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MICRO-SCALE SPATIAL VARIABILITY OF CROP ROOTS, WATER CONTENT, SOIL TEXTURE AND THEIR INFLUENCE ON SOIL WATER EXTRACTION RATES

By

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ABSTRACT

MICRO-SCALE SPATIAL VARIABILITY OF CROP ROOTS, WATER CONTENT, SOIL TEXTURE AND THEIR INFLUENCE ON SOIL WATER EXTRACTION RATES

By

Carlos M. Paglis

Water extraction by roots is an important component in crop growth simulation models. The capability of plants to survive in limited conditions of water supply largely depends on the uniformity and depth of its root system. If roots are not present in some parts of the soil, it is likely that areas where water is available will be left behind during root growth in the soil environment. Roots frequently bypass these soil regions as a consequence of root clumping.

Several models simulate water extraction based on the assumption that roots are uniformly distributed in the soil. However, considering the natural heterogeneity of the soil environment and genetic factors inherent to plant species, the assumption of uniformity of root distribution is not valid. In addition, other factors such as anthropogenic action on soil formation, competition among plants, and soil physio-chemical and biological stresses will also contribute to a non-uniform distribution of the root system. Knowing that this non-uniform root distribution should affect simulation of water extraction by roots, the objectives of this study were to describe the micro-scale spatial variability of crop roots, water content, soil texture and their influence on soil water extraction rates.

To describe such variability, a greenhouse experiment was conducted at Michigan State University, MI, and another one in the field, at Maricopa Agricultural Center, AZ. The plants were grown in a terminal drought condition until they were severely impacted by soil water deficits. Measurements of volumetric water content within soil layers in the greenhouse and in the field experiments were done with a neutron-probe gauge. A small TDR probe was used to determine volumetric water contents in 2.5 cc soil samples collected in a grid pattern in each soil layer at the termination of the both experiments. For each soil sample the amount of roots and soil texture was determined. A functional model for root water uptake was used to simulate water depletion for each soil layer in the greenhouse experiment.

The results revealed that roots were non-uniformly distributed within soil layers in both experiments, and that roots bypassed soil areas leaving water without being extracted. Thus plants could show signs of water deficit despite an appreciable amount of available water in the bulk soil.

A critical value constant, *K,* in a functional water uptake model representing the daily fraction of extractable water was determined for each soil layer to predict the water extraction based on the non-uniform root distribution. Once these values were estimated, the functional model for root water uptake was able to closely predict the water extraction in each soil layer.

to *Janaina*,

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AWC	Available water content
^0C	Degree Celsius
C1	Cylinder one
C2	Cylinder two
cm	Centimeters
DOY	Day of the year
EFV	Extraction front velocity (cm day^{-1})
ha	Hectare
i.d.	Internal diameter
kg	Kilograms
LL	Lower limit
m	Meters
MAC	Maricopa Agricultural Center, AZ
mm	Millimeters
MJm^{-2}	Megajoules per square meter
ml	Milliliters
MSU	Michigan State University, MI
RLD	Root length density (cm cm^{-3})
RSA	Root surface area (cm^2)
RV	Root volume (cm^3)
USDA	United States Department of Agriculture
VWC	Volumetric water content

Introduction

During growth and development of roots into the soil matrix, plant genetic characteristics and soil environment govern the way roots penetrate and exploit the soil around them. Genetic characteristics will determine root branching and growth patterns, which are crop species dependent (Hamblin, 1985; Schieflbein and Benfey, 1991; Zobel, 1996). Soil environment will affect not only the way roots grow, but also other related processes such as water absorption, nutrient transport and biological activities in the vicinity of root system (Kramer and Boyer, 1995).

Soil environment has a major influence on root growth, and is reflected by several types of stresses that roots encounter. These stresses are classified as chemical, biological and physical (Russel, 1977; Jones et al., 1991; Kramer and Boyer, 1995). Chemical stresses are usually attributed to toxic substances, shortage of nutrients or unbalanced distribution of nutrients in the soil (Schiefelbein and Benfey, 1991). Biological stresses induced by flora and fauna of soil, e.g., root diseases, may cause a decrease in water and nutrient absorption by plants. Finally, soil physical stress will limit root growth as a function of variations in soil texture, structure, lack or distribution of water and aeration. In summary, the influence of physical, chemical and biological stresses in the soil can result in an environment that causes non-uniform root distribution.

Uneven distribution of root growth may vary in such a way that roots may be found clustered in the soil. Root clustering is caused not only by the soil environment, but also by plant characteristics, i.e., root geometry and branching

(Tardieu, 1988), and assimilate partitioning between root and shoot (Tardieu, 1989). In addition, competition and chemical interaction among roots will also affect the way roots colonize the soil (Russel, 1977).

Researchers have also observed other causes for root clustering. It has been observed that roots grow clustered inside bio-pores (wormholes, old root channels), soil cracks, around peds and planes of weakness in the soil (Passioura, 1983; Whiteley and Dexter, 1983; Hewitt and Dexter, 1984; Tardieu and Manichon, 1987; Tardieu, 1989; Smucker and Aiken, 1992).

Plants with clustered roots growing in limited supply of water content, will die or become dormant despite water availability in soil (Lafolie et al., 1991; Bruckler et al, 1991a). In this sense, water is left in soil as a result of an incomplete water extraction (Passioura, 1983, 1991). The reasons are once roots are clumped (e.g. inside natural openings) they dry the soil in the vicinity, which will increase the resistance of soil to water movement to the root surfaces (Passioura, 1983). For instance, soil hydraulic conductivity will decrease around roots and water movement from wet regions to dry regions where roots are clumped will be low or impaired. If no more water is added to recharge the soil profile, water availability for root absorption will decrease (Tardieu et al., 1992).

Once roots are clumped, low contact of their surface with soil may occur. For instance, roots growing inside a natural opening may present a discontinuity of contact between their surface and the soil surface. This discontinuity will decrease water absorption in that location, consequently decreasing the amount of water a plant can extract from soil (Passioura, 1983;1991; Tardieu et al., 1992).

Hence, clumping will cause roots to be spatially distributed in the soil and which is of considerable importance in that it can influence the efficiency with which the soil is exploited. This spatial distribution of roots and depth of the root system will be important for water extraction by plants (Robertson et al., 1993a; Dardanelli et al., 1997). It is probable that an incomplete exploitation of water and nutrients will occur if roots are not occupying some soil regions. Under conditions of soil water deficit, this incomplete exploitation may affect crop yield (Boyer, 1982). The responses of crops in such conditions will vary depending upon plant phenological stage, duration and severity of the water deficit period (Asseng et at., 1998).

Analyses of the water uptake pattern by plants indicate that many crops do not fully utilize water found at deep soil layers (Passioura, 1983). Several authors verified an incomplete water extraction in the soil profile (Bland et al., 1989; Robertson et al., 1993a; Passioura, 1983). The reasons for incomplete extraction were attributed to a low root density at depth of water extraction (Robertson et al.,1993 b), onset of crop maturity before deep water extraction commences (Robertson et al. 1993b), uneven root distribution (Robertson et al., 1993a), root clustering (Passioura, 1983), high root axial resistance to water flow (Passioura, 1983; Hamblin and Tennant 1987), and roots growing towards lose regions in the soil after they have been deflected by more dense regions or other kind of obstacles (Dexter and Hewitt, 1978). Water simulation models do not account for these patterns of root growth and the incomplete water extraction. This may be a drawback (McIntyre et al., 1995), because it can lead to spurious results of water extracted by plants. Considering the spatial distribution of roots in the soil matrix as a natural fact and the phenomena of incomplete water extraction, we can assume that roots naturally bypass some soil regions when they are colonizing the soil. This subject needs to be better investigated and incorporated into new models of soil water extraction in the future.

Water Models

Numerous soil water simulation models have been developed in the past with enormous degrees of sophistication. One of the earliest attempts to simulate soil water was the simple water balance of Thornthwaite (1948). This model used average monthly precipitation, soil water storage and estimated potential evapotranspiration.

A microscopic approach was presented later to describe water uptake by root systems (Gardner, 1960; and Cowan, 1965). It considered roots as an infinitely long cylinder of uniform radius and water-absorbing properties, and water flowing in the radial direction towards the root.

In a general sense, water simulation models are classified as budget, semi-dynamic and dynamic models (Jong and Bootsma, 1996). Single budget models, treat the soil profile as a bucket into which water flows until it is full, and the excess of water is considered as runoff or drainage (Aase et al., 1973). In other more advanced models the soil is divided in layers and water flows in a cascading approach from upper to lower zones. For instance, water from precipitation or irrigation flows to lower zones into the soil profile as soon as the upper layer reaches the field capacity (O'Leary et al., 1985). They are useful in characterizing soil climate zones, soil water regimes in arid and semi-arid regions and in irrigation scheduling. They require minimum amount of input data, such as drainage upper and lower limit of water content, daily precipitation and potential evapotranspiration (Jong and Bootsma, 1996).

In semi-dynamic models, water movement within the root zone is also simulated by transferring water among layers with transfer rates based on the water in each layer (Ritchie, 1985). These rates depend on the soil hydraulic properties. The amount of water exceeding the drained upper limit drains into the next layer.

In dynamic models, physical factors that control water movement in the soil control infiltration and redistribution of water (Ross and Bristow, 1990). Dynamic models use Darcy's law combined with the equation of continuity. The resulting equation is commonly referred as Richard's equation with an added term for root water extraction (sink term). The mathematical description of this sink term is hindered by the complex mechanisms involved in water extraction allied to the heterogeneity of the root-soil system (Molz, 1981; Li et al, 1999). Richard's equation is a nonlinear partial differential equation which can be solved analytically only for specific initial and boundary conditions. The approach adopted here is known as macroscopic approach. It is a complex equation to be used, but it has been incorporated not only into more comprehensive crop growth models but also into soil degradation and solute transport models (Jong and Boostma, 1990).

Several water simulation models developed in the past decades are based on the relationship between roots and soil (Hector, 1993). Most water uptake models use the amount of roots per unit volume of soil to calculate water extraction. They assume that roots are uniformly distributed in each soil layer, presenting an exponential decrease in the amount of roots with soil depth (Dwyer, 1988; Klepper, 1991). Based on the complex interactions of the root-soil environment, researchers have questioned the validity of using root length density (RLD) (cm roots cm^{-3} soil) in water extraction models (Hamblin and Tenant, 1987; Bland and Dugas, 1989;Lafolie et al., 1991; Dardanelli et al., 1997). Soil heterogeneity and the dynamic process of the root system as a living organism makes difficult the prediction where roots are and the amount of water being extracted.

Water absorption is not uniform along the root surface. The root surface capable of water extraction moves toward different soil zones during the root growth period. It has been observed that water absorption is higher in new roots compared to old ones (Hamblin, 1985). Variation in water extraction may also occur in the same root, consequently the resistance to water absorption along the roots will be different (Moreshet et al., 1996).

The assumptions of uniform root distribution in simulation models are often not realistic. To overcome this limitation and to better predict water uptake by plants, water extraction should be based only on water depletion with time.

Due to the difficulties and errors in measuring the amount of roots involved in the water absorption process, the quantification of the amount of roots present in the soil is not necessary (McIntyre et al., 1995). A functional model describing root water uptake that does not take into account root length density was proposed by Ritchie et al (1999). This model uses generalizations from measured soil water content changes in the soil profile to predict root water uptake during plant development. The model assumes a minimum threshold of root density at each soil layer to extract water; that transpiration is greater than total water root supply and that values of lower limit water content are accurately determined. Above the lower limit, the root water uptake rate will decline exponentially with soil water content in the same way as described by Passioura (1983). This approach leads to predictions closer to reality, eliminates the uncertainties in complex root system behavior, and it accounts for soil spatial variability.

Spatial Variability of Soil and Roots

When describing soil properties, soil is usually assumed as a homogeneous material (Warrick, 1998). This is a convenient assumption when performing soil tests in laboratory or in conducting field experiments in small plots, for instance, with different fertilizer rates. However, the degree of homogeneity will depend on the scale used in these kinds of studies and the objectives of the researcher (Trangmar et al., 1986).

Soil, in reality, is a heterogeneous medium with physical, chemical and biological properties varying in space and time (Trangmar et al., 1986; Warrick et al, 1986). This heterogeneity has its origin in the natural process of soil-formation factors and in the anthropogenic action (Ahuja and Nielsen, 1990; Tsegaye and Hill, 1998; a,b; Warrick, 1998).

The natural processes of soil formation will form a nested structure with climate operating over large spaces and soil weathering operating in long time periods. During the genesis of the parent material, some variation in chemical composition may occur. This may be natural or due to the presence of different gases or cooling period. Such variation associated to a local action of chemical, physical and biological reactions during the weathering process will lead to a formation of a variable substrate. Other processes, such as erosion and deposition of the parent material may contribute to the soil spatial variability operating more locally or more frequently, e.g., weather (Beckett and Webster, 1971; Trangmar et al., 1986).

Geomorphical processes, for instance, alluvial deposition; geochemical gradients, loss, retention or burial of land surfaces will also contribute to the soil variability in the landscape (Beckett and Webster, 1971).

Anthropogenic action, in addition to the natural processes mentioned above, will affect soil structure and cause variability in several ways, e.g., by intensive tillage practices, localized application of fertilizers and irrigation (Ahuja and Nielsen, 1990; Warrick, 1998).

Soil heterogeneity will affect both soil physical and hydraulic properties. Several works were done in the last few years with the objective of describing such spatial variability. Some of them show spatial variations of pH, soil texture, bulk density, conductivity, ranging from 1 meter to hundreds of meters (Yost et al., 1982; Warrick, 1986; Yeh et al., 1986). Others, show the spatial variability in the distribution of hydraulic conductivity (Moutonnet et al., 1988; Zhang and Berndtsson, 1991; Mallants et al., 1996), water tension (Saddiq et al.,1985; Yeh et al., 1986), spatial and temporal soil water storage capacity (Or and Hanks, 1992), soil water content (Moutonnet et al., 1988), soil water retention (Shouse et al., 1995).

While considering macro-scale variability, few studies dealt with micro-scale variability of soil. Bruckler et al. (1991b) that showed the spatial variability of water potential at small scale. In his work, isocontour lines of water potential and clumped roots were described based on samples taken 0.4 m far from the plant stem. Amato (1991), demonstrated that soil water content varied spatially on soil peds layers at a distances around 0.02 m. This variation in water content affected significantly the amount of roots around these peds.

Based on the degree of spatial variability in the soil, it is expected that plants growing in such conditions are variable too (Brown and Scott, 1984; Saddiq et al., 1985). Considering the relationship between soil and roots, one of the first effects of such variation will probably occur in root growth. We already saw that several types of soil stress may affect root growth. So, considering the natural and/or man-made processes involved in soil spatial variability, these stresses probably will not be uniformly distributed. This means that during the period of root growth in the soil, roots will experience all sorts of different environments in a small area. Without doubt, this may cause an uneven distribution of roots along the soil profile or clumping of roots in some soil regions. Roots tend to preferentially colonize lose zones because they are deflected at the interface between loose and strong zones (Dexter and Hewitt, 1978). Consequently, the soil may present patches of high root density, and others with only a few roots (Tardieu, 1994). Shrinkage cracks or spaces between clods resulted in zones for root clumping (Tardieu and Manichon, 1987; Tardieu, 1989, Passioura, 1983). Moreover, soil biopores may also contribute to root clumping and consequently to the spatial variability of the root system (Passioura, 1983; Whiteley and Dexter, 1983).

