean root distance calculated as $(\pi * RLD)^{-1/2}$ (Gardner, 1960), based on the assumption of root uniform distribution, RLD is average root length density in a soil region ($cm\ cm^{-3}$), and D is soil diffusivity ($cm^2\ day^{-1}$). With these units, τ is expressed in days.

Half of the mean distance between roots was calculated for the two cases of:

a) uniform roots within soil layers

b) roots considered separately for peds and bulk soil.

ii) **the clustered model for peds**, in which the roots found in peds were considered limited to their surface, and peds shape was approximated by a cylinder. The formula used in this case was :

$$\tau = B^2/4D \qquad \text{(Passioura, 1985)}$$

where B= half the distance between root clusters (cm). In case of cylindrical peds with roots limited to the surface, B equals the cylinder radius. In our case results from root measurements showed that there was root penetration limited to the surface 2 cm of the ped. From a visual analysis, though, most of the roots were limited to the surface 1 cm, therefore B was taken as the radius of the cylinder that approximated the ped, to which 1 cm were subtracted.

A D value of 1 cm^2 day^{-1} was used for all calculations.

2) Modeling of water outflow from peds.

Water content changes with time were modeled as a function of distance across peds.

The general assumption was to approximate a ped's configuration as a cylinder and to consider outflow radially symmetrical. This way, the two-dimensional problem could be modeled in one-dimension after transformation of the flow equation (in its diffusivity form) into radial coordinates. The model used was:

$$\frac{\delta\theta}{\delta t} = \frac{1}{r}\frac{\delta}{\delta r}(rD(\theta)\delta\theta/\delta r)$$

with initial and boundary conditions:

$\theta=0.40 \quad r<R0-\Delta r \quad t=0$

$0.19<\theta<0.40 \quad R0-\Delta r<r<R0 \quad t>0$

where θ= volumetric water content (cm^3 cm^{-3})
r= radial distance (cm)
D= soil diffusivity (cm^2 day^{-1})
t= time (days)
R0= maximum cylinder radius

The assumption was of initially uniform water content. The initial value was set at 0.40 cm^3 cm^{-3} because it was the volumetric water content of peds at planting, measured on one replicate tube after preparation. Since the time-course of root growth in peds and water extraction was not measured, some assumptions had to be made as to the time at which uptake from peds started. Extraction was hypothesized to begin at the

time when plants showed severe leaf rolling, that is day 20 for the S+LA treatment from data in chapter 2. This simplifying assumption was suggested by observations from a field experiment exposed in chapter 5, in which roots were found to proliferate in peds more markedly after colonization and water extraction from less compacted soil regions. Experimental data from chapter 3 were used for comparison with simulations. Results on water gradients in the second soil layer were chosen, to minimize effects of soil evaporation and early root growth that may confound results in the first layer.

The boundary condition of water content at 0.19 cm^3 cm^{-3} at the ped's surface corresponds to -1.5 MPa for the same soil extrapolating data from Comegna et al., 1990. The underlying assumption was that if roots started to extract water from peds after establishing into bulk soil and after plants had developed some stress, their potential would be from the beginning of extraction. A condition was imposed that when uptake started, θ varied linearly from 0.19 to 0.40 across an annular region of thickness Δr from the cylinder surface. This ensured stability in the iterative calculations, allowing the use of a D strongly dependent on θ: the gradual change in θ ensured that there would not be sharp changes in $D(\theta)$ that could cause instabilities and prevent the calculations from converging, as noticed in trial model runs. Physically, the condition corresponded to a sink for water of declining

strength across a layer at the ped surface, as opposed to a sink localized outside the surface of peds. Data on final root distribution in peds do in fact show root penetration in the superficial ped layer, although the time-course of root penetration was not measured. A Δr value of 1 cm was chosen.

A sensitivity analysis was performed, in order to test the dependence of flow on variations in the diffusivity-water content relation, and to find the values of $D(\theta)$ that would reproduce by simulation the water content distribution across peds as observed in the greenhouse experiment (Chapter 3). Diffusivity was considered to vary with water content according to:

$$D = \alpha(\theta_o - \theta)^{\beta}$$

where $\theta_o = 0.467$ cm^3 cm^{-3} (saturated water content according to Comegna et al., 1990)

Several cases were analyzed with D values varying from 1 to 150 cm^2 day^{-1} at the wet end (θ=0.4 cm^3 cm^{-3}) and from $4.29*10^{-3}$ to 1 cm^2 day^{-1} at the dry end (θ=0.19 cm^3 cm^{-3}). The following are presented:

i) D=1 (constant)

ii) $1<D<10$ $\alpha=1.37*10^{-1}$ $\beta=-1.548$

iii) $1*10^{-1}<D<10$ $\alpha=1.88*10^{-3}$ $\beta=-3.096$

iv) $4.29*10^{-2}<D<10$ $\alpha=3.80*10^{-4}$ $\beta=-3.665$

v) $4.29*10^{-3}<D<10$ $\alpha=5.32*10^{-6}$ $\beta=-5.214$

vi) $4.29*10^{-2}<D<50$ $\alpha=9.67*10^{-5}$ $\beta=-4.748$

vii) $4.29*10^{-3}<D<50$ $\alpha=1.32*10^{-6}$ $\beta=-6.296$

The corresponding $D(\theta)$ relations are depicted in Figure 4.1.

Runs were made for the cases of radius = 9, 6, and 4 cm, that correspond to the radius of peds in the S+LA, S+SA, and C treatments respectively.

RESULTS AND DISCUSSION

Table 4.1 reports half mean root distance according to Gardner (1960), based on the assumption of random root arrangement in the soil. For all treatments the calculated half average distance between roots was lower than 0.76 cm in the higher layers, and lower than .96 cm in deep layers. An exception was the 50-75 layer of the compacted clay-loam, where the low RLD yielded an average half distance of 3.85 cm. Based on the calculated distance, Passioura's (1985) time constant τ was calculated and the results are reported in table 4.1. For all treatments the time constant value was lower than 1 day in the upper layers (meaning that the gradient in water between the bulk soil and the root surface would be reduced to .37 of its initial value in 1 day) and lower than 2 days in the deeper layer. Again, the CC treatment was an exception, in that the time constant was larger than 1 day in the upper layer and reached 29.6 days in the 50-75 layer, due to the very low root length density. In the 75-100 cm layer no roots were found: the time constant for the layer

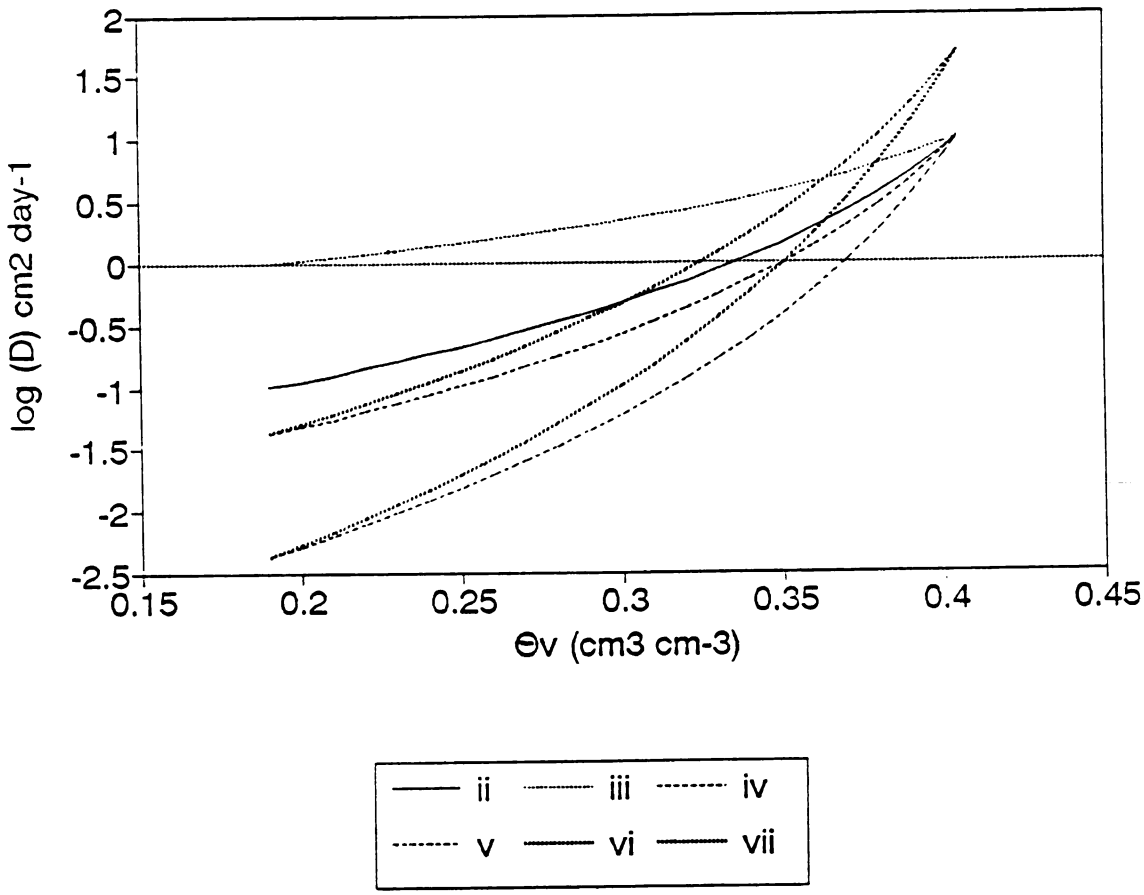

Fig 4.1. Relations between water diffusivity and water content used for the simulations. Soil diffusivity is represented on a decimal logarithmic scale. Relation i is represented by the horizontal line. Curves corresponding to relations ii to vii are indicated in the legend.

is virtually infinite if no flow between layers is assumed. Such a high time constant in the bottom layers explains a limited water extraction, although water distribution was not measured in this treatment, and the time at which roots started extracting water from the 50-75 layer was not recorded. For the other layers in the CC treatment and for all layers in the other treatments, the values of time constant were found to be quite low, thus they do not explain the experimental results: at the end of the experiment the gradient in water content between the center of peds and the area around roots was 43.5%, 25%, and 26% of the initial gradients for the S+LA, S+SA, and C treatments respectively, if the water content around roots is assumed to be 0.19 cm^3 cm^{-3}. Calculations were also made for the peds only,and the values of time constant found, reported in Table 4.2, were higher than the average ones for each layer, due to the lower RLD in peds; values ranged from about 1.6 days in the superficial soil layers to about 2.9 in the deep one, but still they were not sufficiently large to explain the water distribution data found. For the C treatment, being all the roots considered to grow in peds or on ped's face, the within-ped RLD was higher, and τ values were lower (1 to 1.5 days). If τ was calculated assuming clustered roots around a cylinder representing the ped, the values were higher, as reported in Table 4.2. Since root length density does not appear in the formulas for this approach, the τ values were not dependent on

Table 4.1 calculated mean half distance between roots (b) and time constant (τ) based on average root length density in each layer.

treatment	CC	C	S	S+LA	S+SA
Soil layer (cm)			RLD (cm3 cm-3)		
0-25	0.56	0.84	1.56	1.20	1.15
25-50	0.40	0.77	1.28	1.02	1.10
50-75	0.02	0.48	1.04	0.75	0.67
75-100	0.00	0.36	0.68	0.39	0.42
			b (cm)*		
0-25	0.76	0.62	0.45	0.51	0.53
25-50	0.90	0.65	0.50	0.56	0.54
50-75	3.85	0.82	0.55	0.65	0.69
75-100	/	0.95	0.68	0.90	0.87
			τ (days) @		
0-25	1.14	0.76	0.41	0.53	0.55
25-50	1.60	0.83	0.50	0.62	0.58
50-75	29.59	1.33	0.61	0.85	0.95
75-100	/	1.79	0.94	1.61	1.51

* Gardner, 1960 mean half distance $b = (\pi * RLD)^{-1/2}$.
@ Passioura, 1980 $\tau = 2b^2 / D$. $D = 1\ cm^2\ day^{-1}$.

Table 4.2. Calculated mean half distance between roots (b) and time constant (τ) based on root length density in the peds only. In treatment C calculations were not made for layers 50-75 and 75-100, where peds were not clearly distinguishable.

treatment	C	S+LA	S+SA
Soil layer (cm)	RLD (cm^3 cm^{-3})		
0-25	0.64	0.33	0.39
25-50	0.43	0.23	0.36
50-75		0.28	0.31
75-100		0.22	0.23
	b (cm) *		
0-25	0.71	0.98	0.91
25-50	0.86	1.18	0.94
50-75		1.07	1.01
75-100		1.20	1.17
	τ (days) @ for uniform roots		
0-25	1.00	1.91	1.64
25-50	1.48	2.77	1.78
50-75		2.30	2.05
75-100		2.89	2.72
	τ (days) @ for clustered roots		
0-25	9.00	16.00	4.00
25-50	9.00	16.00	4.00
50-75		16.00	4.00
75-100		16.00	4.00

* Gardner, 1960 mean half distance $b = (\pi * RLD)^{-1/2}$.
@ Passioura, 1985 $\tau = 2b^2/D$. D is assumed= 1 cm^2 day^{-1}.
% Passioura, 1985 $\tau = B^2/4D$. D is assumed= 1 cm^2 day^{-1}.
and B = half distance between root clusters.

soil depth, since average ped size was about the same in the different layers. A time constant of only 4 days was calculated for the small peds of the S+SA treatment, and of 9 days in the clay-loam, and 16 days in the S+LA. These values are still not large enough to explain the gradients in θ_v found across large peds at the end of the experiment unless we assume that roots started growing into the peds only late in the experiment. In that case roots would have had only little time to extract water from the aggregates. But this is not likely to have been the case at least for the C treatment, in which roots had only clay-loam soil to grow into. The calculated values for τ were obtained assuming that roots could hold their potential differences from the bulk soil for 24 hours per day, which would not be the case for initial (moist) conditions, but is likely to apply if large gradients are found. If a lower number of hour per day were considered (i.e. 12 daylight hours only) the time constant would grow proportionally.