However, even considering the heterogeneity of soil physical and chemical properties as the main cause of root spatial distribution in the soil (Tardieu, 1994), other factors are also involved, such as plant characteristics (Hamblin, 1985), competition among plants (Russel, 1977), partitioning of assimilates within the plant (Smucker, 1984; Tardieu, 1989) and possible interactions of all these factors with the soil environment.

Understanding the spatial variability of field soil is important for crop production (Saddiq et al., 1985), but more important than that is to describe this variability. Soil spatial variability will largely depend on the scale or frequency of observation. This means that depending on the level of detail needed, heterogeneity that may have been previously defined as random may be found to contain a systematic component (Trangmar et al., 1986). Thus, considering the scale used, soil spatial variability may occur in a few meters to several meters (Warrick et al, 1986).

Researchers have demonstrated that spatial variability of roots in the plane *x-y* has a high coefficient of variation, but no efforts were attempted to explain this variability (Pettygrove et al. 1989). Researchers only explained the variability existing in the vertical dimension. A possible reason for this may be related to the statistical approach used in such studies (Trangmar et al.,1986).

Most studies have tried to explain the variability of soil properties by using classical statistical methods, such as the analysis of variance (Saddiq et al., 1985; Robertson and Gross, 1994). A few other studies tried to explain the soil and root arrangement, by using indices to describe deviations from an expected distribution (Grieg-Smith, 1983,). Spatial autocorrelation (Tardieu and Manichon, 1986; Tardieu, 1988) and the square root of number of roots per sampling unit (Pettygrove et al. 1989) were also used to describe root arrangement in the soil. Nonetheless, these methods do not provide a complete description of the variability of soil properties or root distribution, because the variance does not take into account the distance between observations (Saddiq et al., 1985). Pure statistical treatment of the heterogeneity ignores the existence of spatial correlation (Mallants et al., 1996).

Considering that there is some degree of dependence among observations taken in a grid pattern, geostatistic analysis may be an adequate tool to describe spatial variability (Matheron, 1973; Journel and Huijbregts, 1978; Isaaks and Srivastava, 1989; Goovaerts, 1992, 1994, 1997). Geostatistics can calculate the correlation between observations made at different neighboring locations and the observed correlation structures can then be used to estimate values in unsampled locations by means of Kriging or co-kriging techniques (Isaaks and Srivastava, 1989; Goovaerts, 1992, 1997).

Geostatistic has already been used to study spatial variability of physical and hydraulic soil properties in large scale. But, the possibility to use this technique in studies of micro-scale variability of the soil environment associated with roots, open a new perspective to understand the complex relationship between soil and root in the process of water extraction.

The difficulty involved in determining the amount of water extracted by plants in crop models will be a matter of discussion and study for a long time. New studies must be proposed to fully understand the spatial variability of the soil environment and the factors that govern root growth and development in such environment.

The study proposed in this dissertation does not have the intention of covering all topics mentioned here, but to contribute with a small parcel of knowledge to improve future soil-water extraction models.

To provide such a contribution this study was divided into three chapters. The first chapter has as objectives the characterization of distribution of roots and soil properties at different soil depths. The main objective of the second chapter is to study the spatial distribution of roots and soil properties in different soil depths by using geostatistical analysis. Studies described in these chapters are an attempt to understand and demonstrate that roots bypass soil regions during the growing period. The objective of the third chapter is to characterize water extraction by roots if the bypassing of soil regions is likely to occur.

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Chapter 1

Spatial variability of soil texture, root distribution and water content in different soils. I: Toward micro-scale description.

Introduction

Present water extraction models assume that roots are uniformly distributed in the soil or that root density decreases exponentially with soil depth (Molz, 1981; Dwyer, 1988; Klepper, 1991). Such assumptions simplify not only how roots are distributed in the soil but they also underestimate quantities of water extracted by plants.

Uniform distribution of roots in the soil does not represent reality (Hamblin and Tenant, 1987; McIntyre et al. 1995). The soil environment is a heterogeneous medium for root growth and its properties may vary in space and time (Trangmar et al., 1986; Ahuja and Nielsen, 1990; Warrick, 1998). Consequently, the restrictions imposed on root growth in such a medium may also vary by the same order of magnitude and will affect the way roots colonize and explore the soil. Root growth is determined by several intrinsic factors related to the plants. Genetic characteristics will govern root branching patterns and morphogenesis, while competition and chemical interaction among roots will play a role in its distribution in the soil (Hamblin, 1985; Zobel, 1996). The distribution becomes more complex when one considers the interaction between soil and roots. As a consequence of these interactions, roots should be considered more uneven than uniformly distributed in the soil (Tardieu, 1988).

Uneven root distribution will affect water extraction. Roots are found clustered in the soil due to their growth into natural biopores, planes of weakness, around soil peds, or because roots were deflected towards regions of the soil with a more loose structure (Passioura, 1983; Whiteley and Dexter, 1983; Hewitt and Dexter, 1984; Tardieu and Manichon, 1987; Tardieu, 1989; Amato, 1991; Smucker and Aiken, 1992). Root clustering implies in high concentration of roots occupying and exploring a small volume of soil. If roots are clustered in some parts of the soil it is expected that they will explore these regions as much as possible; thus, an incomplete exploration of other soil regions is more likely to occur.

Incomplete soil exploration may be explained assuming that, once the soil region around the clustered roots was fully explored and all available water was extracted it is quite probable that a dry region will develop around these clustered roots. The hydraulic conductivity will decrease in this part of the soil and the movement of water from wet regions to this dry region will be impaired. If the soil profile is not replenished, water extraction by roots will cease and plants may die or become dormant from a lack of water, even when a supply of water is still available in regions near by. This explanation is acceptable for roots growing around peds, planes of weakness or roots deflected towards soil regions with a loose structure. In case of roots clustered inside biopores, the same explanation could be used; however, in this situation the possibility of lack of contact or irregular contact between roots and the internal surface wall of the biopore will cause some gaps to occur and has to be taken into account. Also, some mechanical impedance to root penetration in the internal pore wall may occur as a function of soil dryness around the roots.

Considering the effects of root clustering in water absorption, it is possible that during root growth some soil layers or some soil regions will be bypassed, leaving regions with water without being extracted (Bruckler et al. 1991; Lafolie et al. 1991). The consequences of that for root water uptake simulation models are that a bias or an overestimation may occur in the calculation of the total amount of water extracted by crops. This may happen because such models do not take into account the non-uniform distribution of roots in the soil. This is not an easy task, considering all the uncertainties involved in the root-soil relationship and the natural spatial variability of the soil. Nevertheless, due to the importance of root distribution in water simulation models for predicting the amount of water extracted by crops, an effort in understanding such relationship is necessary. It must be understood why roots bypass some regions in the soil in detriment to others. Most of the possible causes mentioned in the literature are speculations and there are no experimental evidences for such phenomenon.

The objective of the work described here was to characterize, in micro-scale, root, soil texture, and soil water content distributions within soil layers for two different soils as a first step to understand the reasons why roots are bypassing some sections in the soil.

Material and Methods

Greenhouse Experiment – Michigan

This experiment was done at Michigan State Research Farm, MSU, East Lansing. The soil is classified according to USDA, Soil Conservation Service, as Metea B (Loamy, mixed, mesic Arenic Hapludalfs). Metea series consists of deep and well drained soils that are rapidly permeable in the upper part of the solum and moderately or moderately slowly permeable in the lower part of the solum and in the underlying material. Some results of the soil analysis are presented in Table 1.1. In October of 1997 two steel cylinders with dimensions of 60 cm diameter, 180 cm high and 0.6 cm of wall thickness were pushed into soil to obtain undisturbed soil samples.

The cylinders with contained soil were removed and placed in greenhouse at Pesticide Research Center, Michigan State University, East Lansing, and covered with plastic to maintain their initial moisture contents. Three corn seedlings (variety Cargill 333), with 4 leaves were transplanted on DOY 336 in 1997 in C1 and 20 days later in C2. Plants in each cylinder were fertilized with a NPK formula (19-19-19) at rate of 500 kg ha^{-1} at transplanting day and side fertilized with nitrogen (100 kg ha^{-1}) 20 days later. After transplanting, plants were watered daily until DOY15 in 1998, and water was withheld afterwards.

Daily minimum and maximum temperatures were obtained from a minimum data set recorder (Model LI-1200, Li-cor, Lincoln, NE) located inside the greenhouse. Temperature data from DOY 23 in 1998 to DOY 91 in 1998 are shown in Figure 1.2.

Field Experiment – Maricopa Agricultural Center, Arizona

A field experiment was conducted at Maricopa Agricultural Center (MAC), University of Arizona research and demonstration farm (elevation 358 meters) Soil at MAC is classified as Casa Grande series (fine-loamy, mixed, hyperthermic Typic Natrargids). This soil is a deep, well-drained slowly permeable soil formed in old alluvian. The soil typically has brown reddish to brown sandy loam or sandy clay loam surface horizon from 0-30 cm deep. The subsoil horizon from 30 to 60 cm is usually a reddish brown sandy clay loam, which increases in calcium carbonate content with depth. Below this horizon at depth of 60 to 100 cm is a horizon enriched with calcium carbonate (calcic horizon), which also has a sandy clay loam texture. The depth to the calcic horizon varies from 25 to 100 cm in depth, but commonly occurs between 50 – 80 cm in depth (Post et al., 1988). Some selected soil properties are shown in Table 1.1.

An area with approximately 450 square meters was chosen as a site of experimental plot in March 1999. This area was disced and planted on DOY 22 with barley. Fertilizers were applied on DOY 39 in the water at a dose of 47 kg of N/ha. Another dose of nitrogen, 93 liters ha^{-1} of UAN32 was applied on DOY 69. At planting date the field was irrigated, by siphon system, with approximately 20 cm of water. The next irrigation dates were DOY 23 and 67, with 15 cm of water in both occasions. The irrigation was withheld on DOY 67 in the chosen area, and plants were grown on stored water. This area was chosen due to the non-uniformity among plants when compared to the neighbor areas.

Weather data collected at MAC farm is presented on Figure 1.3.

Plant measurements

Greenhouse experiment

After transplanting, two plants were randomly chosen and marked for nondestructive measurements throughout the growing period in each cylinder. Growing period here is referred as the period after irrigation has been withheld to the end of the experiment (DOY80). General plant aspects such as leaf rolling, leaf growth and dormancy aspect were considered as indicators of severe water deficit. Evapotranspitation for both cylinders were calculated based on water changes in the soil.

Leaf expansion and plant height measurements were taken every two days. For leaf rolling characterization, leaf width measurements were taken at middle portion of leaf blade and at ¼ far from the leaf tip in a fully developed leaf (Carlesso, 1993). The area of each leaf was determined from measurements of leaf length and maximum leaf width multiplied by 0.75 (Stickler et al., 1961). Plant height was taken from the soil surface up to the last visible ligule. Leaf expansion was considered from the period when the leaf emerged from the whorl until the leaf ligule appeared.

No plant measurements were made at MAC farm.

Water measurements

Greenhouse Experiment

Soil water content was measured by neutron scattering technique (CPN, Model 503 DR). One access tube (aluminum, 50mm i.d.) was seated in the center of each cylinder. Readings were made every two days at 15 cm. increments to a depth of 1.20 m. Reading period was from the transplanting date on DOY 336 in 1997 until DOY 81 in 1998.

Field experiment

In the experimental plot, water content was also measured by using the same technique described in greenhouse experiment. Three access tubes (aluminum, 50 mm i.d.) were installed in the field in positions were barley plants were showing different degrees of development. Readings were taken on daily basis from DOY 91 until DOY 103 at 15cm increments to a depth of 1.25 m.

Soil Sampling Procedures

Greenhouse experiment

Following the termination, when corn plants presented severe signs of water deficit and soil water contents approached LL, both cylinders were sliced into 15 cm layers and each layer was analyzed by following two distinct procedures. One procedure was the reading of volumetric water content by using TDR technique (Topp, 1980, 1982) and the other one was the soil sampling per se.

A small TDR probe with 2 dieletric rods 2.1 cm long and 1.4 cm apart were developed to determine VWC in the soil at small scale (Amato and Ritchie, 1995). This probe was calibrated by using two different soils and the equation was used to transform the dielectric constant values observed in VWC. This TDR probe was used with a Tektronix 1503B cable tester (Tektronix, Beaverton, OR), and a computer connected to this cable tester read and stored all the readings automatically. A total of 138 readings were made in a circular grid pattern with each reading position being at 2.5 cm apart (Figure 1.1). A special template was used to direct the TDR readings and also to keep all the samples in the same position and alignment in all layers. In this way a 3 dimensional grid was obtained, allowing further investigation of spatial distribution of the VWC. After the dielectric constant readings were completed, soil samples were collected with a soil sampler (2.54 cm height x 2.54 cm i.d.). Each soil sample was taken in the same position where dielectric constant readings were made. Each sample was packed in whirlpak plastic bag and then stored in a freezer at – 20 °C for further analysis.

Field Experiment

At MAC, a trench with approximately 4 m^2 and about 2 m deep was excavated in order to expose the soil profile to be sampled. This trench was prepared where barley plants were showing severe signs of water deficit. The procedure and equipment used for the dielectric constant readings were the same as those adopted for the greenhouse experiment. The main differences between both experiments are related to the amount of soil samples taken and the positioning of sampling. In the sampling area, 100 soil samples were taken in each soil layer on a square grid pattern with sampling positions located at 2.5 cm intervals (Figure 1.1). In total, 550 soil samples were collected in 6 soil layers at 15 cm increment in depth from 45 cm up to 125 cm. Due to the dry conditions of the soil at the sampling date, it was impossible to sample the first 30cm in the profile. Because of the high soil resistance at 45 cm depth, only 50 samples were collected following the grid sampling.

In the field, each soil sample was packed in whirlpak plastic bag and temporally stored in a container with ice; and at end of the day soil samples where immediately frozen. Soil samples were transported frozen to MSU and stored at –20 °C for further analyses.

Soil Texture Analysis

Soil texture analysis was performed by using the micro-pipette method (Miller and Miller, 1987; Burt et al., 1993) and the textural soil classification proposed by the USDA was followed (Gee and Bauder, 1986). This method was chosen considering not only the small size of each sample and large number of soil samples to be analyzed, but also the facility and fast procedure analyses in comparison to the traditional hydrometer and pipette methods (Miller and Miller, 1987; Burt et al., 1993). The micro-pipette method was used for each soil sample right after each sample was thawed. During the weighting process and washing of sand fraction, each sample was carefully examined for the presence of roots.

This was done in order to recover any possible piece of root and to avoid mistakes during the root analysis. This technique was used for all soil samples collected in both experiments.

Root analysis

Roots were washed from the soil samples by successive wet sieving on sieve 35 (50 μm aperture) and sieve 60 (250 μm aperture). After this procedure roots were put in a methanol solution 15% (v/v) plus 5 ml of Malachite green oxalate solution 1% (w/v) and preserved at 4 °C (Smucker, 1990).