Results of water content modeling for peds with different diffusivity values are reported in Figure 4.2 for a cylinder of radius of 9 cm that approximates a ped of the S+LA treatment. It reports the water content values as function of distance from ped surface for 41 days (the duration of the whole greenhouse experiment). Each curve corresponds to 1 day. Results at 21 days, which corresponded to the interval from severe leaf rolling to total loss of green leaf area in the

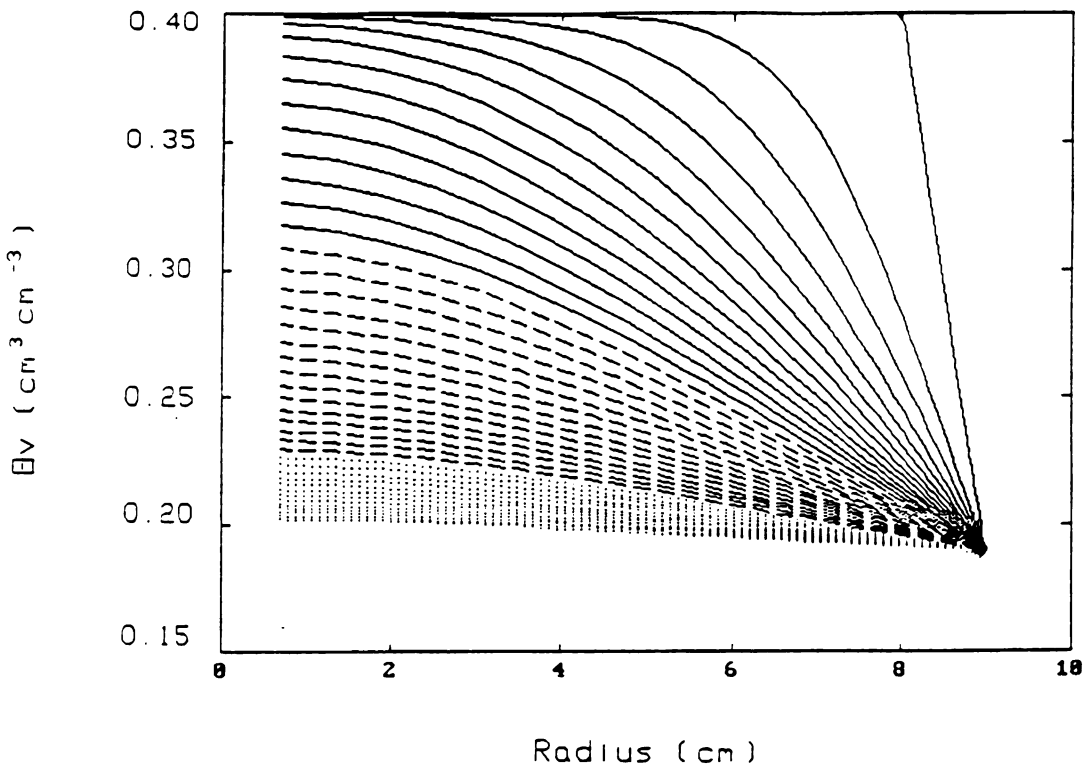

Fig 4.2. Time-course of water content variation as a function of distance from the center of a cylinder of radius=9 cm, with different values of D(θ). Simulations were run for 41 days. a) case i: D=1. Each curve corresponds to one day.

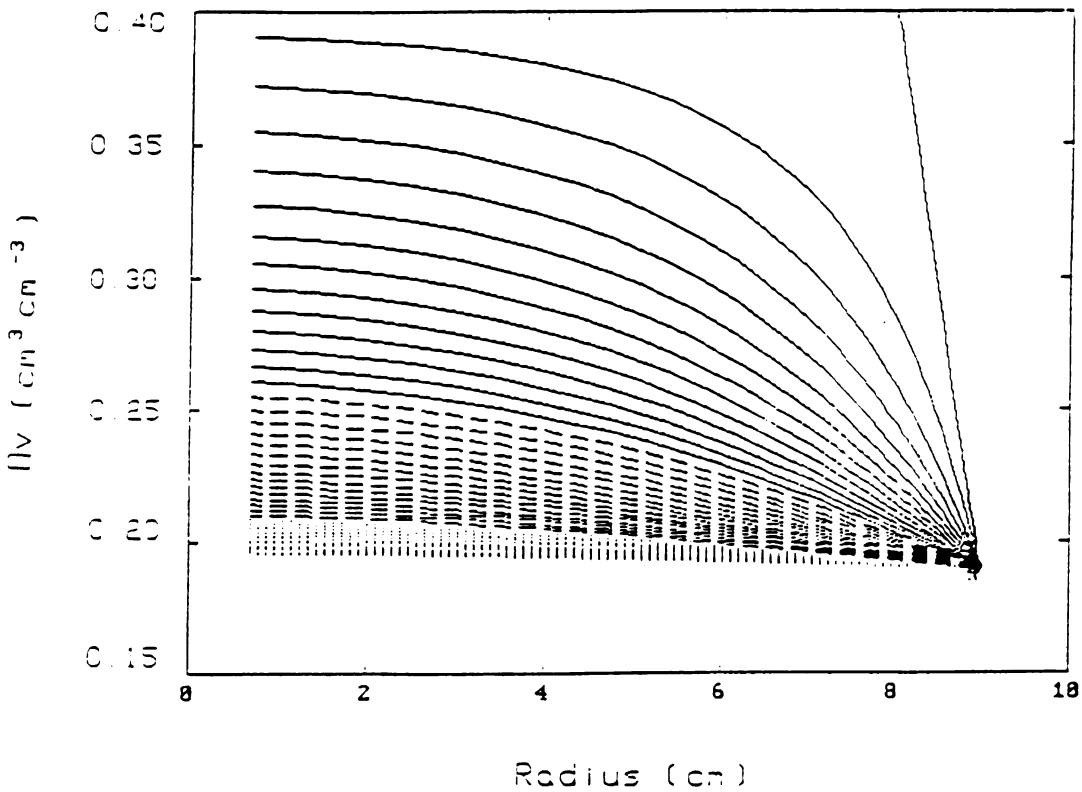

Fig 4.2. Time-course of water content variation as a function of distance from the center of a cylinder of radius=9 cm, with different values of $D(\theta)$. Simulations were run for 41 days. b) case ii: $1<D<10$. Each curve corresponds to one day.

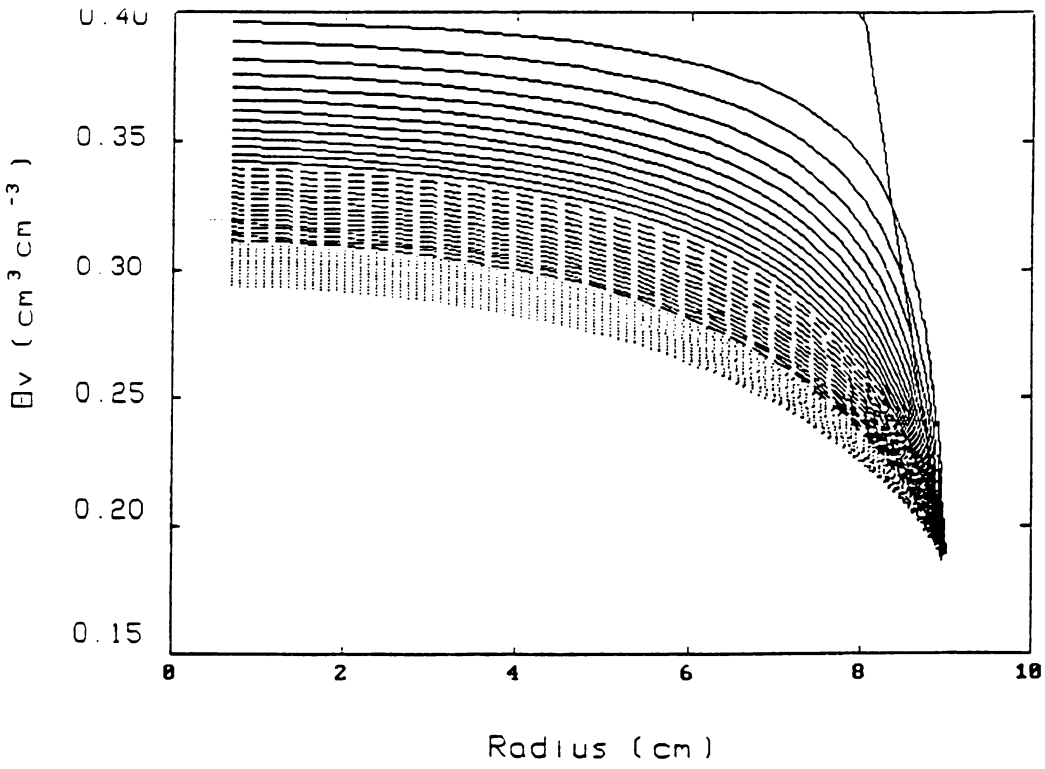

Fig 4.2. Time-course of water content variation as a function of distance from the center of a cylinder of radius=9 cm, with different values of $D(\theta)$. Simulations were run for 41 days. c) case iii: $1*10^{-1}<D<10$. Each curve corresponds to one day.

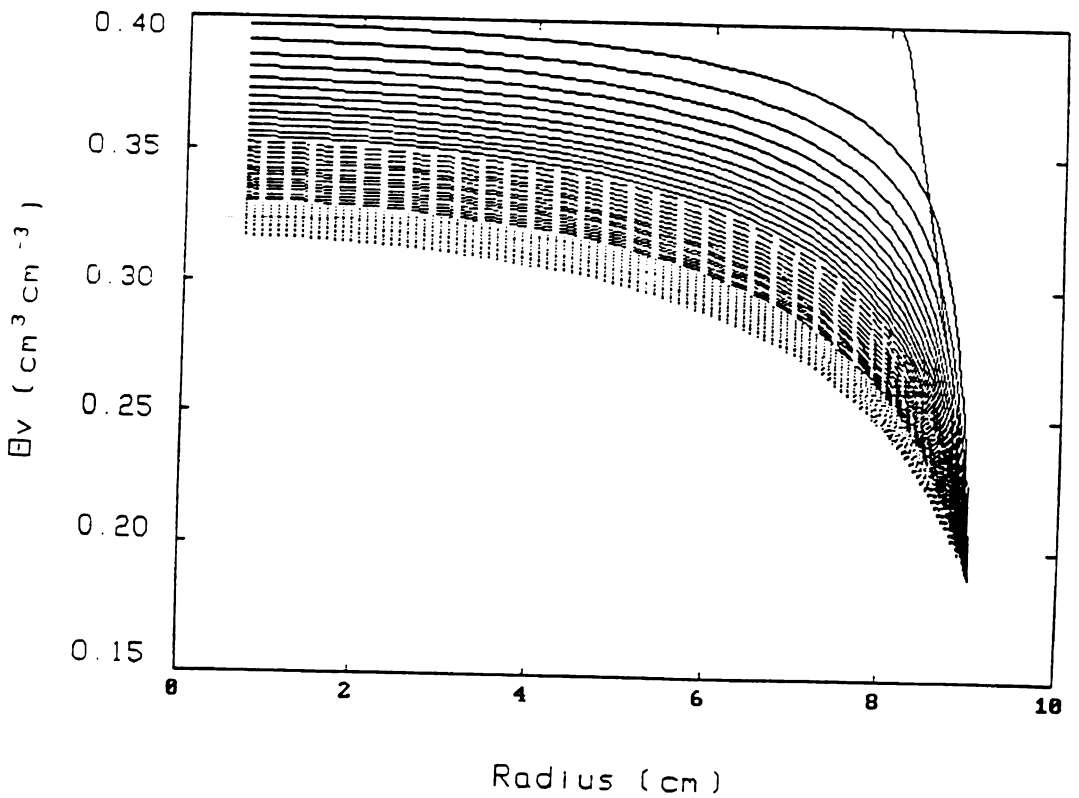

Fig 4.2. Time-course of water content variation as a function of distance from the center of a cylinder of radius=9 cm, with different values of $D(\theta)$. Simulations were run for 41 days. d) case iv: $4.29*10^{-2}<D<10$. Each curve corresponds to one day.

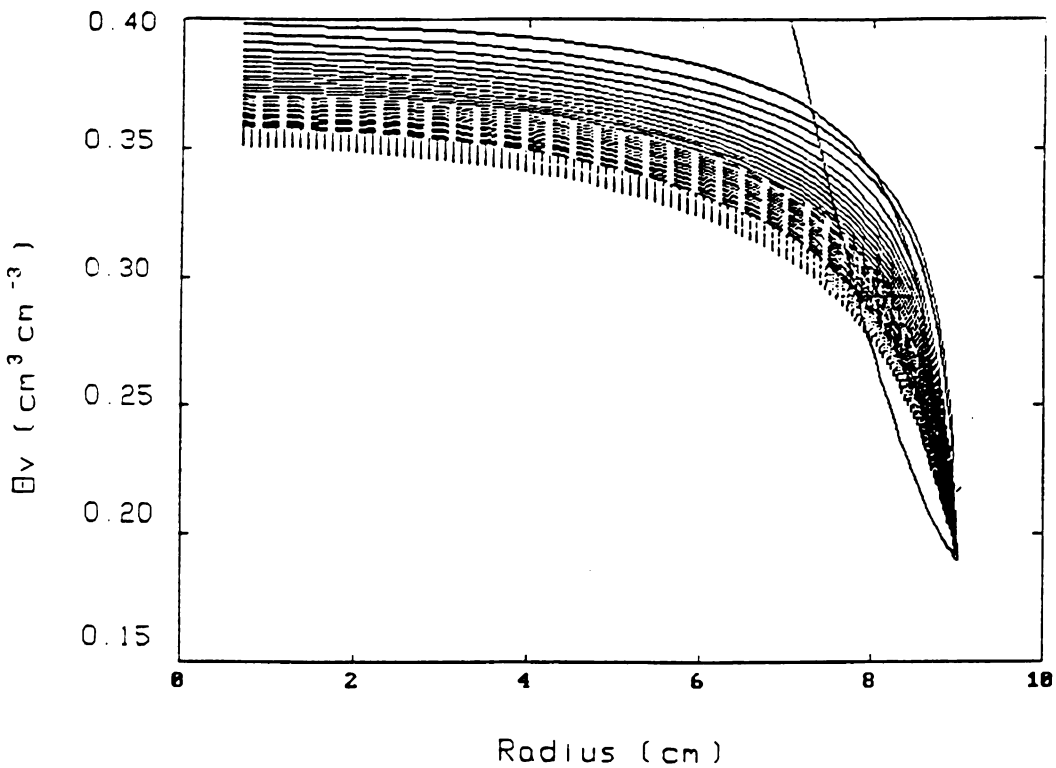

Fig 4.2. Time-course of water content variation as a function of distance from the center of a cylinder of radius=9 cm, with different values of $D(\theta)$. Simulations were run for 41 days. e)case v: $4.29*10^{-3}<D<10$. Each curve corresponds to one day.

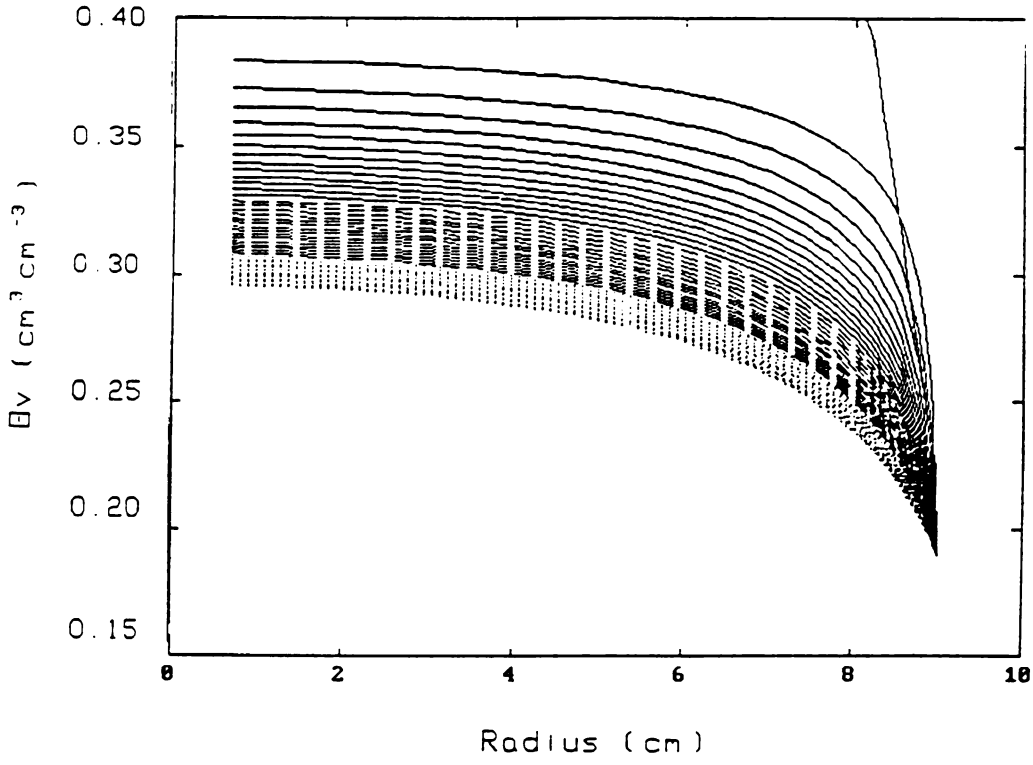

Fig 4.2. Time-course of water content variation as a function of distance from the center of a cylinder of radius=9 cm, with different values of $D(\theta)$. Simulations were run for 41 days. f) case vi: $4.29*10^{-2}<D<50$. Each curve corresponds to one day.