Stained roots were rinsed with distilled water on an ultra fine (25 μm) nylon screen and uniformly distributed on a small clear plastic tray where the roots were covered with a thin film of water for image video recording. Once roots were carefully spread in the tray to avoid overlapping, images were video recorded by a computer controlled robotic camera on VHS videotape (Smucker, 1990). Video recorded images were processed by a Sun Ultra-based computer algorithm in the Root Image Processing Laboratory (RIPL), at Michigan State University (Dowdy et al., 1998; Pietola and Smucker, 1998). The Program WR-RIPL V3.0 was used for measurements of root length. As a result, roots were classified in 5 roots classes based on their diameter. The image resolution used in this process was 276 pixels per 1 cm. Average root width classes were Class 1 (0.2 mm), Class 2 (0.5mm), Class 3 (0.9 mm), Class 4 (1.4 mm) and Class 5 (2.1 mm). All data are for roots without debris (Dowdy et al., 1998). RSA was calculated as a sum of all image areas in all width classes, assuming a uniform cylindrical root shape, with the formula $A=2\pi rL$, where r is root radius and L total root length. RV were calculated as $V= \pi r^2L$.

The same procedure was adopted to analyze the samples collected at MAC.

Statistical Approach

Statistical analysis were performed on the percent of clay, sand, silt, VWC (%), AWC (%), and RLD (cm^3cm^{-3}) for all layers in both experiments by using SAS (SAS Institute, 1990).

Results and Discussion

Greenhouse Experiment

Plant measurements

Several measurements were completed during the period when plants grew on a limited supply of water. All these measurements were used as a basis to decide the termination of the greenhouse experiment and the beginning of soil water measurement with the TDR probe and soil sampling.

For each cylinder three corn plants were measured (Figure 1.4). In the beginning of the growing period, plants in C1 were 12 to 20 cm tall. Initially the growth in height was about 1 cm day^{-1}, thereafter the growth rate was about 2 cm day^{-1} as long as the there was a adequate supply of water in the root zone. After DOY 50 this rate decreased. All plants showed the same rate. Plants 1 and 2 stopped growing before plant 3; however plant 1 had a new growing stage after no sign of growth for almost 24 days. It grew at rate of 1 cm day^{-1} approximately and decreased again by DOY 100. As the other plants stopped growing, more water probably became available for plant 1 and by DOY 100 the rate decreased and no more growth was noticed. Plants in C2 presented similar patterns and rates of growth. However, the rate of growth was lower than that observed in plants growing in C1. Plant 2 stop growing on DOY 20 and plant 1 on DOY 40. Only plant 3 kept growing at rates of approximately 1 cm day^{-1}, probably because more water became available after the other plants stop extracting it. However, this plant reached the maximum height of 75 cm at DOY 80 and then stopped. The reason for plants on C2 being shorter than plants on C1 was probably due to their transplanting date. These plants were transplanted 20 days later than that on C1, but the irrigation was withheld in the same period. In this case these plants were subjected to the same period of water deficit observed in C1.

Leaf growth and rolling were monitored every other day to verify how leaves of corn plants would be affected during the period of water deficit. Based on the results of rolling index in Figure 1.6, it is clear that plant leaves were able to recover the normal area while the water supply lasted; but with time this was not possible anymore. With water deficit increasing, leaves kept rolled to avoid more water loss. For both cylinders the rolling index decreased after DOY 45. In C1 the rolling index reached its maximum values, around 0.6 after DOY 55 and did not recover anymore. For C2 rolling index was more variable, with values ranging from 0.3 to 0.6 after DOY 55. However, it reached values around 0.2 by DOY 75. This occurred at same period when this plant stopped growing in DOY 80. At this time, the cumulative growth was less than that observed in the previous leaves and the cumulative leaf growth for plants in both cylinders decreased around DOY 40 to DOY 45 (Figure 1.5).

Approximately 30 days after the irrigation was withheld water deficit became more severe (DOY 45). The daily evapotranspiration estimated for plants growing in both cylinders decreased after the last irrigation on DOY 15 (Figure 1.7). Plants were able to resist water deficit for almost 30 days, but after that it was evident that water deficit impaired plant growth. By DOY 80 in C1 and DOY 92 C2, leaves showed a coriaceous aspect and a pale green coloration and the experiment was terminated. Water measurements with neutron probe also indicated that plants had reached their maximum of water deficits.

Water measurements with neutron probe

Based on the time course of water depletion for different soil layers, one can see that for the first 4 layers in C1 (soil depths from 30 to 75 cm), the amount of water extracted by plants was higher than that observed at deep layers. There was an exponential decay in water depletion in 30-75 cm but it was not observed at deep layers (from 90 to 120 cm). For C2 the same pattern was observed, plants extracted more water in the upper layers than that at deep layers (Figure 1.8). It is likely that when water extraction stopped for upper layers, indicated by the asymptote in the exponential decay, the lower limit of soil water content was reached at those specific layers. This means that plants roots were not able to extract water from soil, because either there was no more water available or the potential at which water was being held was possibly greater than plant roots could overcome to withdraw it from the soil. The resistance of soil to water diffusion toward the root zone was probably high (Passioura, 1983). Another possibility is that roots may have bypassed some soil regions without extracting all available water in that part of the soil. If roots are not evenly distributed it is not possible to extract all water from the soil. In this case, the neutron-probe can not detect such water variability in the soil. The reason for this is that neutron-probe readings are based on a volume of soil reached by the fast neutrons emitted from the probe. The sphere of influence will vary according to the wetness of the soil from 10 to 25 cm, which makes the neutron probe inadequate for detection in water variability in small scale (Hillel, 1996). As a consequence, patches of high water content will be averaged with dry ones in the sphere of influence, which will bias the amount of water detected. It was assumed that plants had stopped extracting water from deep layers at DOY 76 when the time course graph shows no more variation in water content for several days in all layers.

In this study, available water content was calculated as the amount of water above LL for both experiments. As LL was presumably reached at upper layers, but not at deep ones, its estimation for all soil depths was done based on the volumetric water and clay content at upper layers.

The values of LL and VWC for C1 on DOY15 and on DOY 80 when the experiment was terminated indicate that corn plants extracted almost all the available water in the upper layers (Figure 1.9). However, below 75 cm the amount of water left above LL increased with depth. In this case the soil never reached LL. Measurements with the neutron probe showed no more variation in water content at deep layers. The average of VWC remaining for each layer varied from 2% at 90 cm depth up to 6% at 120 cm and the amount of water left without being extracted below 90 cm was around 15 mm. Based on these values, it was evident that some water above LL was left in deep layers. It seems that roots were not able to extract all water from these layers. Root bypassing of some soil regions could have caused this poor water extraction. As it can be seen in Figure 1.9, in C1, the rate of water extraction at deep layers were occurring, but at low values. If the root system was not exploring these soil layers, then the amount of water left might be explained by an uneven root distribution or low root density at that depths.

A good correlation between roots and AWC was expected for all soil depths. However, low values of R^2 were found when RLD was plotted against the AWC (Figure 1.10). A weak correlation was found, but there were evidences that AWC increased when RLD (cm cm^{-3}) decreased. This weak correlation was probably caused by extreme values of RLD observed in some soil samples. Also, different root regions can extract water at different rates. The correlation became more evident at RLD ranging from 0 to 2 cm cm^{-3}. Similar situation was observed for the correlation between RLD and AWC in the field experiment at MAC. Even with a weak correlation between AWC and RLD, the results indicated that if there are no roots in some soil regions the amount of water left is higher.

By knowing the clay and VWC content for each soil sample, it was possible to establish a relationship among them. The results of this correlation showed low values of R^2 for the upper soil layers in both experiments (Figure 1.11). But despite the weak correlation, a cloud of values for VWC was concentrated around a certain value of clay content. In C1 the average percentage of clay content at 30 and 45 cm was around 6% and the VWC observed was about 8 to 9%. The same analysis was adopted for C2 at 60cm depth and for the field experiment. In this way LL was estimated for all soil layers, based on the clay content, for both experiments.

Water measurements with TDR probe

Measurement of VWC with the TDR probe began after the first part of the experiment has been completed. At this time plants showed signs of water deficit and no more water extraction was detectable at deep layers.

The statistical results for VWC determined by the TDR probe and for AWC, calculated as the amount of water above LL, are depicted on Table 1.2. VWC was higher at deep layers than that at upper layers. The mean and standard deviation were calculated based on 966 TDR readings. All means were significantly different (P=0.01), from each other with the exception of the VWC observed at 15 and 60 cm.

Results for AWC showed significant difference (P=0.01), among soil layers. Available water content was higher at deep layers; but different at 105 cm and 120 cm, and was not different for layers 30, 45 and 60cm (Table 1.2). This indicates that besides of plants are being affected by water deficit at the time when the experiment was finished, some water was left in the soil. Similar results were reported in other experiments (Passioura, 1983; Bland et Dugas, 1989; Amato, 1991; Robertson et al., 1993). Also, the amount of roots found at deep soil layers was low compared to the amount of roots at upper layers (Table 1.2), meaning that there was not enough root to absorb water at deep soil layers. Passioura (1983) argues that root length density lower than 0.05 cm cm^{-3} is not enough to supply water demand and this can explain the water left at deeper layers.

Soil texture analysis

Results for clay, sand and silt content for each of the 670 soil samples analyzed are presented in Table 1.2 for both cylinders. Soil texture was significantly different (P=0.01) for each soil depth. Clay and silt content were higher at deep layers than the sand content, which was higher in upper layers. The higher concentrations of clay content were observed at 90 and 120 cm followed by the clay content at 105 cm, slightly similar to that at 75 cm in C1. This can explain why the water content was high in deep layers than that observed at upper layers, where sand content was found to be 73 to 75 %. The low capacity of sand to hold water and the water extraction by plants explain the lower water contents observed in these layers as observed in the previous sections. Despite the averages of clay, sand and silt content observed in Table 1.2, for each soil layer in C1, these averages tell us nothing about the clay content for each individual soil sample.

Root analysis

In addition to water content measurements and soil textural analysis, the amount of roots were also determined for each soil sample. In C1 the average of RLD for each soil layer was obtained from approximately 138 soil samples (Table 1.2). The results were highly significant (P=0.01) and the greatest values of RLD means were found at 30 and 45 cm, followed by lower densities at deep layers. Below 45 cm RLD means were statistically the same. Again, these results showed that RLD varied with soil depth but it did not take into account the variability found when each sample was individually analyzed. For C2, the average RLD was considered statistically equal and unfortunately, due to soil dryness at top layers, no RLD estimation was possible at 15 and 30 cm depth.

Root surface area (RSA) (cm^2) and RV (cm^3) for C1 followed the same tendency of decreasing with soil depth observed in RLD (Table 1.5). This result was expected, considering that these values were calculated based on RL (cm), which also decreased with soil depth. Class 1 (0.2 mm) and 2 (0.5 mm), were the major contributors to the total root length for each soil layer (Table 1.5) Their contribution was on average 73% of the total root length for all layers. This indicates that in great majority the RLD was comprised of fine roots with small diameters. This certainly had a great impact on the values of water content left at deep layers.

In order to understand the spatial variability of roots, volumetric soil water content and soil texture, a correlation analysis was done (Table 1.4) for the greenhouse experiment. Lower limit and clay content was the best correlation found (Table 1.4). For each layer R^2 (Pearson correlation) was as high as 0.99; however, for RLD versus LL or even RLD versus clay content the correlation was not significant. Other examples of significant correlation with low values of R^2 are found. VWC shows a good correlation with clay content and the same was observed for AWC in some layers. But even for these variables low values of R^2 were found. This means that the statistical approach was not adequate to show the possible relationship among the variables within soil layers.

Field Experiment at MAC

Water measurements

The results of VWC observed during the time course of 10 days for different soil depths are depicted in Figure 1.12. The amount of water did not vary during the period of monitoring. Except for the upper layer at 15 cm where rainfall caused an increase in water content on DOY 92 (Figure 1.3). There were three rainfall events that contributed for the elevation in soil water content for the next few days. After that period, VWC decreased again to the same values observed at the time of installation of the tubes in the field. No more variations in VWC were observed for the other soil depths. Even with high temperatures (30 - 35^{0}C) water content for all layers did not vary (Figure 1.3).

Within soil layers VWC was significantly different (P=0.01) (Table 1.3). Higher values (14% of VWC) were found at bottom layers, 105 and 120 cm, compared to the upper layers that were slightly different. Only the upper layer (45 cm), was the driest one with 9% of VWC. Tube 2 was chosen since plants showed more symptoms of water deficit when compared to the other plants in tubes 1 and 3. AWC was different within layers, with values ranging from about 6% at 75cm depth to 1% at 45 cm depth.

Soil Results

Descriptive statistics are presented on Table 1.3 for the soil samples taken where the access tube number 2 was located. Sand and silt content were statistically different (P=0.01) within soil depths; however, the range of variation was around 6% for sand and 3% for silt. Clay content had the highest variation, ranging from 4% at 75 cm depth up to 12 % at 125 cm depth. Clay content was higher at bottom layers than at upper layers. However, at 45 cm clay content was as high as it was found at 105 cm.

Root analysis

High root concentration was observed at 45 cm, where RLD values were around 1 cm cm^{-3}. RLD decreased with soil depth (P=0.01). RSA (cm^2) and RV (cm^3) also decrease with soil depth (Table 1.5). In the field experiment, class 5 (2.1 mm) had an additional influence on the results obtained. This class contributed with 30% of the total RL (cm) and class1 and 2 together accounted for 41%. This contrasted with the results observed in the greenhouse experiment, where the major classes of root diameter were class 1 (0.2 mm) and class 2 (0.5 mm). Yet at 60 cm depth class1 and 2 were responsible for 56% whereas class 5 accounted for just 19% of the total RL. Interesting to observe is that at 105 cm depth, despite of 1 sample has been found with roots, they were thick, varying from 1.4 to 2.1 mm of diameter. Contrary to this finding, roots were thin at 90 cm having diameter in between 0.2 and 0.5 mm.

Correlation analysis among clay, VWC, AWC, LL and RLD were performed (Table 1.4). Among these variables only the correlation between LL and clay content showed a high value for R^2 (P=0.01). Correlation between AWC and clay content was low, but still significant (P=0.01). RLD showed no correlation with clay or LL, and volumetric water content had poor correlation with clay content at 45 cm and 125 cm depth.

The results presented in both experiments were based on soil samples collected by following a grid pattern for each soil depth. This was done to detect spatial variability of water, roots and soil texture at each layer studied. However, from these results no spatial variability was detected, and therefore it could not explain why plants left water in the soil without being absorbed (Figure 1.9).

The natural processes involved during the soil formation cause the spatial variability of soils (Beckett and Webster, 1971;Trangmar et al., 1985; Warrick et al., 1986; Warrick, 1998), and the degree of variability will be different for each soil and the scale used to detect it (Trangmar et al., 1986). This variability will determine not only the physical and chemical properties of the soil along the profile, but also water properties, soil biology, and even root distribution.

In this study it was possible to see that some variables differed by several units at same soil depth (Tables 1.2 and 1.3). The values of standard deviation and the range of occurrence of the variables studied within soil layers for both experiments support this conclusion. The statistical analysis showed that variables differed among themselves when compared within soil layers. Nevertheless, this type of analysis does not take into account the distance between samples. The only way to verify that some spatial variability occurred was based on the standard deviation and the range for each variable. This variability was assumed because samples were taken in a grid pattern. In this case, not only volumetric water content but also roots and soil texture would be different in some parts of the soil within the same layer. Assuming that samples are different for each position from where they were taken, this could explain why plants left water behind. Usually, it is assumed that macropores, fissures or other natural openings in the soil cause non-uniform distribution of roots (Passioura, 1983; Hewit and Dexter, 1984; Tardieu and Manichon, 1987, Tardieu, 1989). In this study the clay and water content had an important role in the root distribution at each depth. The possible non-uniform distribution of clay may have affected root distribution by directing root growth toward soil zones were water content was lower than that observed where clay content was high. As observed by Dexter and Hewitt (1978), roots tend to colonize loose zones in the soil because they are deviated at the interface between loose and strong zones. As a consequence, soil profile will present patches of high root density and others with only few roots. Since clay can hold high amount of water, if clay content is so high that can cause some impediment to root growth, they will not penetrate that soil region and will bypass it leaving water without being extracted. Chapter 2 of this dissertation will prove that the concept explained here is true. Depending on the resistance of this barrier, roots will growth together in regions where soil penetration and even water extraction is easier. In this way, a natural clumping will occur in that region with severe consequences. For instance, drying the soil region around them could increase the soil resistance to water movement towards the roots (Passioura, 1983). In this case, there is water in the soil, but its hydraulic conductivity is low to allow water movement and consequently no water can be extracted. The only way for plants to survive is by producing new roots in soil regions where conditions are more favorable or to increase absorption in other soil regions (Passioura, 1983); nevertheless, if plants are already stressed by lack of water, production of new roots will further drain the limited carbon reserves of a stressed plant (Smucker, 1984, 1992). New roots at deep layers do not mean a guaranty of water supply, because the amount of roots produced can be insufficient to absorb water or supply the total demand by the plant, for instance, RLD low than 0.05 cm cm^{-3} (Passioura, 1983).

Summary and Conclusions

Based on the results obtained in this study, classical statistical analysis could not provide the basis to detect spatial variability in the soil. It just demonstrated that volumetric water content, roots and soil texture varied within soil layers, and that there was a poor correlation among them at each soil depth. It is not known whether these variables are spatially distributed in each soil layer. Moreover, if such variability exists its degree is not known. Because of the grid pattern adopted during the sampling process and existence of different values found for each soil sample studied, it was assumed that this variability might exist. To find more details about this supposed spatial variability and how it affects root growth and water extraction, a new approach is necessary. This will be the subject of the next chapter in this thesis.

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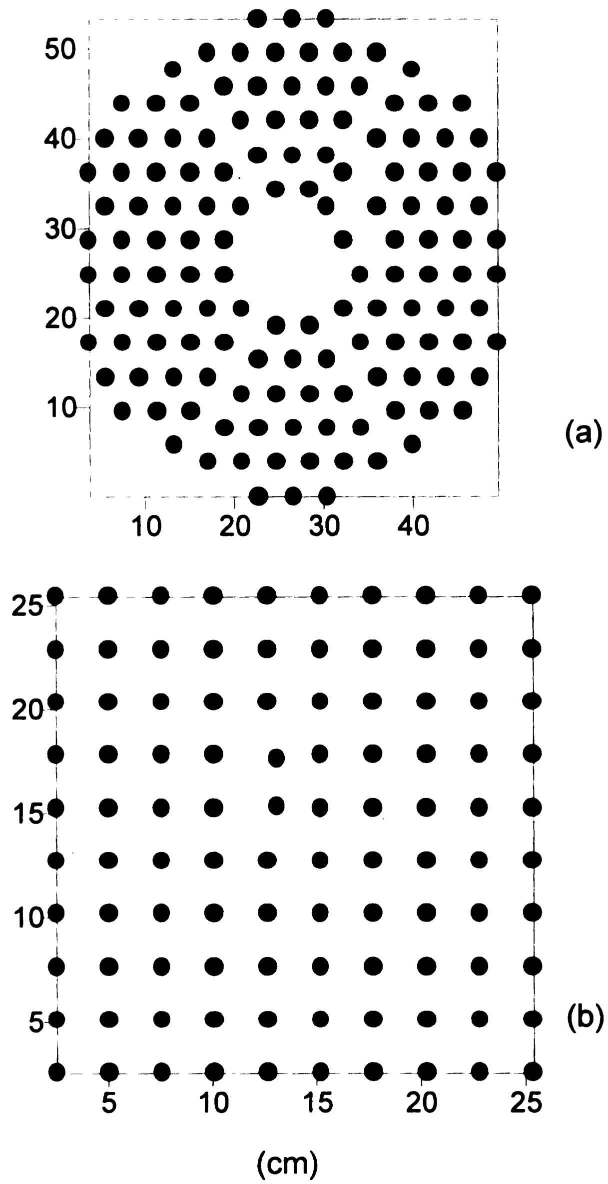


Figure 1.1. Grid sampling used in the greenhouse experiment (a) and in the field experiment. (b).

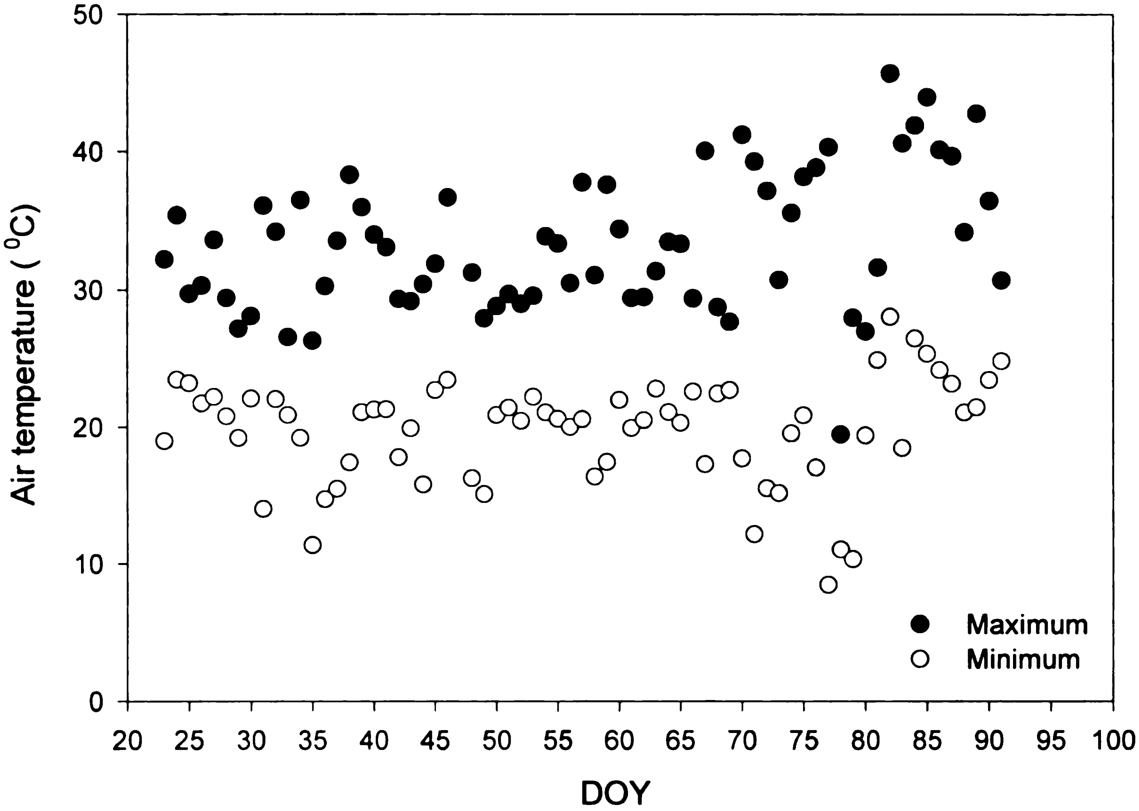


Figure 1.2. Daily maximum and minimum air temperature in the greenhouse at Michigan State University, MI. (1998).

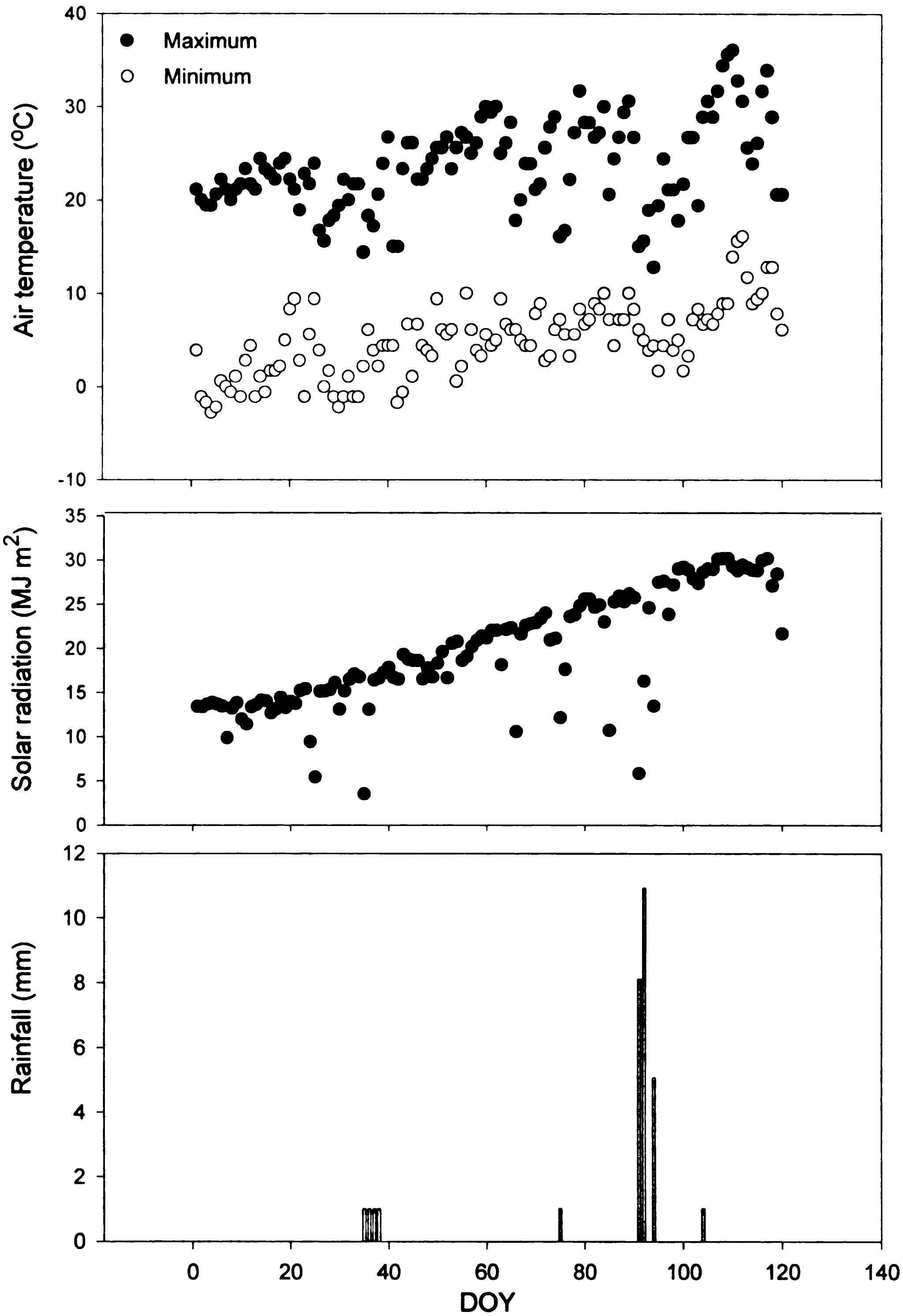


Figure.1.3. Air temperature (^oC), solar radiation (MJ m^{-2}) and rainfall (mm) at Maricopa Agricultural Center - AZ.(1999).

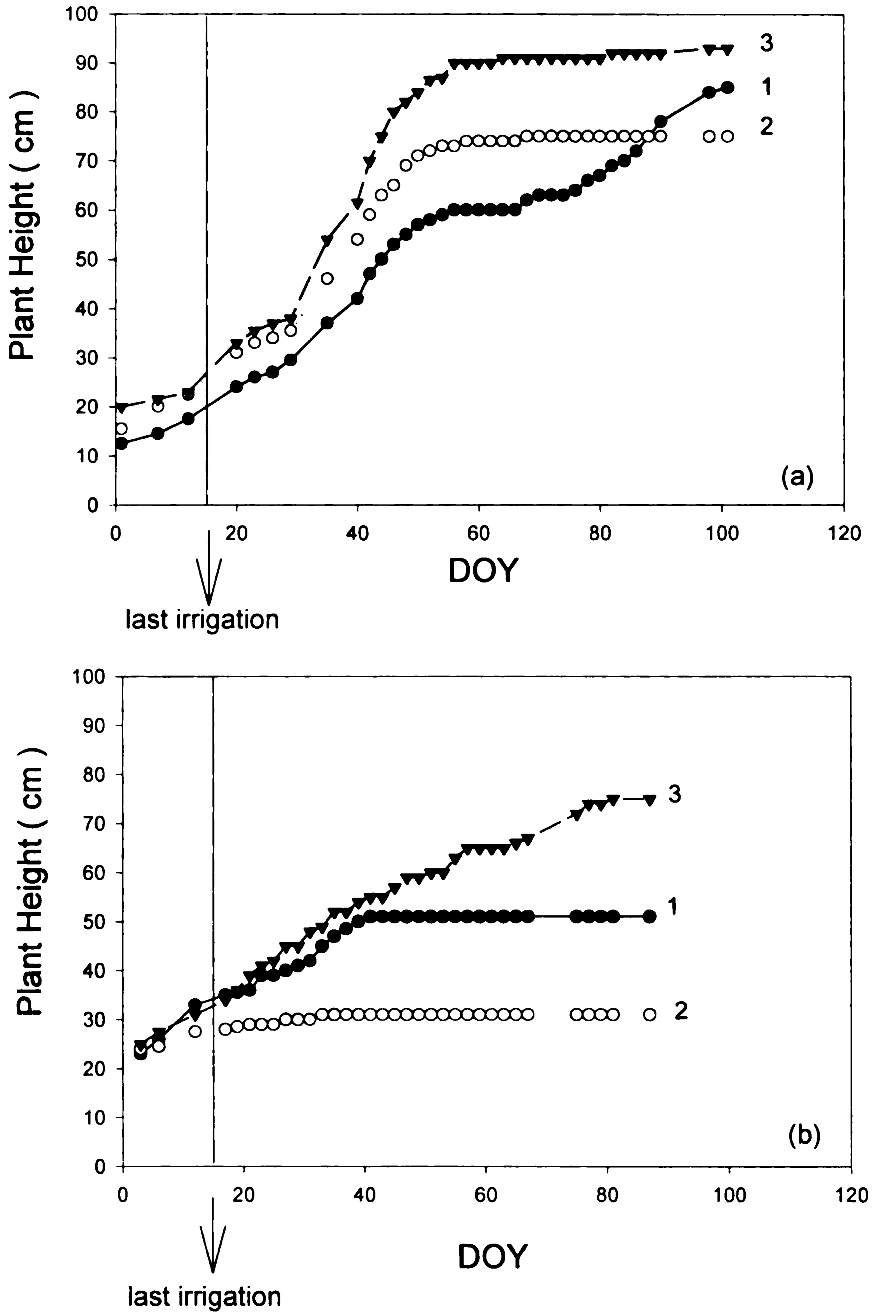


Figure 1.4. Plant height (cm) for three maize plants, C1(a) and C2(b). Greenhouse experiment at Michigan State University , MI.