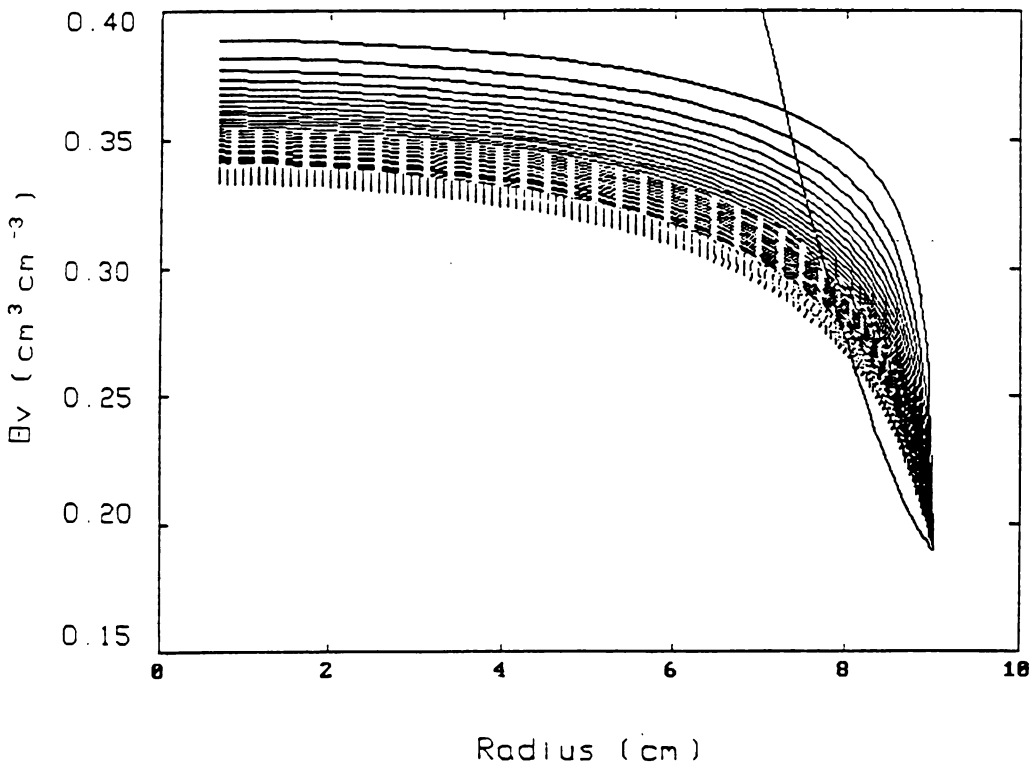

Fig 4.2. Time-course of water content variation as a function of distance from the center of a cylinder of radius=9 cm, with different values of $D(\theta)$. Simulations were run for 41 days. g) case vii: $4.29*10^{-3}<D<50$. Each curve corresponds to one day.

experiment, will be used for comparison with data. With all $D(\theta)$ values depletion was faster in the first few days, and slowed down with time, due to the decrease in D as soil drying proceeded. With a value of D=1 constant (corresponding to the assumptions made for τ calculations above), the final gradient in water content across the cylinder was lower than the experimental results indicated. Water content in the ped after 21 days of extraction was lower both at the surface and in the center. Simulations with different D values showed that water outflow from the center was quite sensitive to D values on the wet end, but a slow change in θ_v at the center of peds could also result from a low D value on the dry end. In the latter case, a steep θ gradient developed in the first few millimeters from the sink, and water content beyond the surface layer was quite uniform at each time. After both 21 and 41 days a considerable amount of water was left in the cylinder using D values of 0.1 cm^2 day^{-1} and below. The $D(\theta)$ relation that better simulated experimental values found was n. iv, that corresponds to D values of $4.29*10^{-2}$ cm^2 day^{-1} at the dry end to 10 cm^2 day^{-1} at the wet end. The same $D(\theta)$ values best reproduced the gradients found in cylinders of 4 and 6 cm in diameter (corresponding to the peds of treatments S+SA and C, respectively). Figure 4.3 reports the simulated values of water content with the above D values after 21 days of extraction along with the experimentally observed gradients. For the C treatment, the assumption that extraction

from peds started on day 20 is less realistic than for the other treatments, because roots in the clay-loam soil were growing in peds from the beginning of the experiment, although the root density and extraction rate in the 25-50 layer (the one used for comparison with simulation) would not have been high from the beginning of the experiment. Also, for treatment C the interval between severe leaf rolling and experiment termination was 14 days, and not 21 as assumed here. The two effects (earlier root proliferation in peds and slower stress development) could partly compensate for each-other.

Values of water diffusivity in the soil found in the literature are quite variable, depending somewhat on the soil type. However, the method of determination of D appears to have a major influence on the results. A wet end diffusivity value of 10 cm^2 day^{-1} is of the order of magnitude reported by Rose (1968) who found values of D at the wet end ranging from 8.4 (clay subsoil)to about 100 cm^2 day^{-1} (sandy clay loam), and by Hanks and Gardner (1965) who report a value of about 40 cm^2 day^{-1} in a silty-clay-loam. On the other hand, a value of $4.29*10^{-2}$ at the dry end is quite low. Rose (1968) reports dry-end values ranging from about $6*10^{-1}$ cm^2 day^{-1} (ignited soil) to about 2 cm^2 day^{-1} (clay). Hanks and Gardner (1965) measured a value of $1*10^{-1}$ cm^2 day^{-1} for a sandy-clay-loam. Gradients of water as a function of distance from a root plane were reported by Dunham and Nye (1973) in a sandy-loam soil, over a 6-day period, but only for soil at quite low initial water

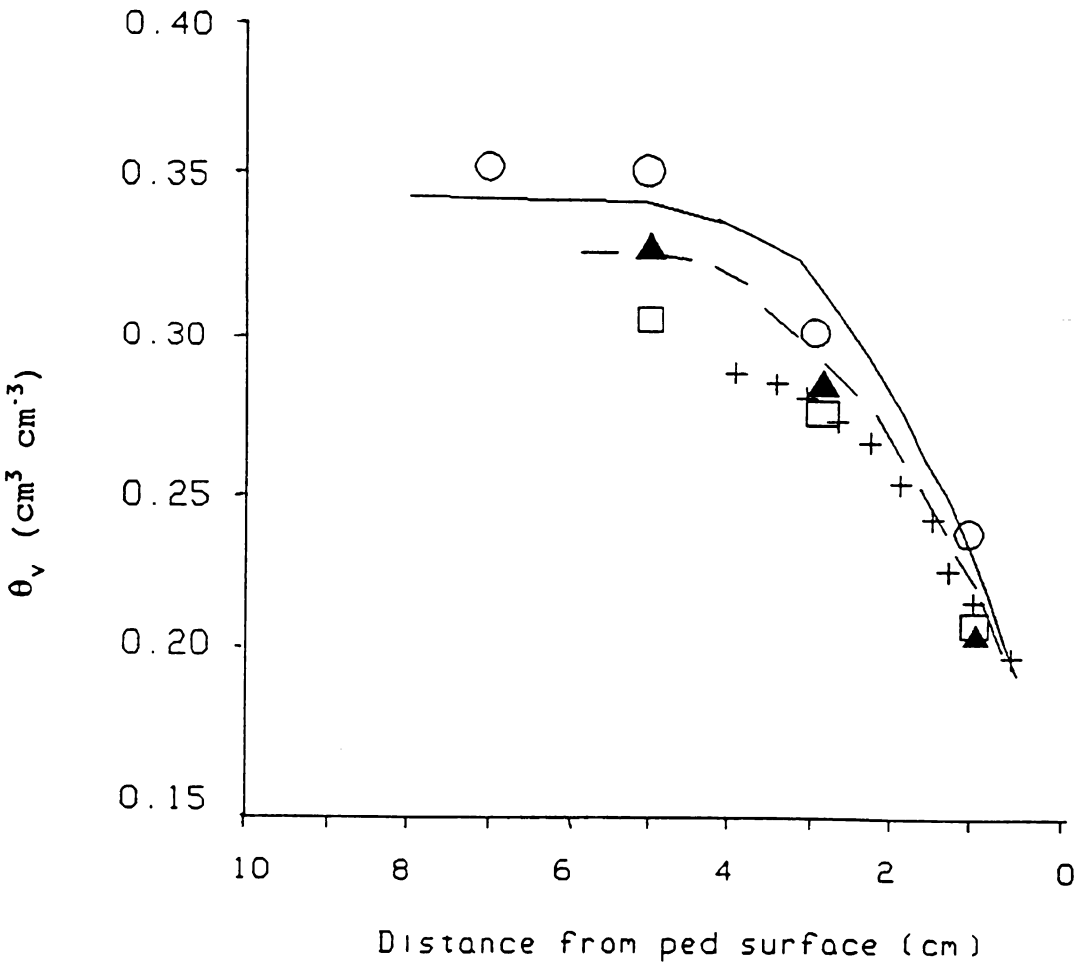

Fig 4.3. TDR-determined water content as a function of distance from peds surface for treatments S+LA (open circles), S+SA (open rectangles), and C (filled triangles), compared with simulated water content along a cylinder radius after 21 days of extraction for cylinders of radius= 9, 4, and 6 cm respectively.

content (0.20 cm^3 cm^{-3}). Diffusivity was not independently measured, but the values calculated from the experiment were as low as $2*10^{-1}$ cm^2 day^{-1} at the dry end. Hsieh et al.(1972) showed that large water gradients can develop between root surface and bulk soil even at quite low bulk soil matric potential (high water content), and over a distance of only 11 mm from the root. Their results can be commented in terms of low diffusivity values, and, although no measurements or calculations were reported, the authors remark that a bed of soil aggregates was used instead of sieved soil, and that would imply a quite low D value.

From the gradients measured in this experiment it can be inferred that the actual soil diffusivity was lower than the one suggested by Passioura (1985) for time-constant calculations. Alternatively, the limited water uptake could be ascribed to a high root resistance as a consequence of direct effects of compaction or hypoxic conditions. This latter factor could be important in the case of the CC soil, in which air filled porosity values would be low. A low diffusivity around roots may be due to localized small-scale soil compaction due to root growth pressure or to microscale discontinuities in peds structure. Root shrinkage in drying soil has been reported by Huck et al. (1970) and Faiz and Weatherley (1982), who argue that the gaps created by reduced root-soil contact would decrease dramatically root water extraction. Herkelrath et al. (1977) developed a model that

included the case of low root-soil contact to explain discrepancies between calculated and measured water uptake rates. Faiz and Weatherley (1982) found that shrinkage could not account for all of the differences in measured and calculated water uptake in an experiment with sunflower. Passioura (1988) argues that shrinkage has not been shown for small roots, and discounts the importance of this factor for reductions in root water uptake.

In summary, for the bottom soil layers of CC a slow water uptake could be predicted from the low RLD, but the unextracted water found in the other cases could not be explained by classical approaches, based on water uptake calculations from half average distance between roots. Results from a clustered root model suggested by Passioura (1985) were closer to what measured, but they could not explain it completely when soil diffusivity was assumed to be equal to 1 cm^2 day^{-1}. Modeling results suggest that diffusivity of water around roots should be quite low to explain the measured gradients in water content across peds. A low diffusivity may be the result of physical soil features like compaction around roots, or root shrinkage.

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CHAPTER 5

MAIZE (ZEA MAYS L.) GROWTH AND WATER UPTAKE IN A VERTIC-USTORTHENTS SOIL. ROOT SPATIAL VARIABILITY AND WATER UPTAKE.

ABSTRACT

In a field experiment three structural situations were studied in a vertic-ustorthents soil: MT (corresponding to minimum tillage), T50 (in which undisturbed peds were surrounded by fragmented soil in the first 50 cm of the profile), and T100 (as in T50, but at 100 cm depth).

Plant growth and development were measured weekly. Vegetative and reproductive biomass were determined at harvest. Soil bulk density, volumetric water content and root length density were determined on four dates. Leaf extension rate (LER) and roots and water spatial distribution were determined in fragmented soil and across peds on two dates during a period without precipitation.

Plant growth and yield varied with soil structure being higher in T100 followed by T50. Leaf appearance rate and tasseling were not affected. Root length density was higher in fragmented soil than in peds and root proliferation into peds increased after colonization of the surrounding fine soil.

Root density within peds was highest in treatment MT, where no fragmented soil was available for root growth.

A higher LER in treatment T100 during soil drying was associated with a higher amount of fragmented soil where most of the water uptake occurred. Access to water was lower in peds scarcely penetrated by roots beyond the 2-cm superficial layer. Mapping of roots and water on two dates showed that spatial distribution was related to soil structure. This was especially noted on the late sampling date. These results suggest new possibilities for simplifications in the modeling of water uptake of clustered root systems.

INTRODUCTION

One of the most studied effects of tillage in fine soils is the improvement of the crop's water relations (Hamblin, 1985). This benefit is often ascribed to the release of mechanical stress that leads to an increase in root density in deep soil layers. Tardieu and Manichon (1987b) argued that low root water uptake in compacted soils can be related to clustering rather than low density of roots. In this case different soil structural situations related to soil tillage should be characterized in terms of their effects on root spatial distribution. Tardieu and Manichon (1987a) reported that 3 types of structure are most commonly found in the soil tilled layer. The first, identified as 'O', is fragmented; the

second, 'B', consists of compacted blocks separated by cavities; the third, 'C', is continuously compacted. In a field study they measured root spatial variability and water uptake for each of the 3 structural situations in loamy soils (Tardieu and Manichon, 1987b and 1987c). Root distribution was found to be clustered and water uptake reduced in the compacted areas for structural types B and C.

In a glasshouse study (Chapter 3) root and water spatial distribution were shown to be closely related to soil structure after roots had withdrawn much of the water from the soil. If this is the case in the field, then it may be possible to predict root clustering and water uptake patterns based on soil structure.

In vertisols the soil structural pattern is determined by tillage and by natural shrinkage and swelling. Both factors can provide a degree of regularity in structural patterns. The distribution of roots and water will also be regular to the extent to which it is affected by structure. In case of a spatially regular pattern of clustering it would be possible to introduce further simplifications in the modeling of water uptake in structured soils. Field studies are necessary to characterize the relations between soil structure and root and water spatial patterns.

A study was conducted on root and water distribution in a swelling soil with three different structural situations. Root growth and water uptake were characterized at the

centimeter scale as a function of soil structure.

MATERIALS AND METHODS

A field experiment was conducted at Guardia Perticara (PZ-Italy) at an elevation of 700 m a.s.l. on a vertic-ustorthents soil in 1989. In order to minimize variability in soil texture an area of 147 m^2 was chosen in which particle size distribution was reasonably uniform. Results from 8 sampling points at 4 depths each are reported in Table 5.1. No spatial trend was apparent from sample results.

Three soil structural situations were created on 49 m^2 plots:

1) **MT**: minimum soil disturbance (corresponding to minimum tillage: soil was tilled at 5 cm to prepare a seedbed). In this treatment the soil was expected to develop the structural status corresponding to its own patterns of cracking upon drying.

2) **T50**: the soil of the whole plot was excavated with a backhoe in two 25-cm layers, and about half of the soil was laid between two plastic sheets and fragmented by pounding. The rest was constituted by peds of average size 24 cm.

The soil layers were put back in place so that large peds were surrounded by loose soil as in the B treatment described by Tardieu and Manichon (1987a) obtained by tillage in wet conditions.

Table 5.1. Soil particle size distribution as a function of soil depth in the experimental field area.

Size class		Sand (2-0.02 mm) %	Silt (0.02-0.002 mm) %	Clay (< 0.002 mm) %
Soil depth (cm)				
0-25	mean	36.5	23.9	39.6
	C.V.	2.7	3.9	3.2
25-50	mean	36.0	24.1	39.9
	C.V.	6.2	5.7	2.4
50-75	mean	37.3	23.9	38.8
	C.V.	4.0	2.7	1.2
75-100	mean	38.0	24.7	37.3
	C.V.	3.2	1.8	2.3

3) **T100:** the soil was prepared as in 2, but up to a depth of 100 cm, in four 25-cm layers. This reduced soil density below normal tillage depth.

The treatments were applied on April 18. They are illustrated in Figure 5.1.

Maize (Zea mays L.) Dekalb Vitrex 200L was sown on July 1, 1989, and thinned at emergence (July 9) to give a population density of 8 plants m^{-2}. Plants were fertilized on July 12 and August 15 with 60 kg N ha_{-1} each time and harvested on November 2, 1989. The temperature and precipitation for the period of the trial are summarized in Figure 5.2.

Non-destructive measurements were made on ten plants per

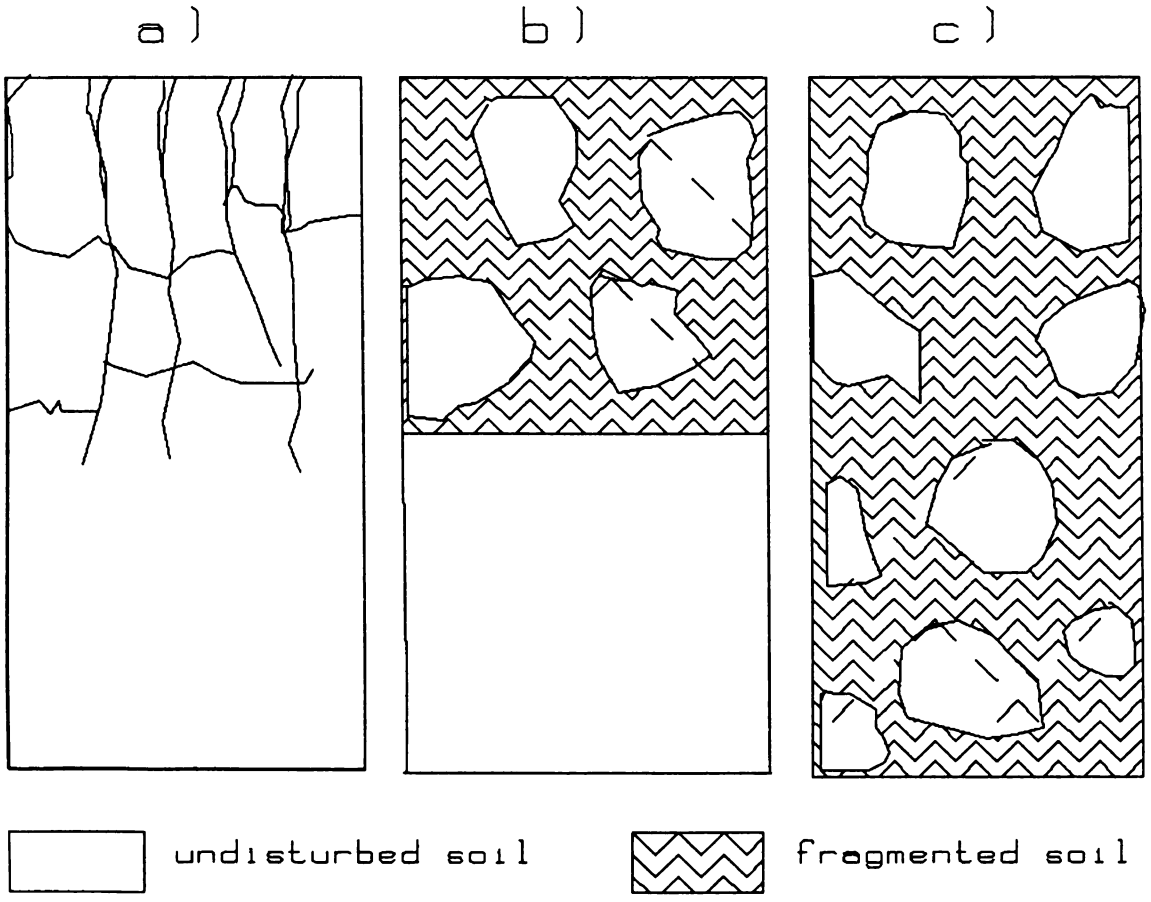

Figure 5.1. Structure of the soil profile for the experimental treatments, up to 100 cm depth. a) MT; b) T50; c) T100.

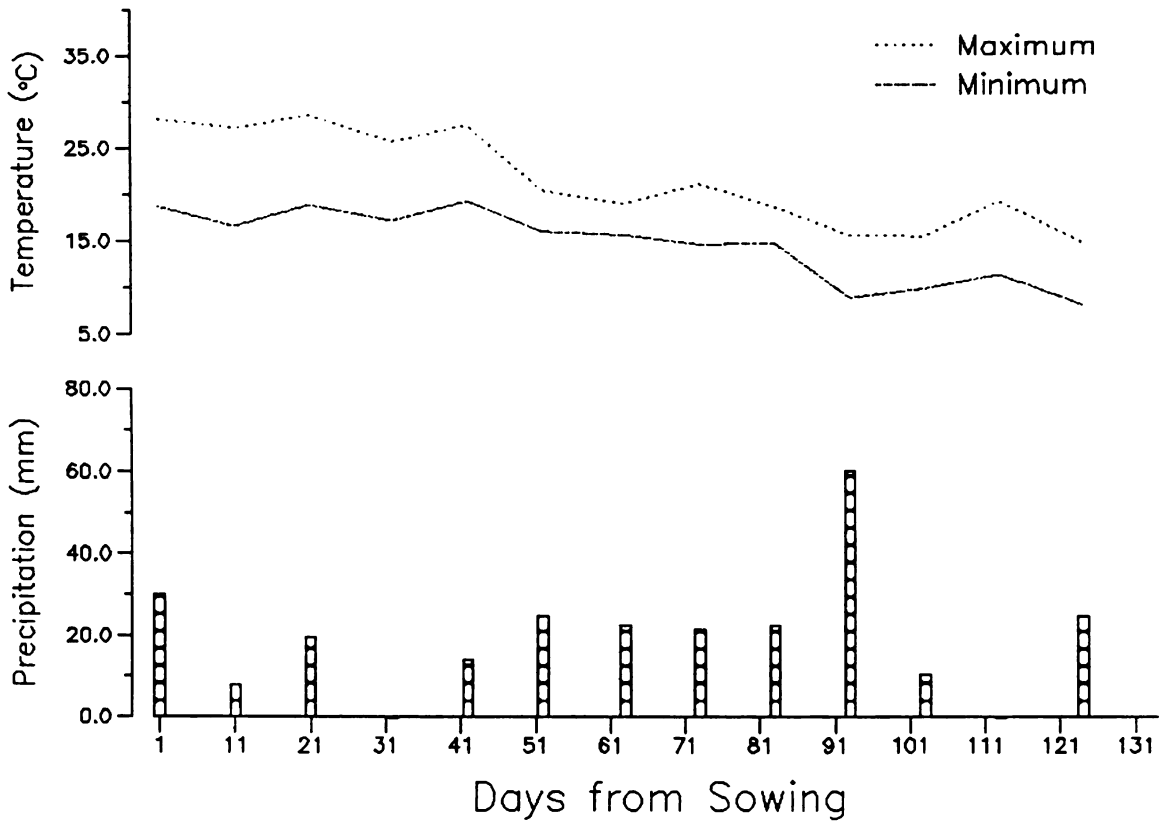

Figure 5.2. Weekly rainfall and minimum and maximum temperature for the crop growing season 1989.

plot. Weekly measurements were made of height to the top ligule, number of fully expanded leaves, and leaf length from tip to ligule. Leaf area was calculated using a relation between area and length presented in a previous paper (Chapter 2). Thermal time from emergence was calculated using a base temperature of 8 °C, according To Ritchie and NeSmith (1991).

After July 28 no precipitation was recorded for 16 days. In order to monitor the effect of water deficit on the plants, leaf extension rates (LER) were measured between July 31 and August 8 on the last three leaves of ten plants per plot.

Ears were harvested on all plants individually and weighed after oven drying at 60 °C. Dry mass of stems and leaves were also determined on all plants at harvest.

Soil sampling was done on large and small scale. Large samples consisted of four 100 cm^3 cores taken in each of the layers: 0-25, 25-50, 50-75 and 75-100 cm. For treatments T50 and T100 samples were taken separately in peds and fragmented soil (two replicates each). There was no fragmented soil in treatment MT; thus samples were taken in undisturbed soil. Water content and bulk density were calculated on the sampled volume after oven-drying at 110 °C. Root length density (RLD) was determined according to Newman (1969). Sampling dates were: July 25, July 31, August 8, and September 8.

Small scale sampling was made on July 31 and August 8 on four 50 x 50 cm horizontal planes for each treatment (at depth of 25, 50, 75, and 95 cm). Soil structural mapping was made

recording the location of cracks, loose soil and peds. On the same planes, before structural mapping notations were made, soil volumetric water content was measured on a 2 by 2 cm grid with time-domain reflectometry (TDR) using 20 mm long probes of the type described in Chapter 1. On the same grid root mapping was also made using the same notation as in Tardieu and Manichon (1986).

Root distribution and water content were also measured on 3 peds per layer in each treatment on the same dates, with the procedure described in Chapter 3 for the greenhouse experiment. The layers were 0-25, 25-50, 50-75, and 75-100 cm from the soil surface.

RESULTS AND DISCUSSION

Plant above-ground growth and development

The time-course of plant height is summarized in Figure 5.3. For all treatments height increased quite slowly in the first 47 days from sowing, and more markedly thereafter. This pattern was probably a result of the low amount of precipitation recorded in the first 5 weeks after emergence (about 29 mm), while in the following 3 week period rainfall was more abundant and regular (60.4 mm). Plants were always highest in treatment T100, followed by T50, and lowest in MT. Final plant height ranged from 133.6 cm in MT to 166 cm in T100. A similar pattern of growth was found in leaf area time-

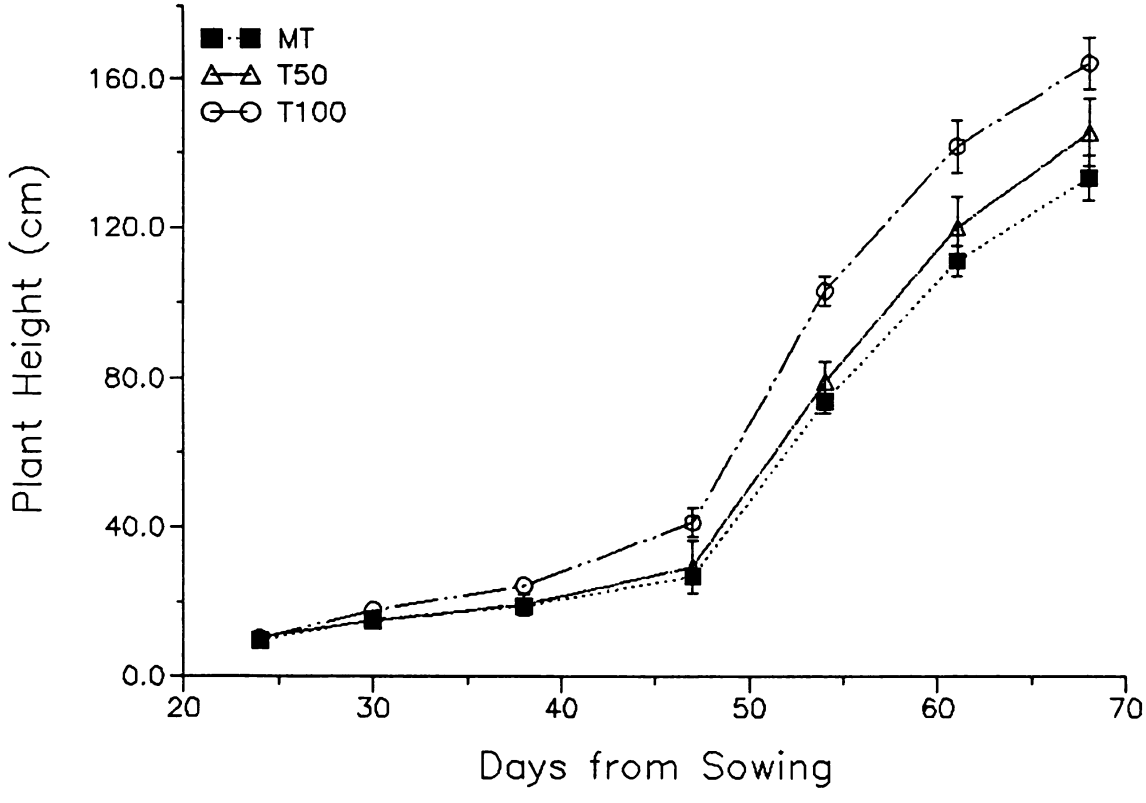

Figure 5.3. Time-course of plant height to the uppermost collar during vegetative growth. Vertical bars represent twice the standard deviation.

course (Figure 5.4) with final values of about 5300 cm^2 per plant measured in the T100 treatment, while T50 and MT plants reached areas of about 3700 and 3400 cm^2 respectively.