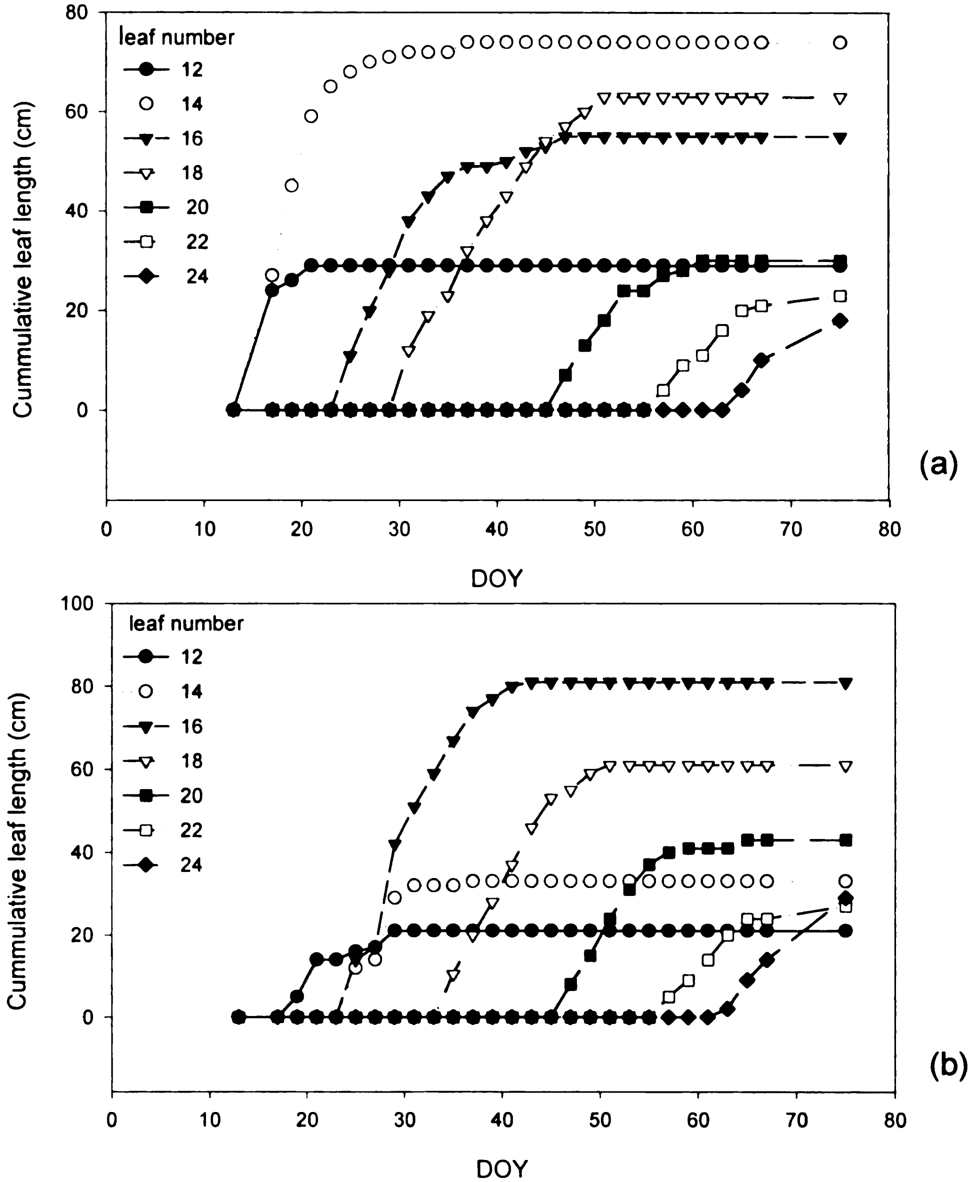


Figure 1.5. Cumulative leaf expansion from day of the year (DOY) 13 to the termination of the experiment at the greenhouse. Data for C1 (a) and C2 (b).

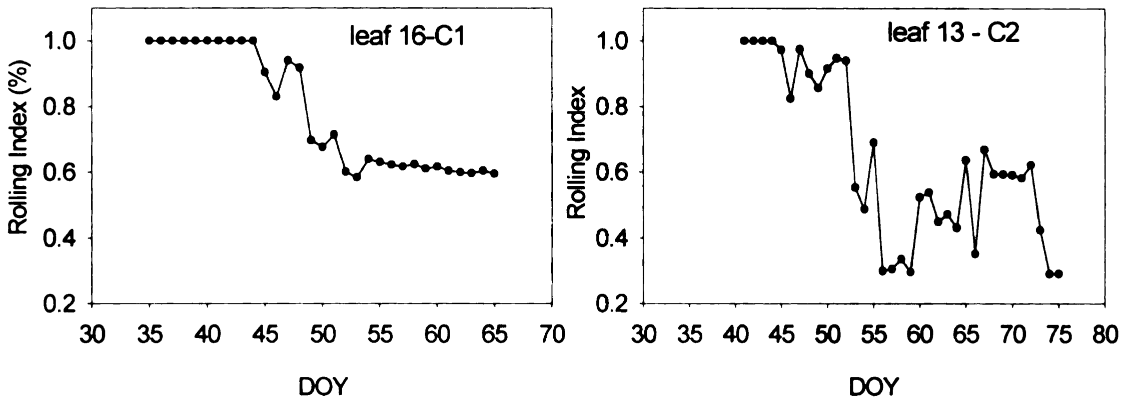


Figure 1.6. Daily leaf rolling (fraction of blade exposed) for different leaves and cylinders, from day of year (DOY)35 and 40, to the end of the greenhouse experiment at Michigan State University, MI.

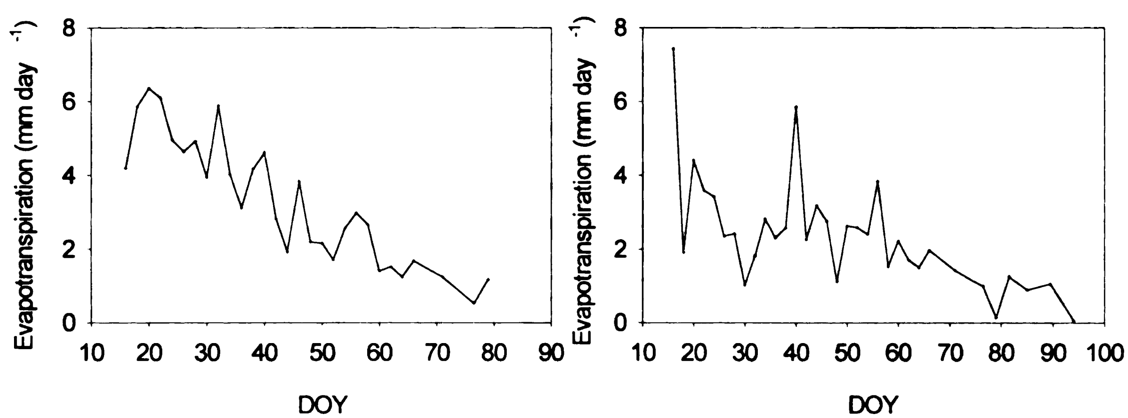
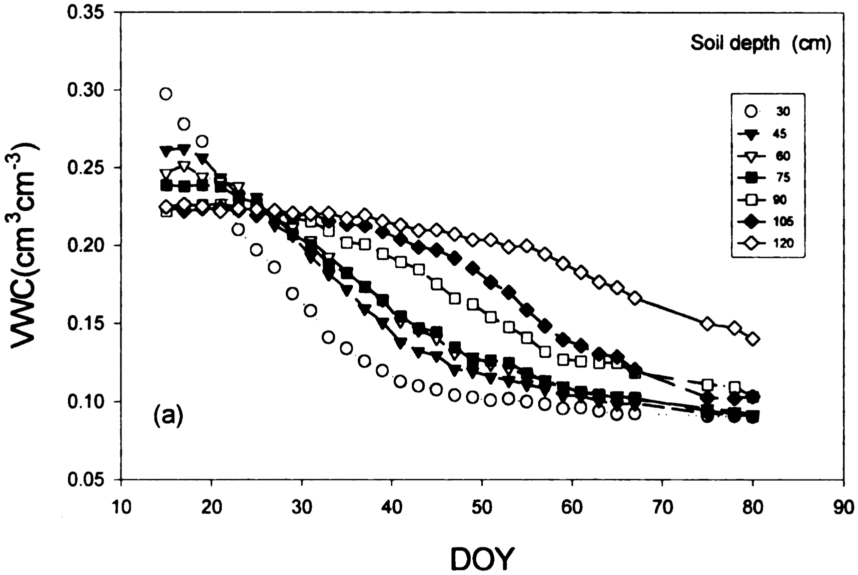


Figure 1.7. Daily evapotranspiration (mm day^{-1}), for C1 and C2, from day of year (DOY) 10 to 90. Greenhouse experiment at Michigan State University,MI.



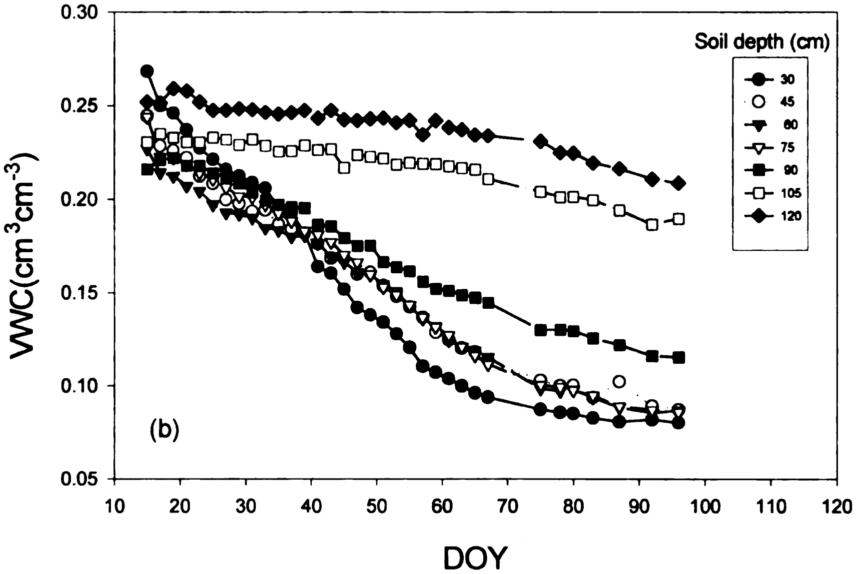


Figure 1.8. Day of year (DOY) and volumetric water content within soil depths (cm) for C1(a) and C2(b) in greenhouse experiment. Michigan State University,MI.

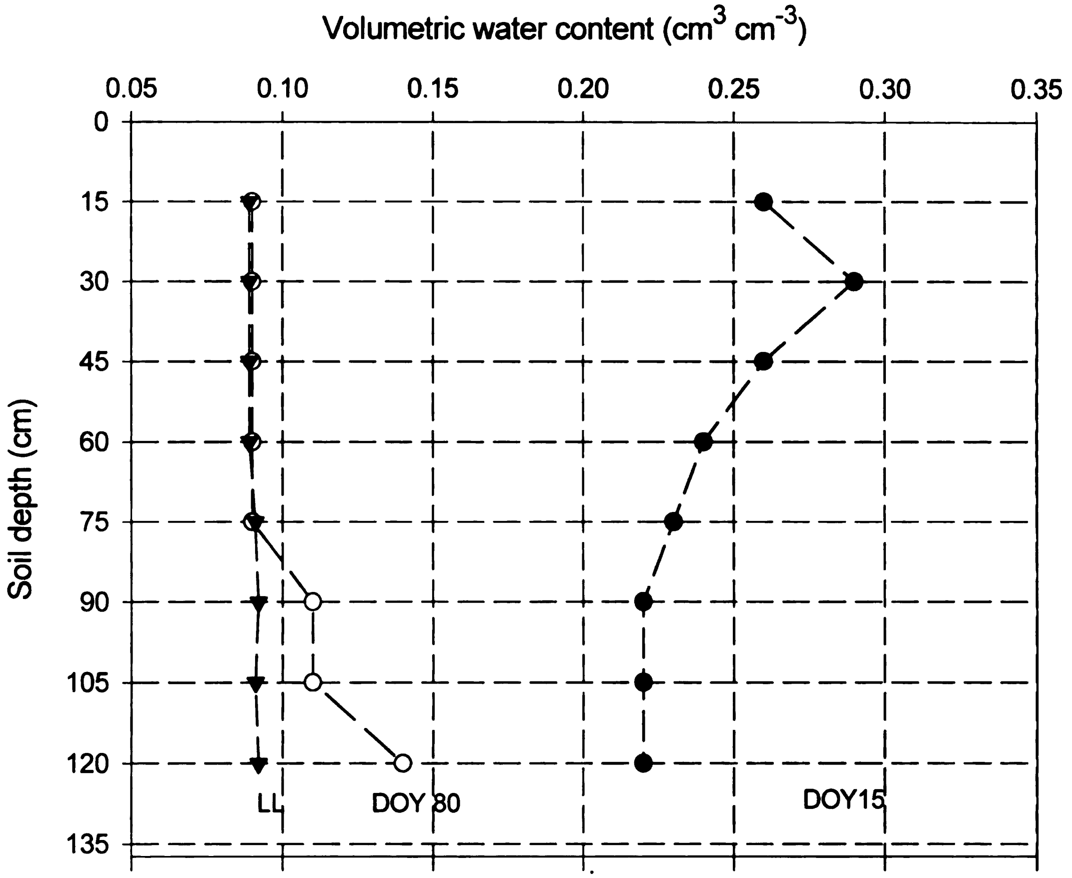


Figure 1.9. Volumetric water content (cm^3cm^{-3}) at different soil depths (cm) for day of year (DOY) 15, 80 and at lower limit (LL) (C1).

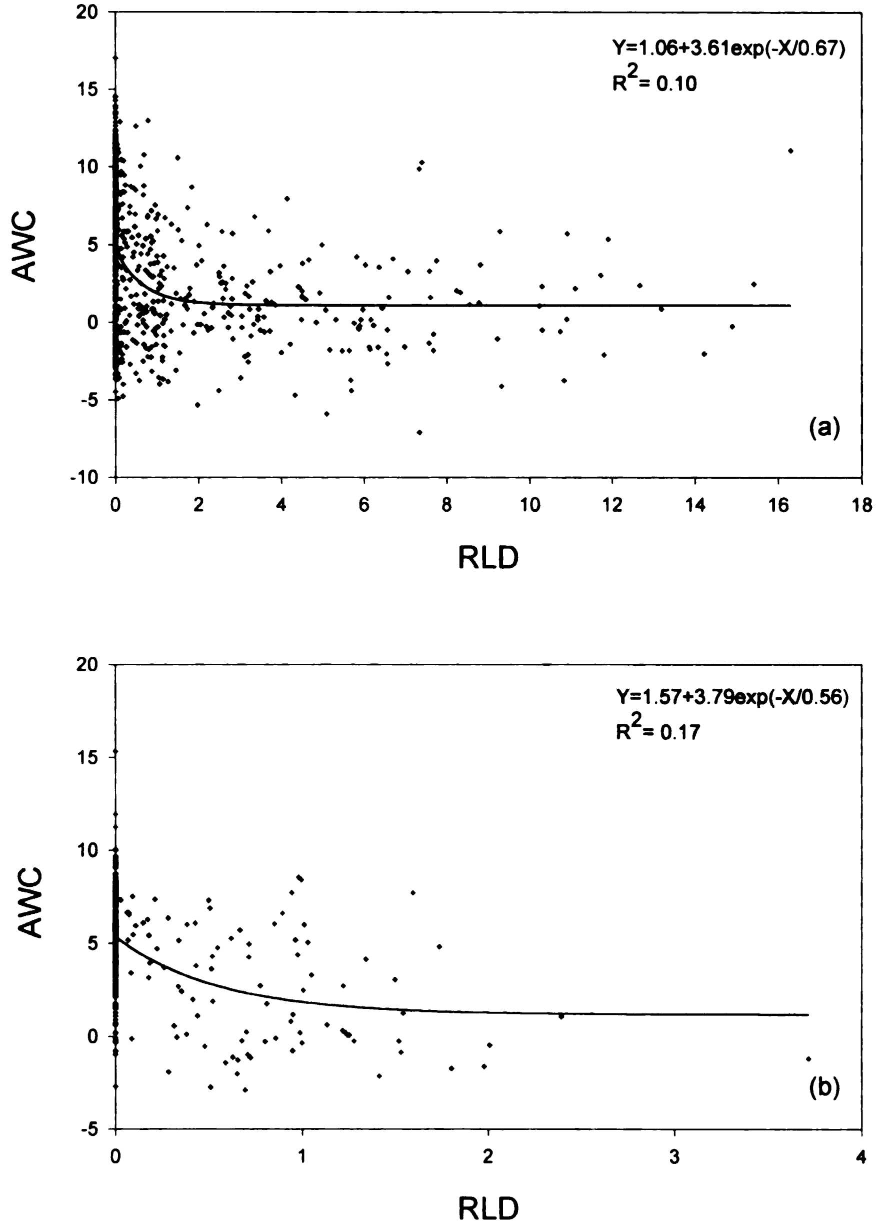


Figure 1.10. Root length density (cm cm^{-3}) (RLD) as function of available water content (%) (AWC) for two different experiments. Greenhouse experiment (a) C1 at Michigan State University, MI; and field experiment (b) at Arizona.

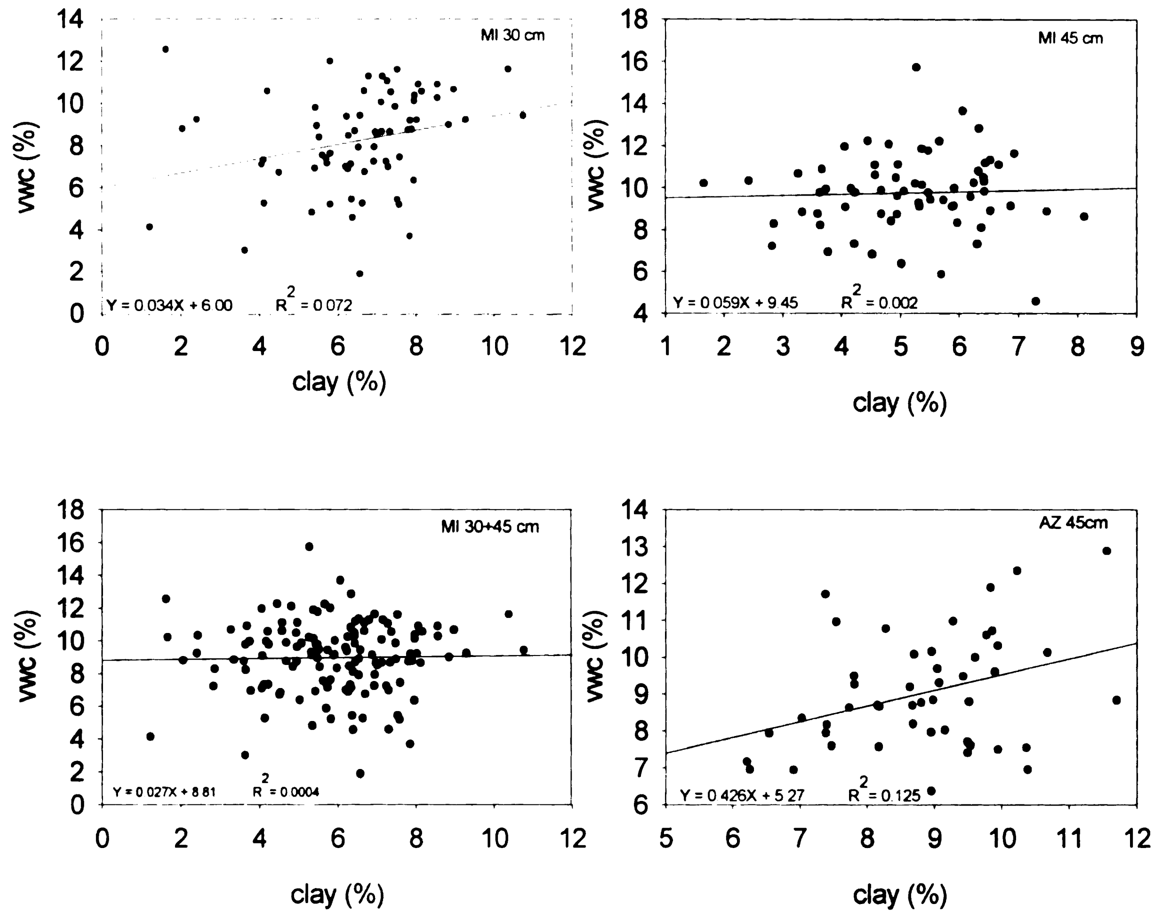


Figure. 1.11. Volumetric water content (VWC) as function of clay content (%) at 30 cm, 45 cm and combined 30+45 depth in the greenhouse experiment, and at 45 cm depth in the field experiment.

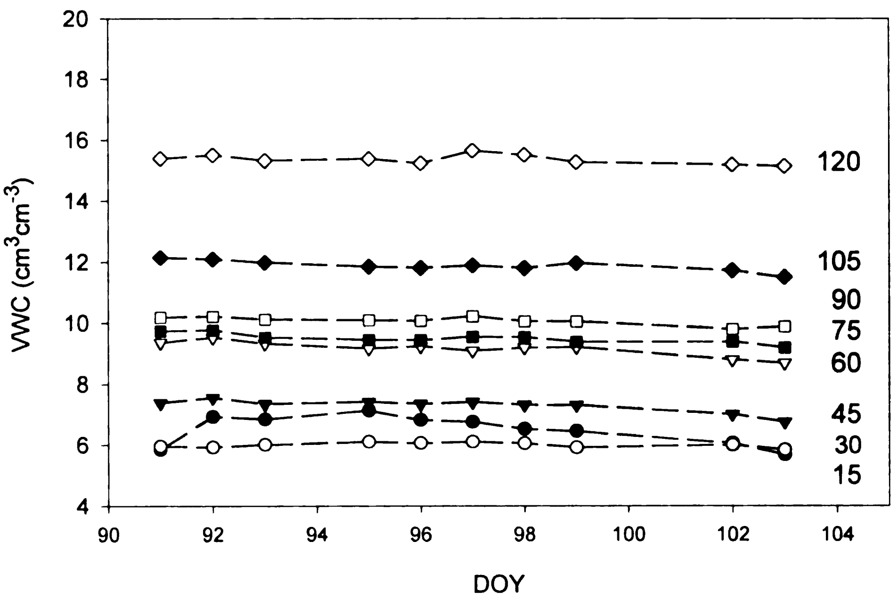


Figure 1.12. Day of year (DOY) and volumetric water content within depths (cm) at Maricopa Agricultural Center - AZ.

Table 1.1. Soil texture analysis, pH and organic matter (%) within soil layers for two locations.

Site	Soil depth	Sand	Silt	Clay	pH	O.M.
	(cm)	(-------------------	%	-------------------)		(%)
Michigan	0 - 30	74.4	18.9	6.7	7.1	0.9
	30 - 45	77.1	16.2	6.7	5.4	0.8
	45 - 60	79.1	14.2	6.7	5.9	0.8
	60 - 75	71.1	20.2	8.7	6.0	0.3
	75 - 90	59.1	22.2	18.7	6.5	0.6
	90 - 105	71.1	18.2	10.7	7.6	0.2
	105 - 120	57.1	30.2	12.7	8.1	0.2
Maricopa	0 -15	76.3	10.4	13.4	8.4	0.6
	15 - 30	80.3	8.4	11.4	8.5	0.3
	30 - 45	81.3	8.4	10.4	8.6	0.1
	45 - 60	80.1	8.5	11.4	8.7	0.2
	60 - 75	80.3	8.4	11.4	8.6	0.2
	75 - 90	81.1	7.5	11.4	8.5	0.2
	90 -105	79.9	8.7	11.4	8.3	0.3
	105 -125	75.9	11.7	12.4	8.2	0.3

Table 1.2. Descriptive statistics. Mean and standard deviation (SD), for some properties at different soil depths. Greenhouse experiment at Michigan State University,MI.

Depth (cm)		Clay	Sand	Silt	VWC	AWC	RLD	LL
		C1						
0-30	Mean	6.55 c	73.89 a	19.56 d	8.62 f	0.54 f	5.60 a	8.98 c
	SD	1.81	1.92	1.93	2.79	0.90	3.51	0.05
30-45	Mean	5.17 c	74.59 a	20.24 d	9.56 e	1.16 f	3.02 b	8.95 d
	SD	1.29	0.91	1.35	2.45	1.34	2.76	0.03
45-60	Mean	5.60 c	75.05 a	19.35 d	8.43 f	0.20 f	0.35 c	8.96 d
	SD	2.24	1.41	2.16	1.64	0.42	0.47	0.06
60-75	Mean	9.33 b	67.63 b	22.88 c	10.35 d	2.51 d	0.06 c	9.07 b
	SD	7.24	9.70	4.19	4.57	3.78	0.14	0.20
75-90	Mean	13.70 a	64.56 c	21.73 c	13.56 c	4.60 c	0.20 c	9.18 a
	SD	5.64	7.56	5.77	3.86	3.20	0.38	0.15
90-105	Mean	10.49 b	63.35 c	26.17 b	15.16 b	5.99 b	0.15 c	9.09 b
	SD	3.26	5.91	6.26	2.72	2.62	0.37	0.09
105-120	Mean	13.03 a	50.60 d	36.37 a	19.14 a	10.12 a	0.03 c	9.16 a
	SD	1.75	3.54	3.75	2.45	2.21	0.13	0.06
Fstat.		35.19**	201.80**	192.57**	235.88**	185.77**	175.74**	59.20**

Table 1.2. (cont'd).

Depth (cm)		Clay	Sand	Silt	VWC	AWC	RLD	LL
					C2			
45-60	Mean	5.71 c	73.81 a	20.46 a	8.26 c	0.55 c	0.07 a	8.36 c
	SD	1.83	1.56	1.70	1.65	0.92	0.34	0.02
60-75	Mean	8.36 b	71.64 ab	19.99 a	9.91 b	2.33 b	0.12 a	8.39 b
	SD	5.06	12.00	9.37	3.43	2.49	0.53	0.06
75-90	Mean	12.58 a	70.53 b	16.88 b	12.93 a	5.10 a	0.07 a	8.45 a
	SD	5.92	10.62	5.93	4.88	4.23	0.37	0.07
Fstat.		69.12**	3.88*	11.35**	60.36**	77.20**	0.49ns	69.02**

ns - not significant

* Significant at 0.05 probability level

** Significant at 0.001probability level.

Table 1.3. Descriptive statistics. Mean and standard deviation (SD), for some soil properties at different soil depths. Field experiment at Maricopa, AZ.

Depth (cm)		Clay	Sand	Silt	VWC	AWC	RLD	LL
30-45	Mean	8.82 b	77.54 c	13.64 b	9.03 c	0.55 c	0.92 a	9.02 b
	SD	1.27	1.45	1.49	1.53	0.89	0.70	0.54
45-60	Mean	5.07 d	80.21 a	14.72 a	12.53 b	5.14 a	0.23 b	7.42 d
	SD	1.12	1.79	1.83	2.15	2.21	0.41	0.48
60-75	Mean	4.30 e	80.42 a	15.28 a	12.80 b	5.71 a	0.03 c	7.10 e
	SD	1.11	4.47	4.61	1.93	0.47	0.13	0.47
75-90	Mean	6.26 c	80.22 a	13.52 b	13.10 b	5.16 a	0.01 c	7.93 c
	SD	1.29	2.70	2.45	1.68	1.81	0.04	0.55
90-105	Mean	9.17 b	78.75 b	12.07 c	14.71 a	5.55 a	0.01 c	9.17 b
	SD	1.85	3.09	3.09	2.89	2.88	0.09	0.79
105-125	Mean	12.49 a	74.81 d	12.70 bc	14.96 a	4.37 b	0.00 c	10.59 a
	SD	3.20	5.50	3.08	2.69	2.31	0.00	1.36
Fstat.		266.99 **	35.21 **	15.21 **	55.84 **	44.45 **	93.01 **	266.99 **

** Significant at 0.01 probability level.

Table 1.4. Statistical correlation for volumetric water content (VWC), lower limit (LL), available water content (AWC), root length density (RLD) and clay within soil depths at two different locations.

	Soil depth	VWCxCLAY		VWC X RLD		LLxCLAY		LLxRLD		AWCxCLAY		AWCxRLD		RLDxCLAY	
Michigan C1	0-30	0.26	*	-0.06	ns	0.96	**	-0.21	ns	0.11	ns	0.07	ns	-0.21	ns
	30-45	0.04	ns	-0.19	ns	0.98	**	-0.08	ns	0.06	ns	-0.20	ns	-0.08	ns
	45-60	0.07	ns	-0.07	ns	0.97	**	0.01	ns	-0.19	ns	-0.08	ns	0.00	ns
	60-75	0.90	**	-0.09	ns	0.96	**	-0.07	ns	0.88	**	-0.06	ns	0.07	ns
	75-90	0.71	**	0.16	ns	0.97	**	0.22	*	0.69	**	0.13	ns	0.22	*
	90-105	0.61	**	-0.07	ns	0.97	**	0.04	ns	0.59	**	-0.08	ns	0.04	ns
	105-120	-0.03	ns	0.04	ns	0.95	**	0.10	ns	-0.01	ns	0.04	ns	-0.05	ns
Michigan C2	45-60	-0.01	ns	-0.09	ns	0.99	**	0.04	ns	0.14	ns	-0.07	ns	0.47	ns
	60-75	0.86	**	0.09	ns	0.99	**	0.16	ns	0.84	**	0.08	ns	0.16	ns
	75-90	0.29	**	-0.001	ns	0.98	**	-0.13	ns	0.29	**	-0.02	ns	-0.13	ns
Arizona	30-45	0.35	*	-0.05	ns	0.97	**	0.04	ns	0.15	ns	-0.07	ns	0.03	ns
	45-60	-0.11	ns	-0.06	ns	0.95	**	-0.13	ns	0.32	**	-0.01	ns	0.13	ns
	60-75	0.02	ns	-0.08	ns	0.98	**	0.01	ns	0.22	*	-0.08	ns	0.02	ns
	75-90	-0.01	ns	-0.03	ns	0.90	**	0.10	ns	0.38	**	-0.06	ns	0.10	ns
	90-105	0.08	ns	0.00	ns	0.97	**	-0.13	ns	-0.18	ns	0.03	ns	-0.13	ns
	105-125	0.50	**	-		0.91	**	-		0.00	ns	-		-	

Pearson correlation

** Highly significant at $P<0.01$

* Significant at $P<0.05$

Table 1.5. Root Length (RL) for five width classes, total root length (TRL), root surface area (RSA) and root volume (RV) within soil depths. Data for corn in Michigan and barley in Arizona.