The number of fully expanded leaves is plotted in Figure 5.5 against thermal time from emergence. The rate of leaf appearance decreased after the second sampling and was quite low until the fourth sampling, at 47 days from sowing, as reported for plant height and leaf area. An increase in leaf appearance rate was measured when the rainfall amount was higher, between 47 and 68 days from sowing. Ritchie and NeSmith (1991) reported that the relation between the number of leaf primordia or leaf tips and thermal time is linear, but the number of fully expanded leaves increases non-linearly with thermal time. This phenomenon is discussed in relation to the more rapid expansion of the last internodes, and to the observation that the final size of the last leaves is smaller than in the middle section. A nonlinear relation between the number of expanded leaves and thermal time was reported also by Muchow and Carberry (1989) for tropical maize sown at different dates for fully irrigated and water stressed conditions. Treatments in which the crop was stressed during early vegetative growth showed a lower appearance rate than fully irrigated maize, and a higher one after rewatering so that he final number of leaves was the same for all treatments. The periods during and after stress were analyzed separately so that a linear fit could be used to

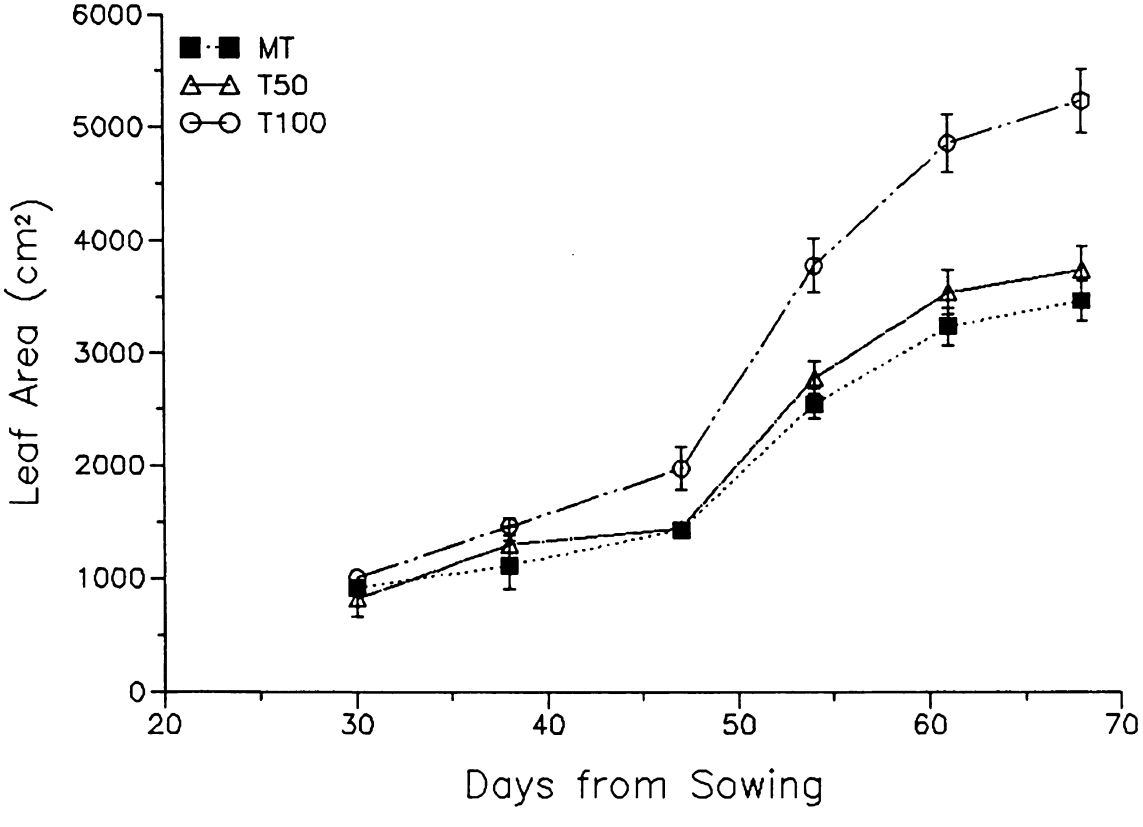

Figure 5.4. Time-course of leaf area per plant during vegetative growth. Vertical bars represent twice the standard deviation.

satisfactorily describe the relation between thermal time and the number of fully expanded leaves. In the present experiment there was little variability in leaf appearance rate between treatments, and the final number of leaves was the same for all structural situations, unlike the other measured plant characters. A linear fit was found to describe adequately the relation between number of leaves and thermal time after emergence for the two separate periods of lower and higher rainfall (respectively before and after the fourth sampling), similarly to what reported by Muchow and Carberry (1989). The linear regression lines and parameters are reported in Figure 5.5. The slope of the line corresponding to the first period is intermediate between the values reported by Muchow and Carberry (1989) for water stressed and fully irrigated, and in the second period it is smaller than both, probably because in our case the second period corresponded to a higher amount of rainfall, but not to full irrigation. Tasseling for 75% of the plants was recorded on September 7 in all treatments.

Based on the presented data, the effect of treatments on development were less important than those on growth.

Leaf extension rate (LER) for the period August 1 to August 8 is reported in Figure 5.6 for all treatments. Leaf extension on August 1 was highest in treatment T100 and lowest in MT. Elongation decreased with time, and the differences between treatments became more evident, especially between T50 and T100. Final LER values of MT and T50 were 54 and 72%

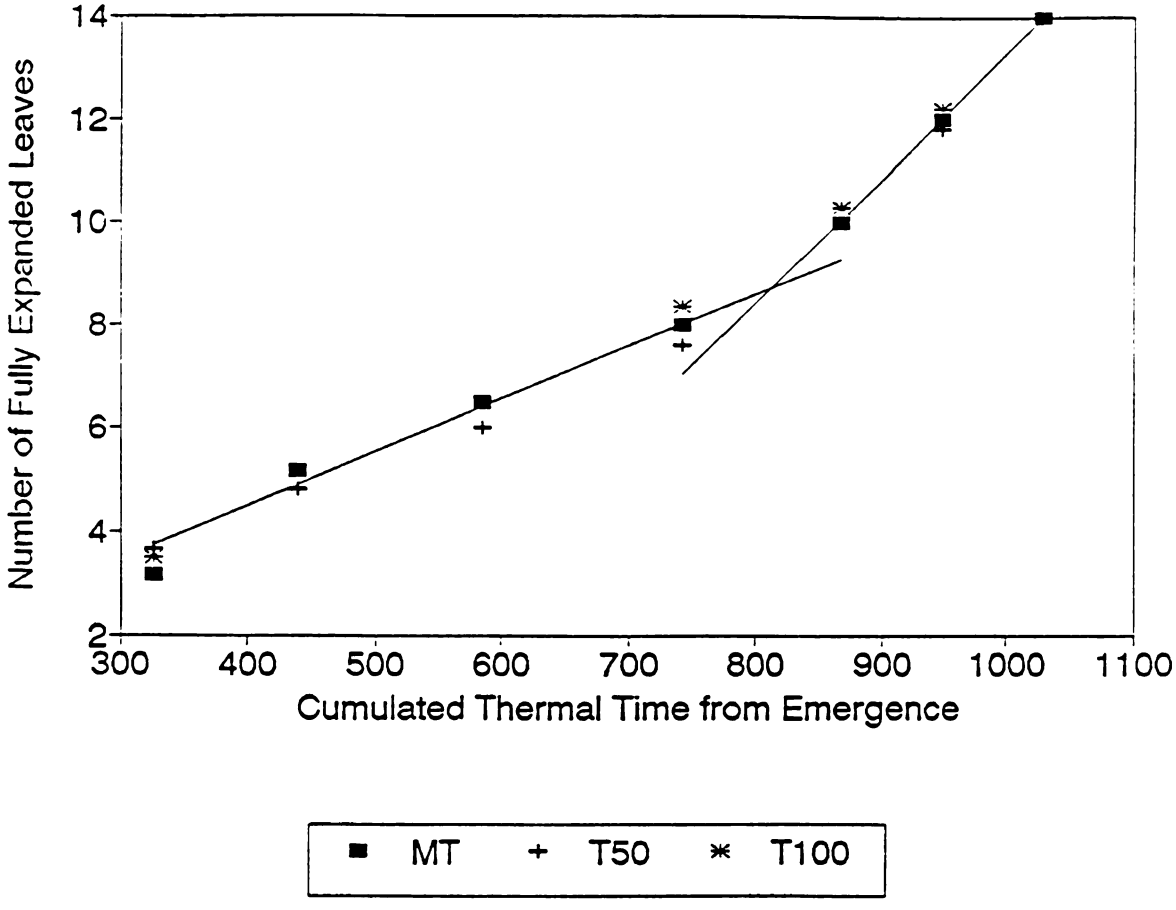

Figure 5.5. Relationship between the number of fully expanded leaves and thermal time from emergence for treatments MT, T50, and T100. Each point is the mean of observations on 10 plants. The fitted line for the period of lower water supply (before the fourth sampling) is $y=0.433+0.0102x$ ($R^2=0.92$). For the period of higher water supply (after the fourth sampling) it is $y=-10.9452+0.0242x$ ($R^2=0.99$).

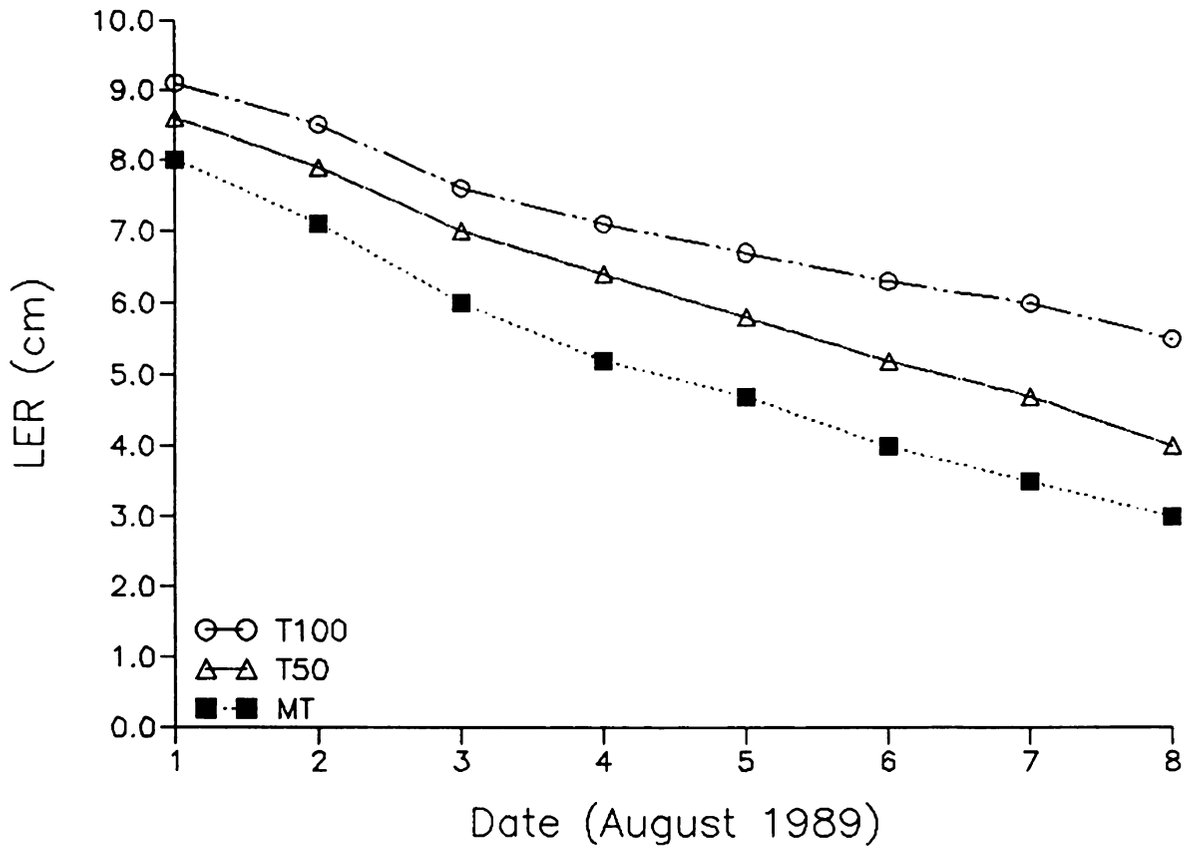

Figure 5.6. Leaf extension rate between August 1 and August 8 in the three experimental treatments.

Table 5.2. Final vegetative and reproductive biomass (g) after oven-drying at 60 °C.

	Stem + leaves	Ears	Grain
	Treatment		
MT	50.5	68.6	51.5
T50	69.6	93.6	74.1
T100	82.2	94.3	75.9

respectively of T100 LER.

Final plant biomass and yield data are summarized in Table 5.2. Average stem and leaf biomass was higher in treatment T100, followed by T50 and MT. Ear weight averaged 68.6 g for MT and between 93.6 and 94.4 g in T50 and T100.

Soil and root

Bulk density values for all treatments are reported in Table 5.3. In all treatments bulk density was higher on August 8, at low soil water content, and lower on September 8 especially in the surface layers, following a rainfall. The values found are similar to those reported for the same soil in 1988 (Comegna et al., 1990). The sampling depths were different in Comegna et al. (1990), where measurements were made after a 8-year tillage experiment. A direct comparison with values found in this experiment would therefore be

Table 5.3. Bulk density (g cm-3) and coefficient of variation (CV, %) From 100 cm^3 cores. a) average per layer.

		Sampling date			
		7/25	7/31	8/8	9/8
Soil layer (cm)					
		Treatment MT			
5-25	mean	1.48	1.48	1.50	1.40
	CV	4.67	2.26	5.34	2.73
25-50	mean	1.55	1.51	1.56	1.42
	CV	3.84	4.67	5.16	5.88
50-75	mean	1.58	1.54	1.58	1.56
	CV	2.84	4.99	2.84	4.67
75-100	mean	1.56	1.58	1.58	1.56
	CV	3.63	5.16	4.26	4.23
		Treatment T50			
5-25	mean	1.36	1.37	1.41	1.44
	CV	13.57	9.82	5.80	5.37
25-50	mean	1.44	1.47	1.52	1.49
	CV	11.38	10.15	8.99	8.01
50-75	mean	1.56	1.56	1.64	1.61
	CV	4.20	3.55	4.20	4.93
75-100	mean	1.58	1.58	1.58	1.57
	CV	2.80	6.93	5.55	3.55
		Treatment T100			
5-25	mean	1.36	1.38	1.38	1.40
	CV	9.95	11.65	9.41	8.22
25-50	mean	1.47	1.48	1.49	1.46
	CV	10.65	9.65	8.41	6.22
50-75	mean	1.47	1.47	1.49	1.51
	CV	6.02	7.90	7.09	9.65
75-100	mean	1.49	1.49	1.48	1.55
	CV	8.17	7.37	5.48	5.09

Table 5.3. Bulk density (g cm-3) and coefficient of variation (CV, %) from 100 cm^3 cores. b) fine soil and peds for treatments T50 and T100.

Soil depth (cm)		Sampling date 7/25 fine soil	7/25 peds	7/31 fine soil	7/31 peds	8/8 fine soil	8/8 peds
				Treatment T50			
5-25	mean	1.21	1.52	1.26	1.48	1.35	1.47
	CV	2.55	4.93	4.93	2.55	4.20	3.55
25-50	mean	1.31	1.58	1.35	1.59	1.43	1.61
	CV	4.93	3.52	3.52	4.93	6.93	6.93
				Treatment T100			
5-25	mean	1.25	1.48	1.24	1.51	1.27	1.48
	CV	2.55	2.55	3.55	4.93	3.55	4.20
25-50	mean	1.35	1.60	1.37	1.59	1.40	1.58
	CV	4.93	4.93	6.93	3.52	2.55	6.93
50-75	mean	1.41	1.53	1.38	1.57	1.42	1.57
	CV	4.93	3.55	4.20	4.3	4.93	4.93
75-100	mean	1.41	1.58	1.41	1.58	1.42	1.54
	CV	3.52	6.93	5.55	2.80	3.55	3.55

incorrect, but it can be pointed out that a higher value of BD was measured in this experiment for the MT treatment compared to the disturbed treatments in the surface layer, while Comegna et al. (1990) reported a lower value in the 10-20 cm treatment of a minimum tillage plot compared to tilled treatments. This was attributed to the effects of tillage on biological activity, a long term effect that would not be likely to produce measurable differences in the time-frame of the present experiment.