		RL(cm)							
	Soil	Class 1	Class 2	Class 3	Class 4	Class 5	TRL	RSA	RV
Site	Depth (cm)	(0-0.2 mm)	(0.2-0.5mm)	(0.5-0.9mm)	(0.9-1.4mm)	(1.4-2.1mm)	(cm)	(cm^2)	(cm^3)
Michigan	0-30	3473.67	2617.26	531.41	171.47	123.40	6917.22	643.57	9.59
(C1)	30-45	1511.35	1288.84	373.46	170.81	194.78	3539.24	440.12	9.26
	45-60	180.70	95.98	51.82	49.34	85.14	462.98	89.45	2.75
	60-75	67.62	25.31	1.81	0.97	0.00	95.72	5.66	0.05
	75-90	158.27	126.29	10.64	8.17	6.54	309.91	27.45	0.42
	90-105	95.80	77.93	12.61	8.67	9.16	204.17	22.52	0.44
	105-120	13.48	27.45	4.17	0.87	0.48	46.45	4.94	0.06
Michigan	45-60	46.88	46.68	21.94	10.62	11.94	116.93	21.83	0.53
(C2)	60-75	71.17	38.09	22.92	27.52	40.91	195.89	43.90	1.40
	75-90	23.62	23.62	14.91	18.54	28.38	128.65	29.66	0.96
Arizona	30-45	130.32	104.72	81.06	78.76	172.91	567.76	156.95	5.40
	45-60	108.18	57.93	35.39	36.27	56.49	294.26	61.71	1.94
	60-75	19.45	7.91	3.18	2.35	5.15	38.03	5.86	0.17
	75-90	5.56	0.79	0.00	0.00	0.00	6.36	0.26	0.00
	90-105	0.98	1.07	1.54	3.23	4.69	11.51	4.23	0.15
	105-125*	-	-	-	-	-	-	-	-

(*) No roots found at this layer.

Chapter 2

Spatial variability of soil texture, root distribution and water content in different soils. II: A Geostatistical approach to describe micro-scale spatial variability.

Introduction

Soil environment is a complex media to host plant growth (Russel, 1977; Jones et al., 1991; Kramer and Boyer, 1995). The inherent heterogeneity of soil properties will affect not only root growth, but also water content and the interaction among them (Ahuja and Nielsen, 1990). Such complex environment offers several restrictions to root growth through physical, chemical and biological stresses, which may vary at different scale in space and time (Russel, 1977; Kuiper et al., 1988; Bennie, 1996). Thus, roots may experience different environments when growing through the soil matrix (Passioura, 1991). The heterogeneous nature of soil causes a high degree of variability in root growth, which consequently affects the top portion of the plant (Brown and Scott, 1984).

Understanding the soil spatial variability is important for crop production (Saddiq et al., 1985). Usually, studies of spatial variability involve distances that can vary from meters to hundreds of meters (Yost et al., 1982; Warrick et al., 1986), and the spatial variability of soil physical, chemical and hydraulic properties will be treated according to the scale adopted (Trangmar et al., 1986). Studies about the micro-scale variability of such properties or related to spatial variability of root growth are scarcer (Amato, 1991; Tsegaye et al., 1998a,b). Few studies were done, but none of them used robust tools to analyze the results achieved (Tardieu, 1989; Bruckler et al. 1991b).

Studies of spatial variability demand that sampling procedure be made in a grid pattern to consider the dependence among sampled regions (Isaaks and Srivastava, 1989). Since the magnitude of soil properties at one location is usually related to the magnitude at another location in the same area, the use of classical statistics, that assumes spatial independence, is not appropriate (Brown and Scott, 1984).

A branch of statistics, referred as geostatistics, was developed by Matheron (1973) to solve the problems concerning the spatial variability. Geostatistical analysis calculates correlation among observations made at different locations (Trangmar et al., 1985,1986; Isaaks and Srivastava, 1989). The observed correlation can then be used in practical applications to estimate values at unsampled locations by means of kriging and co-kriging techniques (Journel and Huijbregts, 1978; Isaaks and Srivastava, 1989; Goovaerts, 1992, 1994, 1997).

Considering the natural variability of soil properties and the uneven distribution of roots on the soil matrix, geostatistical analysis may be a valuable tool to understand the complex inter-relationships between soil and roots. By visualizing kriged maps, geostatistics can help us to assess how roots are distributed in the soil when crops grow under different environmental conditions.

The results obtained in geostatistical analysis could improve water extraction models. Water extraction could be better predicted and crop yield improved if such water models could take into account spatial variability of root distribution.

The goal of this study was to apply the principles of geostatistical analysis in two data sets collected in two different locations, to understand the bypassing of soil regions and uneven distribution of roots, during periods of water deficit.

Material and Methods

The data set used to describe the spatial variability of soil water content, roots and soil texture were collected at Michigan State University Research Farm, East Lansing, MI and Maricopa Agricultural Center, Maricopa, AZ.

All procedures adopted to measure volumetric water content, as well as the methodology used to analyze root and soil samples were described in chapter one.

The values for available soil water content in each soil sample were calculated by the difference between volumetric water content at the end of the experiment and the respective lower limit for each sample. Values of lower limit of soil water content for each soil layer, and consequently for each soil sample, were estimated by using the equations showed in Figure 1.11. In this case, it was assumed that at upper layers, LL was reached and that this value was equal to the average of VWC determined by the TDR measurements. By plotting the VWC found for each sample and the clay content in each sample for the upper layers, it was possible to establish a simple relationship to estimate the LL for deep layers based on the values of clay content.

Statistical Approach

Statistical analysis were performed on the percent of clay, sand, silt, VWC (%), AWC (%), and RLD (cm cm^{-3}) for all layers in both locations.

Each variable was first subjected to a classical statistical analysis to obtain the minimum and maximum values, mean, variance and standard deviation within each soil layer using the GLM procedure in SAS (SAS Institute, 1990). The degree of spatial variability for each variable, except for sand and silt, was determined by geostatistical methods (Vieira et al., 1983; Trangmar et al., 1985; Isaaks and Srivastava ,1989). A semivariogram model, which mathematically describes the moment of inertia around the diagonal of the associated h-scatterplot, and thus indicating how points are spatially correlated in a scatterplot (Trangmar, 1985, Isaak and Srivastava, 1989; Goovearts, 1997), was fitted to each variable to find the parameters necessary to utilize a kriging procedure.

A semivariogram consists of four basic parts; the nugget effect, range, sill and the structural variance (Figure 2.1). The nugget effect (Co) represents the unexplained or random variance, which is caused by sampling error, or variability of the variable which cannot be detected by sampling scale used (Trangmar et al., 1985). The Range represents the distance over which the variables exhibit no spatial dependence, and is defined by the value at which the curve reaches the sill. Sill approximates the sample variance, and is the region of relatively constant semivariance. It is the point where semivariance is at its maximum value. The structural variance (C) is the portion of the total variation correlated with distance.

The semivariogram model gives us the values of sill, range, Co, and C, which are used in the kriging procedure. Kriging is a technique of making optimal, unbiased estimates of variables studied at unsampled locations using the values obtained in the semivariogram and the initial data set (Trangmar et al.,1985). Semivariogram models for the variables in this study were calculated by using GSPlus+ (Robertson, 1998). Each property was kriged and mapped based on the values obtained in the semivariogram model, with Surfer V. 6.0 (Golden Software, 1997).

Results and Discussion

The study of spatial variability by using the geostatistical approach sometimes requires the same results produced by classical statistics, e.g., means, standard deviation, variance, histograms (Isaac and Srivastava, 1989). This is only the initial step to characterize the spatial variability of the variables being studied.

The results of the statistical analysis performed for soil texture, VWC and AWC, RLD are depicted on Tables 2.1, 2.2 and 2.3 for Michigan and Arizona. In general, clay content increased with depth for both places. In the greenhouse experiment this increase in clay content was observed below 75 cm in C1 and below 90 cm in C2. In C1 the average of clay content changed from 5% at 60 cm to 13% at 120cm depth. However, maximum values were found at 75 cm, 26% of clay, and 90 cm, 27% of clay. Variance and standard deviation were also high for these layers. Yet, the variation of clay content in C2 was about 5 to 13%, almost the same range observed for C1. At MAC, the average of clay content also increased below 75 cm depth going from 4% to 12%. Contrary to the results of variance and standard deviation observed at Michigan, at MAC their values increased with depth. Values for standard deviation varied from 1.1 to 3.2 and variance ranged from 1.2 to 10.2.

RLD (cm cm^{-3}) decreased with depth in both places and the highest concentration was found at the upper layers; 0-30 cm and 30-45 cm at Michigan and 30-45 cm at MAC. The amount of roots at bottom layers was low for both layers, with complete absence of roots at 105-125 cm at MAC. For this experiment the high concentration of calcium carbonate at 45-60 cm may have impeded the root development in deep layers. Subsoil with naturally high mechanical impedance due to factors such as duripans, fragipans, petrocalcic layers, or placic layers have a great impact in root growth in some soil layers (Bennie, 1996). At 45-60 cm maximum values of RLD were around 3.7 and 1.7 cm cm^{-3}, compared to values of 0.85 (60-75cm), 0.43 (75-90 cm) and 0.0 cm cm^{-3} (125cm). For the experiment at Michigan, this variation was around 16.3 (0-30 cm) to 0.79 cm cm^{-3} (120 cm) with a slight increase in RLD at 75-90 and 90-105 cm.

An increase in VWC and AWC followed the increase in clay content in both places and this is probably a consequence of the capacity of water retention by clay minerals. Nevertheless, the increase in available water content could also be a consequence of roots bypassing some soil regions leaving water behind during root growth or connected to the clay content. It was reported by Dwyer et al. (1988) that root depth and distribution were influenced by AWC and soil physical characteristics, and that the maximum root depth was inversely proportional to AWC.

The range (R), sill (Co+C), nugget effect (Co), and nugget to sill ratio (Co/Co+C) for AWC and RLD in all soil depths in both places are depicted on Table 2.4. The nugget to sill ratio, expressed as percentage, can be regarded as a criterion to classify the spatial dependence of the variables observed in this study. If this ratio is less than 25%, the variable has strong spatial dependence; if the ratio is 25-75%, the variable has moderate spatial dependence; otherwise, the variable has weak spatial dependence (Chien, et al.,1997).

These results show that AWC had a strong to weak level of spatial dependence for C1, with values ranging from 20% to 99%. A weak spatial dependence in C2 was also observed. For the field experiment, the results for AWC were similar to the results observed in C1 in the greenhouse experiment. This degree of the spatial dependence varied from 0.9% to 83%. Root length density also showed moderate to weak spatial dependence both in C1 and in field experiment. A weak dependence was observed in C2 and at 105-125 cm for RLD, probably because the low amount of roots found. Usually, the spatial variability of soil properties is related to intrinsic and extrinsic factors. Intrinsic factors (soil formation factors, parent material) will determine strong spatial dependence; on the other hand, extrinsic factors (soil management practices) will determine weak spatial dependence. Nevertheless, in soil properties it is normal to observe a moderate spatial dependence (Cambarella, 1994; Chien, et al., 1997).

The range for AWC and RLD varied from 5 cm to about 45 cm in the greenhouse experiment and from 3 cm to 9 cm in the field experiment (Table 2.4). Usually, the Range observed for some soil properties varies from few meters to hundreds of meters. For instance, there are reports where sand range varied from 5 m up to 1000 m, clay range was 723 m, silt 1290 m, and soil water content with range about 16m (Warrick, 1986; Chien et al., 1997). But, surprisingly, in this study this variation was about centimeters, and this could be due to the scale adopted. Depending on the objectives and scale of the observation needed, these results could be considered as part of the nugget variation in other studies of spatial variability of soil properties. However, in this study the spatial variability could be detected at this small scale. Above the observed R there was no spatial relationship. When linear models were used, R showed high values, meaning that the spatial dependence could not be detected in small scale. For example, RLD for soil layers at 30 and 45 cm depth in C1, the difference between the minimum and maximum values and the standard deviation observed were high (Table 2.1). This could be caused by some samples presenting high values of RLD when compared to the average of all samples.

The values for sill, range and nugget for AWC and RLD were obtained by using the GSPlus+ software (Robertson, 1998) and then used as input in Surfer to obtain the krigged surface maps (Figures 2.2, 2.3 and 2.4). These values were obtained after semivariogram models were fitted to pairs of data observed at lag distances for each variable at each soil layer in both places. For the greenhouse experiment, 98% of the models fitted were spherical, and 2% were linear. For the field experiment all models were spherical. These models were fitted automatically by the GSPlus+ (Robertson, 1998). The user can, in most situations, change the values obtained in the automatic fit; however, this would be time consuming and sometimes worthless considering that the model presented automatically by the program was the one with the best fitted value. To determine how well these models were fitted to the semivariogram, an indicative of goodness fit (IGF)(without units) was used, where values close to zero indicated better fit of the model.

To make the relationship between AWC and RLD more evident, cut-off values were attributed to RLD and AWC. RLD received a value equal to 1cm cm^{-3} and the cut-off value for AWC was 10%. This means that values above the cut-off values for both variables were made equal to the cut-off values established. This was done because some samples presented results extremely high and others extremely low, which made the comparison among surface maps extremely difficult.

In a broad sense these maps show that AWC was higher at deep layers than that observed at upper layers. In the greenhouse experiment, AWC below 75 cm depth for C1 was higher than 10%. There are some patches with values below 10% but these patches follow some patterns in their distribution for all layers. Exception made at 120 cm where AWC is higher than 10% in almost the entire layer analyzed. This pattern was probably caused by two reasons. One reason is that AWC was considered to be the amount of water above the LL. As it was said before, the LL was calculated by using the clay content for each individual sample. Analyses of correlation performed in the previous chapter show that a strong correlation between clay content and LL occurred, with R^2 values around 96%. This value means a positive correlation, or an increase in clay content means an increase in LL. In some way, this irregular distribution of AWC is connected to the amount of clay. The same analogy was adopted when the analysis for C2 and the field experiment.

The second reason, is a function of the amount of and root distribution in these layers. Soil layers presenting high values of RLD had less AWC. It means that roots extracted all water they could independent of their distribution on a specific layer. This can be seen in Figure 2.2, for layers 30 and 45 cm, where values for AWC are around 0 to 4% and RLD is as higher as the cut-off value. However, below 45 cm the pattern of AWC distribution is function of root distribution. Here we can see that the roots bypassed soil layers leaving water behind, without being extracted. This characteristic is evident in soil layers at 60, 75, 90 and 105 cm. At 60 and 75 cm depth, spots with high values of AWC were found outside the zones of high concentration of roots. Arrows in these surface maps indicate the spots where high concentrations of roots are opposed to low values of AWC. At 90 and 105 cm the evidence of bypassing is stronger than that observed in the previous layers. The surface map at 90 cm shows some spots, indicated by arrows, where the bypassing is occurring. This map clearly shows that in some soil regions roots are clumped and that the water extracted was high in these regions. However, at short distances far from these clumps, AWC reaches values around 8-9%. The same thing is observed in the surface map at 105 cm. The explanation for this root clumping may be related to the clay content. In the greenhouse experiment, for C1, clay content was different at each soil layer (Table 2.1). The range observed between the minimum and maximum values of clay content, for instance at 90cm depth, varied from 3 to 27%. Such variation is also observed at other layers. If these samples were taken in a grid pattern at each soil layer, one can say that clay content presented spatial variability. Thus, this variability could have affected root growth throughout soil matrix.