Regarding treatment effect in all soil layers, soil bulk density was lower in the plots where the soil had been disturbed but its distribution was bimodal with higher values corresponding to peds and lower to fragmented soil. In a previous paper (Chapter 3) values of bulk density were compared with root growth limiting values calculated according to Jones et al.(1991) and the meaning of such values was discussed. Values from the present study are intermediate between non-limiting and totally-inhibiting bulk density according to Jones et al. (1991), based on the soil sand percent by weight. This suggests that some reduction in root growth should be a result of bulk density in this experiment. Values found in the surface layer for T50 and T100 on the first two dates are lower than the non-limiting bulk density, indicating that no effect of soil compaction on root growth was to be expected in these cases. Bulk density values in this experiment, though, correspond to a range of soil water

contents, as reported below, while calculations proposed by Jones et al. (1991) were developed for soil at field capacity. Other limitations of this approach are discussed in chapter 3.

Table 5.4 reports the values of volumetric water content as a function of soil depth in all treatments. On all dates θ_v was higher in the undisturbed soil and the variations in water content were lower for this treatment. Water content distribution was bimodal in the other plots, where less extraction was measured from peds compared to fragmented soil. This observation agrees with what reported by Tardieu and Manichon (1987c), who measured lower water uptake from compacted soil regions in loamy soils with a 'B' structural type, which compares to the structure of the T50 and T100 treatments.

The RLD (Table 5.5) varied between treatments in amount and distribution along the profile. In treatment MT it ranged from about 0.8 to about 1.4 cm cm^{-3} on different dates in the top 25 cm, and decreased dramatically with depth. In T50 the distribution was similar to that found in MT 25 days after sowing, but subsequently it was higher up to 50 cm, corresponding to the disturbed soil layers. In T100 the decrease of root density with depth was less pronounced and the final total RLD was higher than in the other treatments. As described in chapter 3, if root density values were disaggregated into peds and fragmented soil the distribution appeared bimodal with higher values in the fine soil and lower

Table 5.4. Volumetric water content (cm^3 cm^{-3}) on 100 cm^3 cores.a) average per layer. sd= standard deviation.

Soil depth (cm)		Sampling date 7/25	7/31	8/8	9/8
		treatment MT			
5-25	mean	0.285	0.278	0.259	0.266
	sd	0.023	0.015	0.012	0.025
25-50	mean	0.330	0.325	0.320	0.280
	sd	0.025	0.026	0.018	0.026
50-75	mean	0.358	0.354	0.352	0.341
	sd	0.028	0.027	0.018	0.019
75-100	mean	0.378	0.376	0.367	0.349
	sd	0.023	0.019	0.029	0.018
		Treatment T50			
5-25	mean	0.285	0.263	0.244	0.273
	sd	0.079	0.105	0.119	0.077
25-50	mean	0.295	0.290	0.283	0.260
	sd	0.106	0.091	0.088	0.071
50-75	mean	0.341	0.337	0.286	0.290
	sd	0.021	0.019	0.015	0.023
75-100	mean	0.365	0.365	0.360	0.350
	sd	0.017	0.019	0.029	0.026
		Treatment T100			
5-25	mean	0.235	0.266	0.247	0.287
	sd	0.114	0.093	0.108	0.053
25-50	mean	0.294	0.293	0.287	0.256
	sd	0.100	0.099	0.088	0.069
50-75	mean	0.320	0.315	0.256	0.262
	sd	0.085	0.088	0.123	0.064
75-100	mean	0.371	0.368	0.304	0.267
	sd	0.016	0.043	0.059	0.075

Table 5.4. Volumetric water content ($cm^3\ cm^{-3}$) on 100 cm^3 cores b) fine soil and peds for treatments T50 and T100. sd=standard deviation.

Soil depth (cm)		Sampling date 7/25 fine soil	7/25 peds	7/31 fine soil	7/31 peds	8/8 fine soil	8/8 peds
				Treatment T50			
5-25	mean	0.229	0.341	0.189	0.337	0.160	0.328
	sd	0.020	0.019	0.020	0.019	0.022	0.021
25-50	mean	0.220	0.370	0.226	0.354	0.221	0.345
	sd	0.021	0.014	0.021	0.014	0.024	0.016
				Treatment T100			
5-25	mean	0.186	0.347	0.200	0.332	0.171	0.324
	sd	0.020	0.019	0.019	0.018	0.020	0.019
25-50	mean	0.223	0.365	0.223	0.363	0.225	0.349
	sd	0.017	0.016	0.016	0.015	0.017	0.016
50-75	mean	0.260	0.380	0.253	0.377	0.169	0.343
	sd	0.023	0.026	0.022	0.025	0.023	0.026
75-100	mean	0.360	0.382	0.356	0.380	0.262	0.346
	sd	0.024	0.028	0.023	0.027	0.024	0.028

Table 5.5. Root length density (cm cm^{-3}) and coefficient of variation (CV, %) on 100 cm^3 cores.a) average per layer.

Soil depth (cm)		Sampling date 7/25	7/31	8/8	9/8
		treatment MT			
5-25	mean	0.68	0.78	0.85	1.37
	CV	45.50	43.00	58.05	55.80
25-50	mean	0.20	0.23	0.36	0.68
	CV	35.20	37.60	70.20	60.76
50-75	mean	0.08	0.12	0.15	0.20
	CV	41.20	43.20	87.75	75.64
75-100	mean	0.00	0.07	0.07	0.08
	CV	/	68.00	65.40	67.10
		Treatment T50			
5-25	mean	0.70	0.76	0.81	1.38
	CV	55.35	52.89	63.86	59.71
25-50	mean	0.30	0.50	0.71	1.21
	CV	60.27	63.96	77.22	65.01
50-75	mean	0.08	0.17	0.22	0.29
	CV	57.34	62.40	76.50	73.20
75-100	mean	0.01	0.06	0.06	0.12
	CV	65.10	61.88	67.40	73.81
		Treatment T100			
5-25	mean	0.67	0.87	1.00	1.60
	CV	57.56	55.01	62.58	61.50
25-50	mean	0.36	0.50	0.75	0.99
	CV	59.06	66.52	79.54	63.71
50-75	mean	0.15	0.20	0.45	0.65
	CV	59.06	25.40	73.98	70.78
75-100	mean	0.02	0.08	0.10	0.30
	CV	64.97	71.39	65.00	68.00

Table 5.5. Root length density (cm cm^{-3}) on 100 cm^3 cores.b) fine soil and peds for treatments T50 and T100.

Soil depth (cm)		Sampling date 7/25 fine soil	7/25 peds	7/31 fine soil	7/31 peds	8/8 fine soil	8/8 peds
				Treatment T50			
5-25	mean	1.25	0.04	1.42	0.07	1.37	0.13
	CV	26.87	23.00	24.80	19.00	31.00	22.00
25-50	mean	0.54	0.01	0.93	0.03	1.27	0.07
	CV	22.17	17.00	28.83	24.00	28.40	23.40
				Treatment T100			
5-25	mean	1.25	0.10	1.60	0.08	1.51	0.18
	CV	26.33	22.54	25.80	19.76	30.38	22.66
25-50	mean	0.66	0.00	0.88	0.02	1.28	0.11
	CV	22.83	/	29.98	24.96	29.25	22.63
50-75	mean	0.28	0.03	0.32	0.00	0.82	0.07
	CV	28.67	24.54	30.43	/	35.91	25.49
75-100	mean	0.04	0.00	0.13	0.00	0.17	0.03
	CV	25.11	/	32.17	/	23.91	18.49

in the peds. The time-course of root distribution shows that the percentage of roots found in peds increased with time. Thus root proliferation in peds increased after colonization in the less compacted areas. Root distribution in and around peds on July 31 and August 8 is summarized in Tables 5.6 to 5.8 for all treatments. As reported for large scale sampling, RLD was higher outside peds. Values of RLD in peds increased remarkably between the first and second sampling date, especially in deep soil. Data show that root penetration beyond the ped's superficial layer was only occasional, as reported in chapter 3 for a greenhouse study with the same soil. Values of root density in peds were higher in MT (Table 5.6) than in other treatments (Tables 5.7 and 5.8). As for the greenhouse study in chapter 3, this is interpreted in terms of compensatory growth: since no fragmented soil was available in treatment MT for roots to grow, proliferation inside peds was higher. However roots did not generally penetrate peds in MT beyond the superficial 2-cm layer and in fact a large part of the roots were at the ped surface.

Water content distribution across peds is summarized in Tables 5.6 to 5.8. On July 31 in all treatments peds in the superficial 50 cm showed a gradient in water content between the surface and the center. This indicates that water was being extracted from peds. The peds surface layer had a lower water content in treatment MT, probably in relation to the higher root density around peds, that constituted a stronger

Table 5.6. Root length density and volumetric water content across peds in treatment MT on two dates. sd=standard deviation.

		ped layer (cm)		
		0-2	2-4	4-6
		7/31		
RLD (cm cm^{-3})				
0-25	mean	1.20	0.00	0.00
	sd	0.22	0.00	0.00
25-50	mean	0.35	0.00	0.00
	sd	0.06	0.00	0.00
θ (cm^3 cm^{-3})				
0-25	mean	0.281	0.352	0.372
	sd	0.026	0.018	0.019
25-50	mean	0.309	0.360	0.375
	sd	0.023	0.017	0.012
		8/8		
RLD (cm cm^{-3})				
0-25	mean	1.23	0.10	0.00
	sd	0.25	0.17	0.00
25-50	mean	0.52	0.00	0.00
	sd	0.30	0.00	0.00
θ (cm^3 cm^{-3})				
0-25	mean	0.280	0.333	0.339
	sd	0.023	0.017	0.021
25-50	mean	0.280	0.347	0.369
	sd	0.019	0.014	0.020

Table 5.7. Root length density and volumetric water content in fragmented soil and across peds in treatment T50 on two dates. sd=standard deviation.

		bulk soil	ped layer (cm)				
			7/31				
RLD (cm cm^{-3})			0-2	2-4	4-6	6-8	8-10
0-25	mean	1.35	0.23	0.00	0.08	0.00	0.00
	sd	0.30	0.10	0.00	0.07	0.00	0.00
25-50	mean	0.87	0.10	0.00	0.00	0.00	0.00
	sd	0.16	0.05	0.00	0.00	0.00	0.00
θ (cm^3 cm^{-3})							
0-25	mean	0.200	0.286	0.342	0.364	0.370	0.375
	sd	0.013	0.016	0.016	0.018	0.021	0.022
25-50	mean	0.241	0.306	0.364	0.379	0.380	0.386
	sd	0.002	0.025	0.020	0.015	0.024	0.023
			8/8				
RLD (cm cm^{-3})							
0-25	mean	1.40	0.44	0.00	0.00	0.00	0.00
	sd	0.20	0.03	0.00	0.00	0.00	0.00
25-50	mean	1.15	0.24	0.04	0.00	0.00	0.00
	sd	0.13	0.02	0.06	0.00	0.00	0.00
θ (cm^3 cm^{-3})							
0-25	mean	0.172	0.280	0.337	0.350	0.360	0.365
	sd	0.013	0.024	0.021	0.016	0.019	0.019
25-50	mean	0.231	0.299	0.359	0.364	0.367	0.376
	sd	0.015	0.021	0.020	0.014	0.015	0.020

sink. Peds below 50 cm in the T100 treatment had a quite uniform water content, this suggesting that no appreciable extraction had occurred. The difference in θ_v values between peds and outer soil are due in part to the different soil densities. This implies different relations between water content and potential, and in part to some water uptake from roots in the bulk soil. On August 8 water gradients across peds were also found in the lower layers of treatment T100, indicating that uptake was taking place in those layers also. The largest variations in water content were recorded in the fragmented soil rather than in peds, indicating that despite root proliferation in the ped's superficial layer, most of the water uptake was still occurring in the fragmented soil. An exception was treatment MT, in whose peds larger variations in water content were measured. This can be explained with the larger root density and with the smaller size of peds, that implies a faster depletion by a diffused sink at the surface (Crank, 1975, Passioura, 1985).

Figures 5.7 to 5.12 report mapping of structure, roots, and water at 25 cm from the soil surface in the three treatments, on July 31 and August 8. Since the mapping technique was destructive, different planes were sampled on the two dates. Structural maps for treatment MT show that cracking had occurred creating structural units of about 12 cm. Cracking was quite regular. In treatment T50 and T100 peds were clearly distinguishable from fragmented soil, and in a

Table 5.8. Root length density and volumetric water content in fragmented soil and across peds in treatment T100 on two dates. sd=standard deviation.

		bulk soil	ped layer (cm)					
		7/31						
			0-2	2-4	4-6	6-8	8-10	10-12
RLD (cm cm^{-3})								
0-25	mean	1.44	0.26	0.00	0.00	0.00	0.00	0.00
	sd	0.30	0.01	0.00	0.00	0.00	0.00	0.00
25-50	mean	0.80	0.07	0.00	0.00	0.00	0.00	0.00
	sd	0.23	0.04	0.00	0.00	0.00	0.00	0.00
50-75	mean	0.30	0.00	0.04	0.00	0.00	0.00	0.00
	sd	0.10	0.00	0.06	0.00	0.00	0.00	0.00
75-100	mean	0.08	0.00	0.00	0.00	0.00	0.00	0.00
	sd	0.05	0.00	0.00	0.00	0.00	0.00	0.00
Ov (cm^3 cm^{-3})								
0-25	mean	0.377	0.290	0.340	0.353	0.370	0.380	0.385
	sd	0.020	0.023	0.017	0.020	0.017	0.018	0.024
25-50	mean	0.248	0.335	0.377	0.385	0.390	0.388	0.388
	sd	0.016	0.025	0.020	0.020	0.021	0.023	0.024
50-75	mean	0.290	0.374	0.375	0.380	0.381	0.382	0.383
	sd	0.023	0.012	0.015	0.019	0.023	0.016	0.019
75-100	mean	0.350	0.376	0.381	0.384	0.383	0.378	0.382
	sd	0.025	0.012	0.015	0.016	0.019	0.021	0.018
		8/8						
RLD (cm cm^{-3})								
0-25	mean	1.55	0.59	0.00	0.00	0.00	0.00	0.00
	sd	0.25	0.02	0.00	0.00	0.00	0.00	0.00
25-50	mean	1.26	0.36	0.09	0.00	0.00	0.00	0.00
	sd	0.20	0.03	0.00	0.00	0.00	0.00	0.00
50-75	mean	0.60	0.23	0.00	0.00	0.00	0.00	0.00
	sd	0.12	0.03	0.00	0.00	0.00	0.00	0.00
75-100	mean	0.13	0.10	0.00	0.00	0.00	0.00	0.00
	sd	0.08	0.05	0.00	0.00	0.00	0.00	0.00
Ov (cm^3 cm^{-3})								
0-25	mean	0.172	0.272	0.335	0.339	.360	0.370	0.374
	sd	0.015	0.020	0.022	0.014	0.015	0.019	0.002
25-50	mean	0.231	0.310	0.353	0.369	0.378	0.377	0.377
	sd	0.013	0.021	0.025	0.014	0.017	0.018	0.020
50-75	mean	0.246	0.290	0.365	0.364	0.369	0.371	0.372
	sd	0.025	0.024	0.014	0.014	0.024	0.022	0.017
75-100	mean	0.300	0.320	0.371	0.368	0.371	0.371	0.373
	sd	0.023	0.023	0.021	0.018	0.018	0.019	0.023

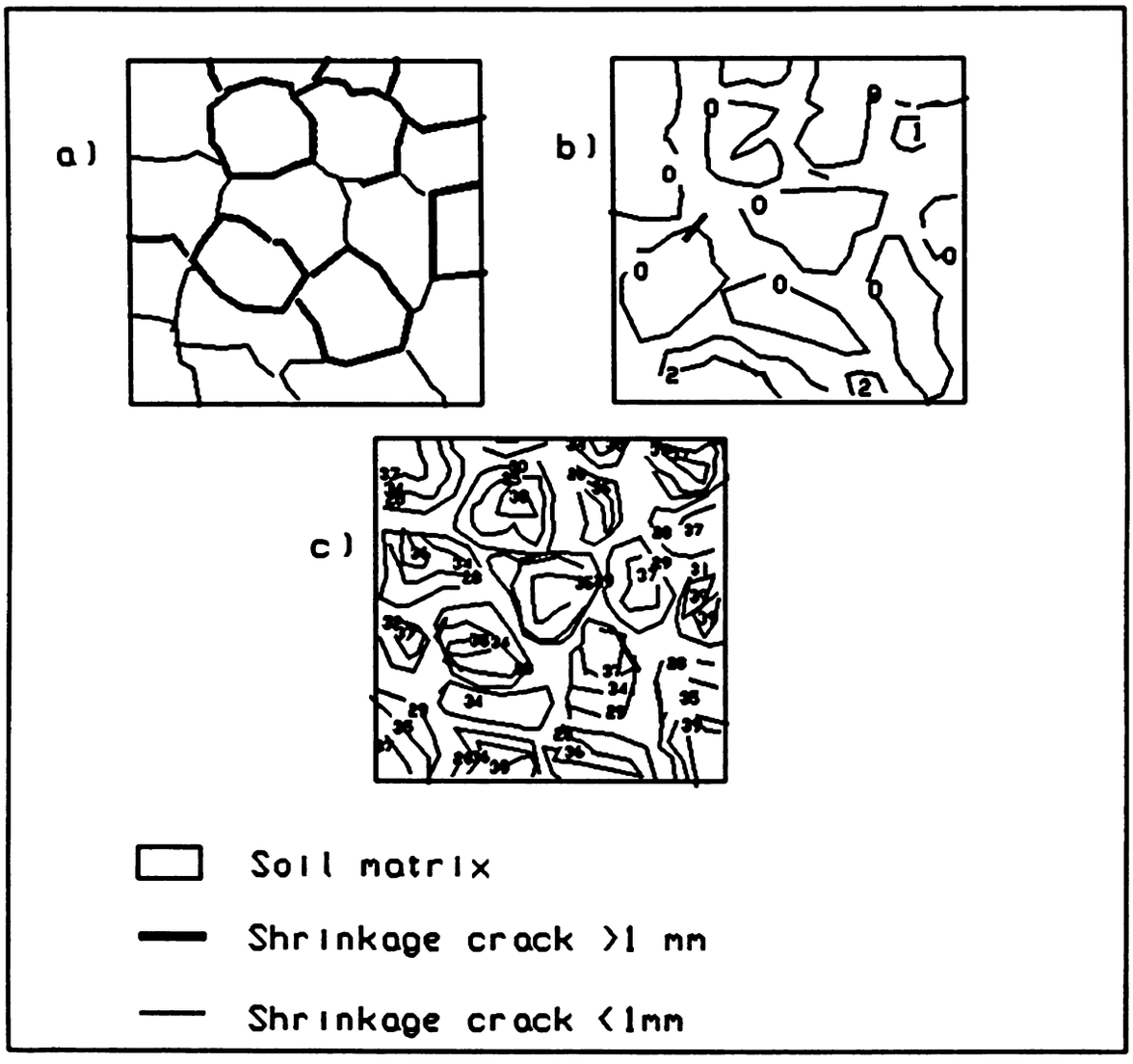

Figure 5.7. Mapping of structure, roots and water at 25 cm from soil surface for treatment MT on July 31. a) structural mapping; b) root density; c) TDR-determined volumetric water content.

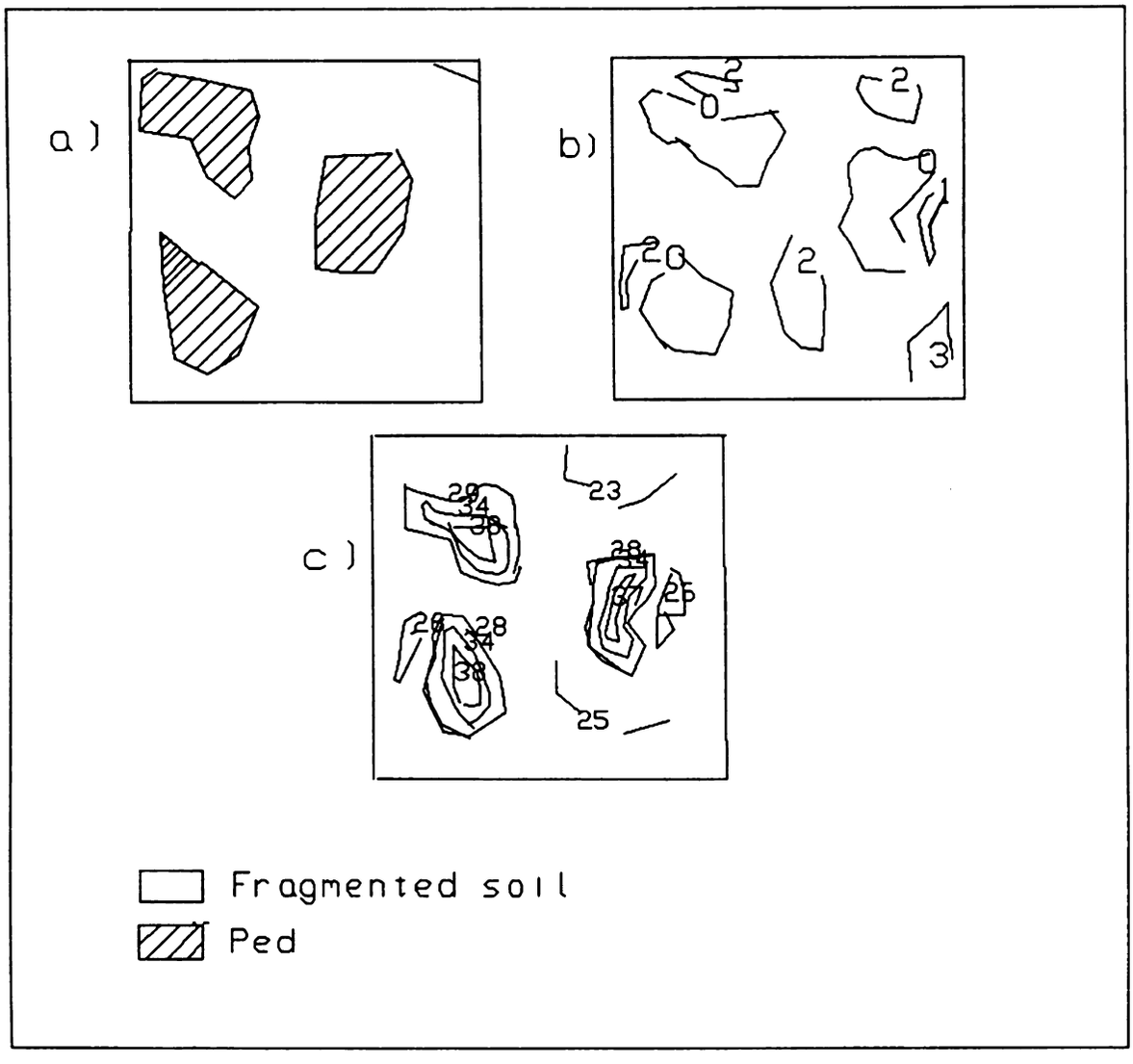

Figure 5.8. Mapping of structure, roots and water at 25 cm from soil surface for treatment T50 on July 31. a) structural mapping; b) root density; c) TDR-determined volumetric water content.

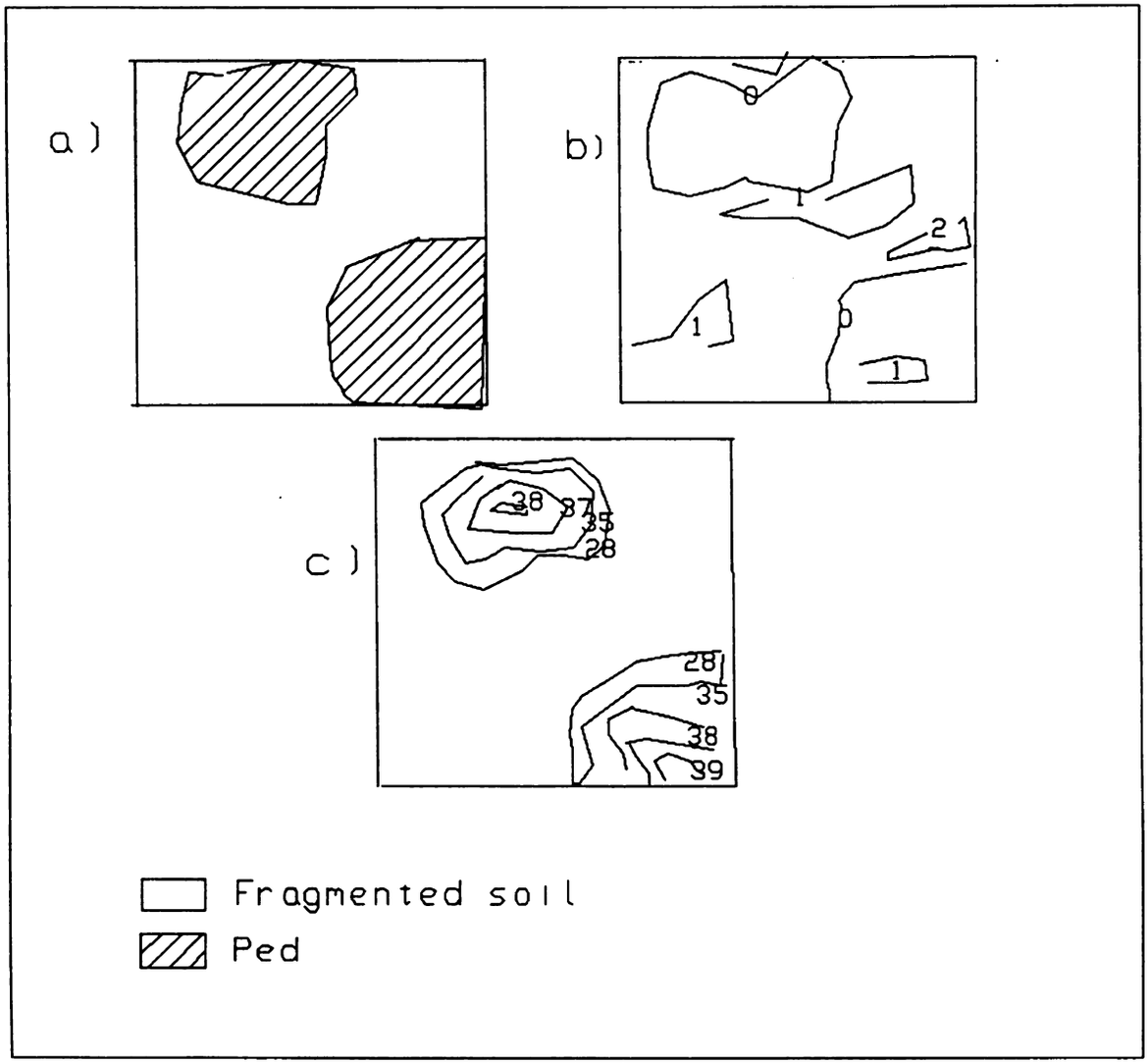

Figure 5.9. Mapping of structure, roots and water at 25 cm from soil surface for treatment T100. on July 31. a) structural mapping; b) root density; c) TDR-determined volumetric water content.

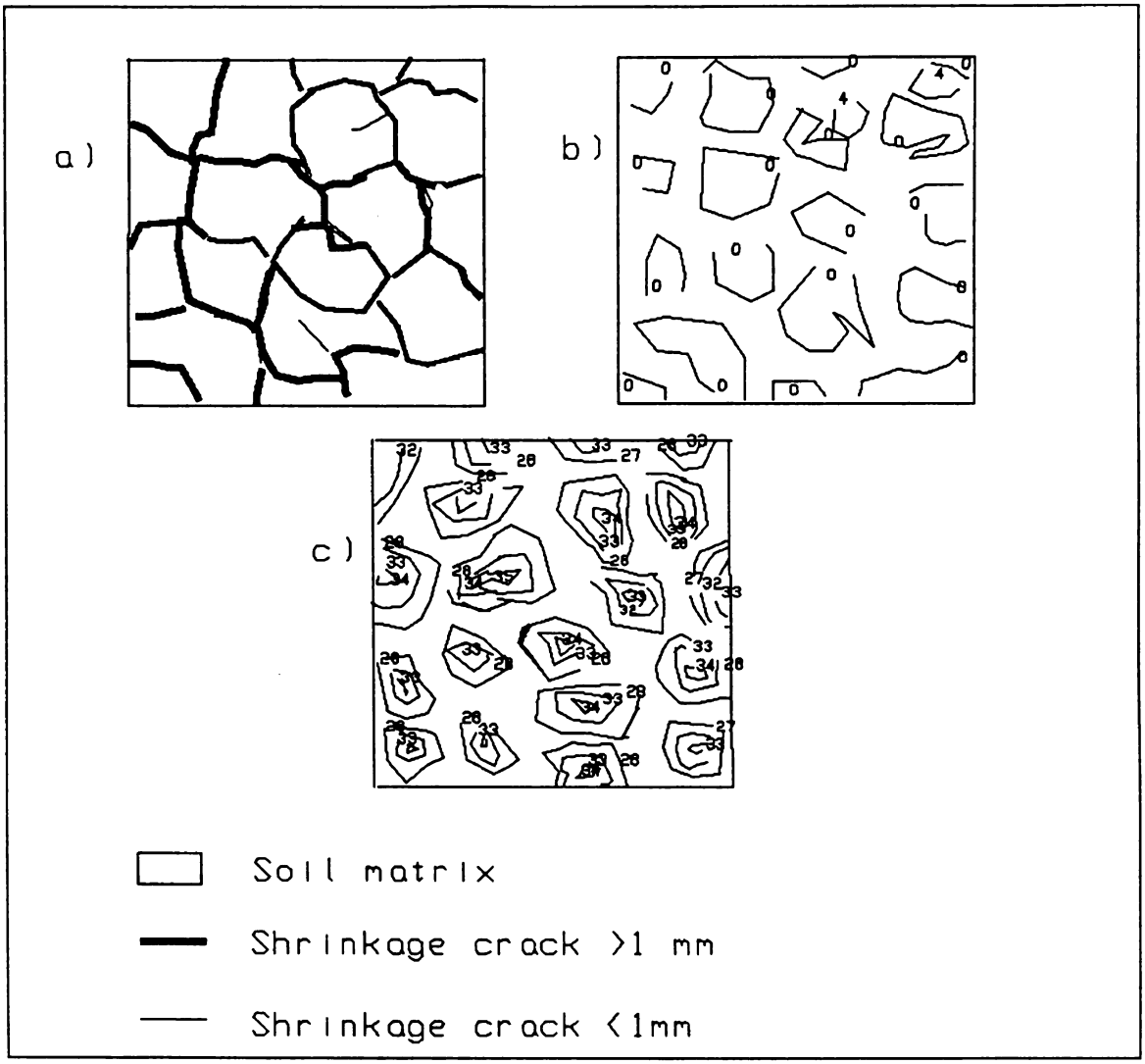

Figure 5.10. Mapping of structure, roots and water at 25 cm from soil surface for treatment MT on August 8. a) structural mapping; b) root density; c) TDR-determined volumetric water content.

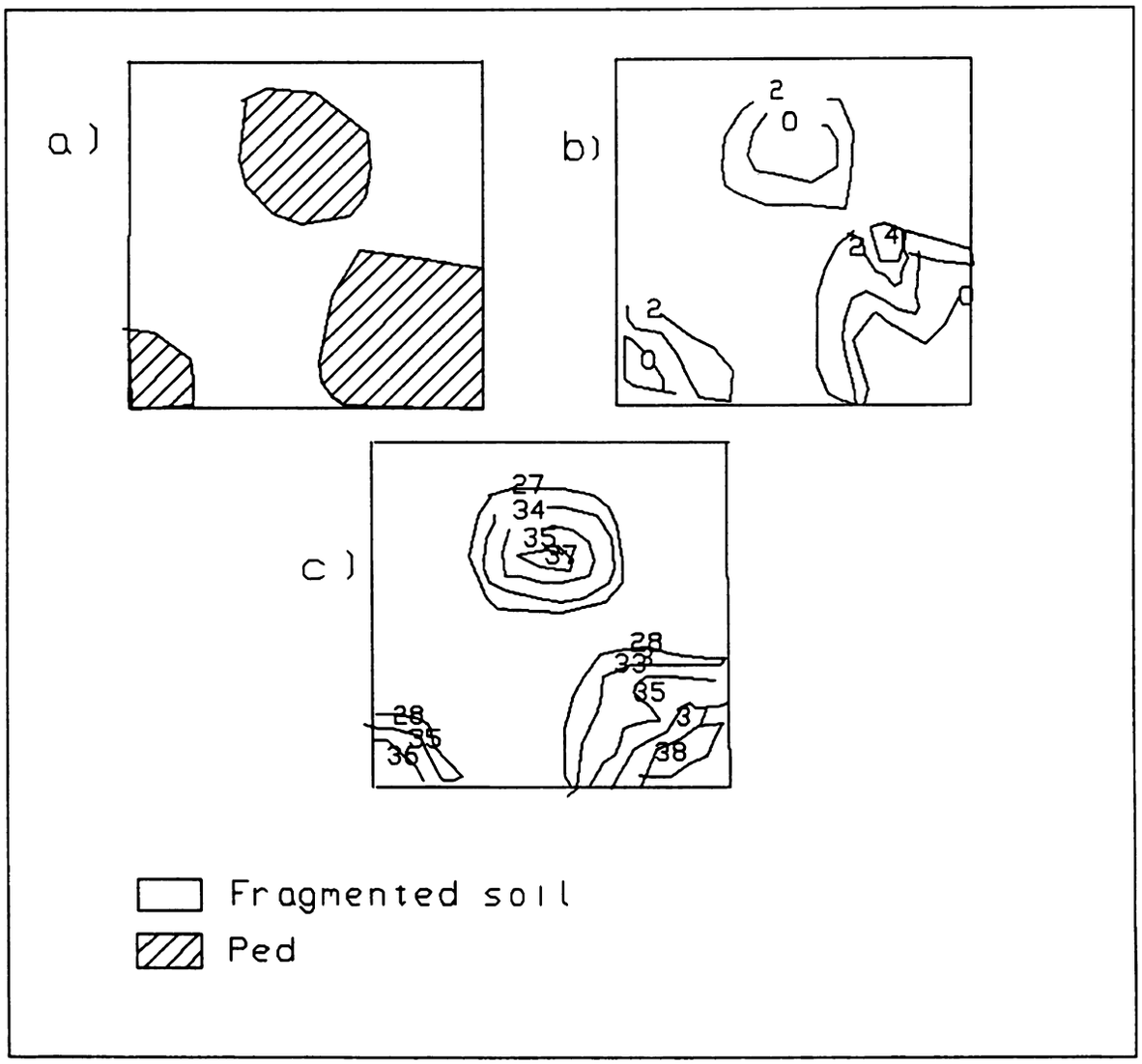

Figure 5.11. Mapping of structure, roots and water at 25 cm from soil surface for treatment T50 on August 8. a) structural mapping; b) root density; c) TDR-determined volumetric water content.

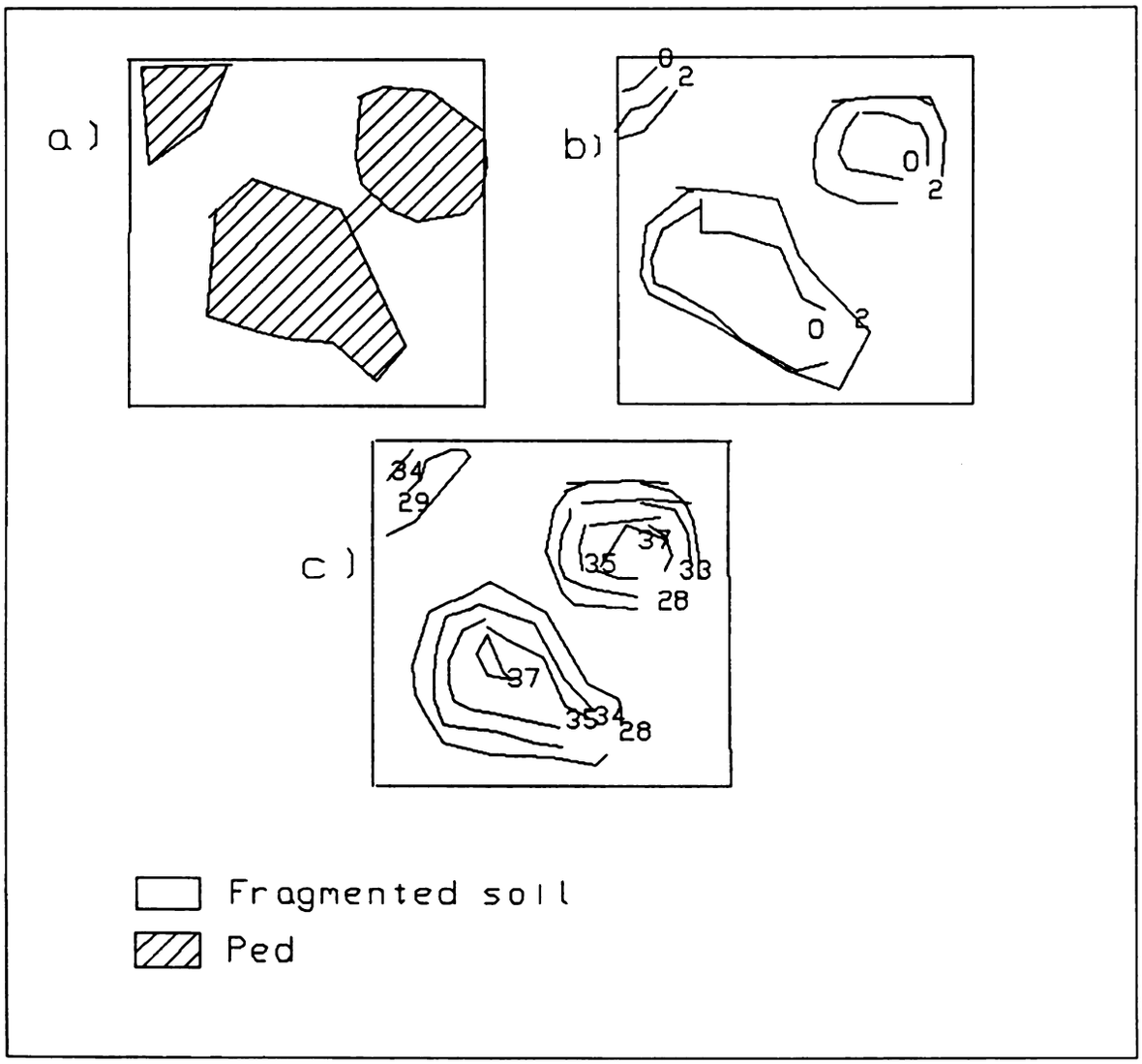

Figure 5.12. Mapping of structure, roots and water at 25 cm from soil surface for treatment T100. on August 8. a) structural mapping; b) root density; c) TDR-determined volumetric water content.

few cases cavities were observed. Root distribution was related to soil structure as follows. Roots were found in the bulk soil, and in the 0-2 cm layer in peds, but only occasionally inside peds. Root distribution in the bulk soil and at ped surfaces was more regular on the second date of sampling. Water content on the first date was quite uniform in the bulk soil while in peds it increased with distance from the surface. Within the ped's superficial 2-cm layer, water distribution was not uniform, but it was lower where roots were present. On the second date, both root and water distribution were more uniform in peds as a function of distance from surface.

In summary, plant growth, yield and leaf elongation varied with soil structure, while leaf appearance rate and tasseling were less affected. Many studies in the literature report that in compacted soils plant growth and yield are reduced (see Hamblin, 1985 for a discussion). Many physical and chemical properties are associated with compaction. In several cases yield reduction in compacted soils is associated with water stress (Hamblin, 1985). Philips and Kirkham (1965) pointed out that fertilization can alleviate plant growth and yield reductions associated with compaction. This is classically interpreted as indicating that compaction reduces the soil volume explored by roots making less resources (water, nutrients) available. Poor aeration is also commonly found in compacted soils, and its effects both on root growth

(Voorhees et al., 1975, Schumacher and Smucker, 1984) and functionality (Everard and Drew, 1987), and on top growth (Smit et al., 1989) are documented. Studies in controlled conditions, though, showed that soil strength can play a direct role on reducing plant growth, independent of water and oxygen availability (Masle and Passioura, 1987). In the field it is not always possible to quantitatively discern the effects of the single factors because soil strength increases as soil drying occurs and both amount and functionality of roots are affected. Data on higher top growth in treatments T50 and T100 can be partly attributed to higher availability of fragmented soil. Water uptake was found to occur mainly in the finer soil, and low water access in peds was responsible for the plants experiencing water deficit even though the average water content of the soil was still high. Values for the average θ_v in each soil layer (Table 5.4.a) were for the most part higher than 0.280 cm^3 cm^{-3}. According to Comegna et al. (1990) this corresponds to a soil matric potential of above 0.5 MPa, based on laboratory determinations for the same soil used in this experiment. Water deficiency symptoms such as severely reduced leaf extension would not be predicted from these values. Only in a few instances θ_v values were as low as 0.244 to 0.273 cm^3 cm^{-3} (corresponding to about 0.8 to 0.5 MPa according to Comegna et al., 1990). An analysis of data taken separately for fragmented soil and peds (Table 5.4.b), and of water content gradients across peds (Tables 5.6 to 5.8),

though, shows that water content values were much lower (as low as 0.160 to 0.225 cm^3 cm^{-3}) in the areas where root density was higher (fragmented soil and first layer of peds). This would explain why the plants were experiencing water deficiency stress even though regions of higher water content were present in the soil, since those region were inaccessible for roots. A lower leaf elongation rate in a period of no rainfall in treatments MT and T50 was therefore likely caused by a lower access to water in compacted areas, although direct effects of increasing soil strength in drying soil around roots may have played a role. Non-water related effects of soil strength on growth reduction were not investigated, but cannot be excluded in this experiment.

Root and water spatial distribution were related to soil structure, and in the August 8 mapping more than on July 31. The relation between structure and root and water spatial distribution needs further investigations, especially regarding its time-course. It has been argued (Passioura, 1985) that water uptake in clustered roots does not depend on RLD but on distance between clusters, provided root density in the cluster is large enough for the roots to constitute a uniform sink (i.e. a surface around peds). In that case water uptake could be modeled solely based on the clusters geometry, rather than on root density measurements. Where root clusters are related to a fairly regular soil structural pattern, as in the presented cases, this could introduce further

simplifications in water uptake modeling. It was shown in this experiment that on the first mapping date root distribution around and inside the surface of peds was not uniform, but it was more so on the second date. Further characterization of such time-course is needed to discern cases in which uptake could indeed be modeled based on structural patterns.

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SUMMARY

SUMMARY AND CONCLUSIONS

The main objective of this research was to study the effect of soil structure on root clustering and its consequences for water uptake in water-limited conditions.

A time-domain reflectometry technique was tested for the determination of small scale spatial distribution of water in the soil. Volumetric water content values higher than 0.07 cm^3 cm^{-3} were reliably measured with 21 mm-long, 14 mm-spaced waveguides in a clay-loam and in a sandy-loam soil.

In a glasshouse experiment plant growth and water uptake were affected by soil structure. In a compacted clay-loam treatment plant growth was slow and water uptake minimal, resulting in a quasi-stationary state with no signs of wilting. This behavior was discussed in terms of direct effects of soil strength and possibly poor aeration on plant growth. Incomplete water uptake would therefore be a consequence rather than a cause of limited growth. The evidence was circumstantial, though, and the lack of acute water deficit symptoms may be explained also with early developed water deficiency stress leading to reduced growth and sufficient osmotic adjustment to maintain leaf turgor. Further studies are needed to discriminate direct and indirect effects of soil strength

on water uptake. In other treatments where compacted soil regions (peds) were present plants lost nearly all leaf area after wilting, while irrigated controls showed no leaf rolling and a higher final leaf area. This indicates that water availability had been a limiting factor. In those treatments root penetration in peds was limited to the 2-cm outer layer and un-extracted water was left in the central layers of the compacted units. Peds of larger diameter had a larger final water content than smaller ones.

Results from modeling of water uptake from peds showed that incomplete water extraction was due in part to root clustering, but also that a diffusivity value as low as $4.29*10^{-2}$ in dry soil around roots was necessary to reproduce by simulation the experimentally found water gradients in peds. Such a low D value could be the result of soil-root interface discontinuities like gaps due to root shrinkage or to local compaction due to growing roots pressure. Since root penetration and water extraction time-course were not measured in the experiment, some of the modeling assumptions need to be verified and investigated further, possibly with non-destructive techniques.

A field experiment on a swelling soil showed that the relief of soil strength caused better plant growth and yield in water-limited conditions. Roots were clustered in all treatments, not being able to penetrate compacted soil areas beyond the 2-cm outer layer unless macropores were present. Water uptake in those areas was lower than in soil of lower strength, more uniformly colonized by roots.

Results show that water uptake patterns were strongly dependent on root spatial arrangement. Since root distribution was closely related to soil structural status, this suggest the possibility of modeling water uptake of clustered roots in structured soils based on information on soil structural status rather than on actual measurement of root spatial variability that is lengthy and destructive. In vertisols structural patterns are largely due to the soil's own cracking patterns that are regular to an extent. In addition, structure is determined by tillage whose effects are also spatially regular, on a scale depending on the type of tillage implements. This introduces further possibilities of simplification in modeling.

The uptake dynamics of roots growing around peds need to be characterized further, and the time dynamics of plant growth need to be accounted for, in order to be able to predict the degree of actual root presence around peds at each time. The relations between soil structure and rooting patterns vary with time (plant growth stage) and with other plant conditions, like stress development. The variability with time was evident in the field mapping results: on the first mapping date the roots did not colonize the whole peds surface layer, while a week later root density around peds was more regular. Also, the ratio of root density found in peds and in fragmented soil was higher on later dates than early in the season. Furthermore, compensatory effects have to be taken into account. In both glasshouse and field experiments root density within peds was found to be higher in

treatments where soil of lower strength was not available for roots to grow. Therefore, root geometry as affected by structure has to be understood as a whole profile phenomenon, rather than a local effect, as studies on seedlings in small containers may suggest. Further studies are therefore needed in the field or in conditions that allow for the mentioned levels of complexity to be accounted for.