The relationship between AWC and RLD was presented in Figure1.10. In this figure the R^2 is low, meaning a poor correlation; but it was not possible to give a good interpretation without looking at the surface map of these variables. Now, it is evident why the correlation was poor; roots were clumped and there was a spatial variability for AWC.

An interesting feature is observed in Figure 2.2 for soil depths from 60 to 105 cm. The classical statistical analysis showed that the amount of roots decreased within soil depths (Table 2.1). One can observe that in these layers the variation in the amount of roots occurred in one specific zone of the soil and that this zone is located at least at the same position in all soil depths. Considering the variation observed in RLD in these layers we can say that roots grew clumped and bypassed the entire soil layer located at the depth of 75 cm;

thus, not absorbing water. The same kind of analysis adopted for C1, was used in C2 and similar results were observed.

For the field experiment, the same evidences of root clumping and soil bypassing were observed for soil layers at 45 and 60 cm. The RLD and AWC were spatially distributed and zones of high water extraction were located at same position where the high values of RLD were found (Figure 2.3). Below 60 cm, the amount of roots decreased and the AWC was more disperse, without following a specific pattern.

All surface maps discussed here, for both places, indicated that there is strong evidence to explain why roots were clumped and bypassed some soil regions. In this study, by sampling the soil in a grid pattern, it was possible to see that the same variable differed by several units at same soil depth. Usually it is assumed that macropores, fissures or other natural openings in the soil cause non-uniform distribution of roots. Based on the results presented here, clay and water content had an important role in the root clumping and distribution at each soil depth. The non-uniform distribution of clay observed in this case affected root distribution by directing root growth toward soil zones where water content was lower than that observed in regions with high clay content. Generally, clay can hold high amount of water; however, if clay content is so high that can cause impediment to root growth, roots will not penetrate that soil region and will bypass it leaving water without being extracted. For root to elongate, the mechanical impedance of the soil against the cross section of the root must be less than the pressure exerted by the root itself (Bennie, 1996). If root growth pressure is higher than the pressure or resistance that soil and cell wall is exerting, then root will grow and penetrate that region; otherwise they will stop or branch in another direction. Depending on the impedance offered by the soil in determined regions, roots will grow together and will be clumped in regions were the soil penetration and even water extraction is easier. In this way, a natural clumping will occur in that region with several consequences, such as, by drying the soil region on the vicinity of roots as we saw in all surface maps. This could increase the soil resistance to water movement from other parts of the soil towards the roots. In this case, there is water in the soil around roots, but its hydraulic conductivity is low to allow water movement and consequently no water extraction can occur.

Amato (1991) showed that roots could grow around soil peds but not penetrate them. In her work, it was seen that the interior of these peds held a considerable amount of water inside, but this water was not available for roots to absorb it, resulting in an increase in water stress. Thus, a considerable amount of water was left, resulting in a localized region of soil water gradients. Thus, it is true that some regions in the soil can hold more or less water, which affects the volume of water extracted by roots. To survive in this situation, plants need to produce more roots at deep layers or to increase water absorption in soil regions were water still available. Nevertheless, new roots at deep layers or at different soil region do not mean a guaranty of water supply. The amount of roots produced can be insufficient to absorb water and supply the total demand of water by plant as a function of transpiration (Passioura, 1983). Also, water could be held tightly in the soil by clay particles at potentials higher than that plant could overcome.

Summary and Conclusions

In this study, the analysis of the spatial variability of AWC and RLD for the greenhouse and field experiments, was the determining factor to demonstrate that roots can bypass soil regions and leave water without being extracted. As a consequence of the bypassing, plants will be affected by water deficit even when a supply of water is still available in the soil. Similar results may be achieved in other circumstances and for different soils; however, studies like this one in other soils need to be repeated to verify whether or not this phenomenon can be manifested again.

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Table 2.1. Descriptive statistics for root length density (RLD), volumetric water content (VWC), available water content (AWC), clay, sand, silt and lower limit (LL) within soil depths. Greenhouse experiment (C1) at Michigan State University.

Depth (cm)	Min.	Max.	Mean		Variance	SD
			RLD (cm cm^{-3})			
0-30	0.67	16.30	5.60	a	12.35	3.51
30-45	0.00	12.67	3.02	b	7.60	2.76
45-60	0.00	2.14	0.35	c	0.22	0.47
60-75	0.00	0.86	0.06	c	0.02	0.14
75-90	0.00	1.74	0.20	c	0.15	0.38
90-105	0.00	2.20	0.15	c	0.14	0.37
105-120	0.00	0.79	0.03	c	0.02	0.13
			VWC (%)			
0-30	1.87	19.26	8.62	f	7.76	2.79
30-45	2.41	20.09	9.56	e	6.03	2.45
45-60	4.46	14.40	8.43	f	2.70	1.64
60-75	4.09	22.52	10.35	d	20.85	4.57
75-90	4.16	19.91	13.56	c	14.88	3.86
90-105	8.82	23.77	15.16	b	7.40	2.72
105-120	10.98	26.32	19.14	a	5.98	2.45
			AWC (%)			
0-30	0.00	3.69	0.54	f	0.81	0.90
30-45	0.00	6.77	1.16	f	1.81	1.34
45-60	0.00	1.65	0.20	f	0.17	0.42
60-75	0.00	13.15	2.51	d	14.30	3.78
75-90	0.00	10.56	4.60	c	10.27	3.20
90-105	0.00	14.56	5.99	b	6.88	2.62
105-120	3.66	17.00	10.12	a	4.92	2.21
			Clay (%)			
0-30	1.22	10.76	6.55	c	3.26	1.81
30-45	1.66	8.11	5.17	d	1.66	1.29
45-60	2.46	13.52	5.60	c	5.02	2.24
60-75	0.41	26.96	9.33	b	52.47	7.24
75-90	3.34	27.36	13.70	a	31.76	5.64
90-105	3.34	19.97	10.49	b	10.65	3.26
105-120	9.08	18.57	13.03	a	3.05	1.75
			Sand (%)			
0-30	68.21	77.28	73.89	a	3.68	1.92
30-45	72.82	77.40	74.59	a	0.82	0.91
45-60	70.54	82.12	75.05	a	1.98	1.41
60-75	47.98	80.08	67.63	b	94.15	9.70
75-90	53.07	82.22	64.56	c	57.19	7.56
90-105	50.99	75.90	63.35	c	34.87	5.91
105-120	44.55	74.28	50.60	d	12.55	3.54

Table 2.1. (cont'd)

			Silt (%)			
0-30	15.61	24.94	19.56	d	3.74	1.93
30-45	16.99	23.42	20.24	d	1.82	1.35
45-60	10.06	23.23	19.35	d	4.68	2.16
60-75	15.51	35.66	22.88	c	17.55	4.19
75-90	8.66	33.66	21.73	c	33.30	5.77
90-105	17.82	41.93	26.17	b	39.20	6.26
105-120	13.19	42.82	36.37	a	14.04	3.75
			LL(%)			
0-30	8.84	9.10	8.98	c	0.0029	0.05
30-45	8.85	9.03	8.95	d	0.0012	0.03
45-60	8.87	9.17	8.96	d	0.0031	0.06
60-75	8.82	9.54	9.07	b	0.0385	0.20
75-90	8.90	9.55	9.18	a	0.0233	0.15
90-105	8.90	9.35	9.09	b	0.0078	0.09
105-120	8.81	9.31	9.16	a	0.033	0.06

Within columns, means followed by the same letter are not significantly different

Duncan at 0.01 probability.

Table 2.2. Descriptive statistics for root length density (RLD), volumetric water content (VWC), available water content (AWC), clay, sand, silt, and lower limit (LL) within soil depths. Greenhouse experiment (C2) at Michigan State University, MI.

Depth (cm)	Min.	Max.	Mean		Variance	SD
			RLD (cm cm ^{3})			
60	0.00	3.51	0.07	a	0.12	0.34
75	0.00	5.22	0.12	a	0.28	0.53
90	0.00	3.60	0.07	a	0.13	0.37
			VWC (%)			
60	2.99	13.90	8.26	c	2.74	1.65
75	4.54	17.89	9.91	b	11.81	3.43
90	3.12	25.91	12.93	a	23.88	4.88
			AWC (%)			
60	0.00	3.51	0.55	c	0.85	0.92
75	0.00	5.22	2.33	b	0.28	2.49
90	0.00	17.56	5.10	a	17.97	4.23
			Clay (%)			
60	0.84	9.60	5.71	c	3.37	1.83
75	0.82	20.09	8.36	b	25.67	5.06
90	2.82	25.51	12.58	a	35.08	5.92
			Sand (%)			
60	69.14	77.89	73.81	a	2.45	1.56
75	52.39	87.26	71.64	ab	104.17	12.00
90	48.64	88.58	70.53	b	112.94	10.62
			Silt (%)			
60	16.16	24.69	20.46	a	2.90	1.70
75	10.11	95.65	19.99	a	87.96	9.37
90	5.48	32.74	16.88	b	35.25	5.93
			LL(%)			
60	8.29	8.41	8.36	c	0.0006	0.02
75	8.29	8.55	8.39	b	0.0044	0.06
90	8.32	8.62	8.45	a	0.006	0.07

Within columns, means followed by the same letter are not significantly different

Duncan at 0.01 probability.

Table 2.3. Descriptive statistics for volumetric water content (VWC), available water content (AWC), root length density (RLD), clay, sand, silt and lower limit (LL) within soil layers. Field Experiment at Maricopa Agric.Center, AZ.

Depth(cm)	Min.	Max.	Mean		Variance	SD
		VWC (%)				
30-45	6.38	12.88	9.03	c*	2.35	1.53
45-60	5.23	16.90	12.53	b	4.63	2.15
60-75	6.09	16.72	12.80	b	3.73	1.93
75-90	9.32	19.05	13.10	b	2.83	1.68
90-105	7.37	23.36	14.71	a	8.38	2.89
105-125	10.25	23.06	14.96	a	7.23	2.69
		AWC (%)				
30-45	0.00	3.29	0.55	c	0.80	0.89
45-60	0.00	10.00	5.14	a	4.88	2.21
60-75	0.00	9.37	5.71	a	3.79	0.47
75-90	0.73	11.24	5.16	a	3.29	1.81
90-105	0.00	15.33	5.55	a	8.31	2.88
105-125	0.00	9.59	4.37	b	5.36	2.31
		RLD (cm cm ^{3})				
30-45	0.00	3.72	0.92	a	0.48	0.70
45-60	0.00	1.74	0.23	b	0.17	0.41
60-75	0.00	0.85	0.03	c	0.02	0.13
75-90	0.00	0.43	0.01	c	0.01	0.04
90-105	0.00	0.89	0.01	c	0.01	0.09
105-125	-	-	-	-	-	-
		CLAY (%)				
30-45	6.21	11.70	8.82	b	1.62	1.27
45-60	2.53	7.95	5.07	d	1.26	1.12
60-75	1.68	7.33	4.30	e	1.24	1.11
75-90	3.35	8.97	6.26	c	1.67	1.29
90-105	3.75	12.47	9.17	b	3.43	1.85
105-125	7.29	19.89	12.49	a	10.25	3.20
		SAND (%)				
30-45	74.19	80.48	77.54	c	2.09	1.45
45-60	76.38	85.28	80.21	a	3.20	1.79
60-75	49.14	94.94	80.42	a	20.02	4.47
75-90	69.79	88.32	80.22	a	7.27	2.70
90-105	59.94	83.32	78.75	b	9.52	3.09
105-125	62.79	82.18	74.81	d	30.29	5.50

Table 2.3. (cont'd)

		SILT (%)			
30-45	10.57	17.27	13.64 b	2.23	1.49
45-60	10.13	19.81	14.72 a	3.34	1.83
60-75	0.43	46.19	15.28 a	21.28	4.61
75-90	6.77	22.54	13.52 b	6.01	2.45
90-105	6.11	29.09	12.07 c	9.55	3.09
105-125	6.44	23.24	12.70 c	9.52	3.08
		LL(%)			
30-45	7.91	10.25	9.02 b	0.29	0.54
45-60	6.34	8.65	7.42 d	0.23	0.48
60-75	5.98	8.39	7.10 e	0.22	0.47
75-90	6.69	9.10	7.93 c	0.30	0.55
90-105	6.86	10.58	9.17 b	0.62	0.79
105-125	8.37	13.74	10.59 a	1.86	1.36

* within columns, means followed by the same letter are not significantly different
Duncan at 0.01 probability

Table 2.4 Results for geostatistical analysis in the greenhouse experiment at Michigan State University and field experiment at Arizona. Available water content (AWC) and root length density (RLD) within soil layers.

	Depth (cm)	Model	Range (cm)	Co	Co+C	Co/(Co+C) (%)	IGF
			---AWC (%)---				
	30	SPH	12.73	0.068	1.074	93.00	3.54E-01
	45	SPH	3.65	0.001	0.967	99.00	2.81E-01
	60	SPH	4.11	0.164	1.033	84.00	7.28E-02
	75	SPH	29.76	1.380	5.244	20.83	1.02E-03
	90	SPH	66.45	0.114	1.820	93.80	6.32E-03
Michigan	105	SPH	44.68	0.483	1.188	59.30	6.78E-03
C1	120	SPH	10.85	3.397	1.927	63.81	5.18E-03
			---*RLD* (cm cm ^{3})---				
	30	LN	38.8	0.45	1.278	64.80	4.55E-01
	45	LN	39.21	1.036	1.483	30.10	2.06E-01
	60	SPH	11.59	0.153	1.045	85.00	1.53E-01
	75	SPH	5.11	0.151	0.996	84.80	2.19E-05
	90	SPH	8.22	0.140	1.007	86.10	1.92E-01
	105	SPH	9.65	0.105	1.090	90.40	8.16E-01
	120	SPH	5.44	0.001	0.950	99.00	3.57E-01
			---AWC (%)---				
	60	SPH	5.86	0.171	1.043	83.30	1.22E-01
Michigan	75	SPH	56.10	0.069	1.591	95.60	2.69E-01
C2	90	SPH	38.61	0.175	1.276	86.00	3.39E+00
			---*RLD* (cm cm ^{3})---				
	60	SPH	12.91	0.001	0.954	99.00	8.93E-01
	75	SPH	10.77	0.005	0.953	99.00	5.93E-01
	90	SPH	13.08	0.001	0.963	99.00	6.45E-01
			---AWC (%)---				
	45	SPH	4.52	0.198	1.044	81.00	2.58E-02
	60	SPH	4.11	0.199	1.004	80.20	6.12E-02
	75	SPH	3.43	0.245	1.004	75.60	6.02E-06
	90	SPH	2.77	0.165	0.996	83.40	1.31E-01
Arizona	105	SPH	3.02	0.128	0.985	0.87	8.32E-01
			---RLD (cm cm ^{3})---				
	45	SPH	5.05	0.069	0.984	93.00	1.02E-01
	60	SPH	5.72	0.086	1.025	91.06	1.16E-01
	75	SPH	3.53	0.174	1.005	82.70	8.25E-02
	90	SPH	9.27	0.368	2.27	83.80	5.47E-01
	105	SPH	3.71	0.001	0.993	37.00	4.03E-01

LN - linear model, SPH -spherical model, Co-nugget effect, Co+C - sill, C-structural variance and IGF- Indicative Goodness of Fit.

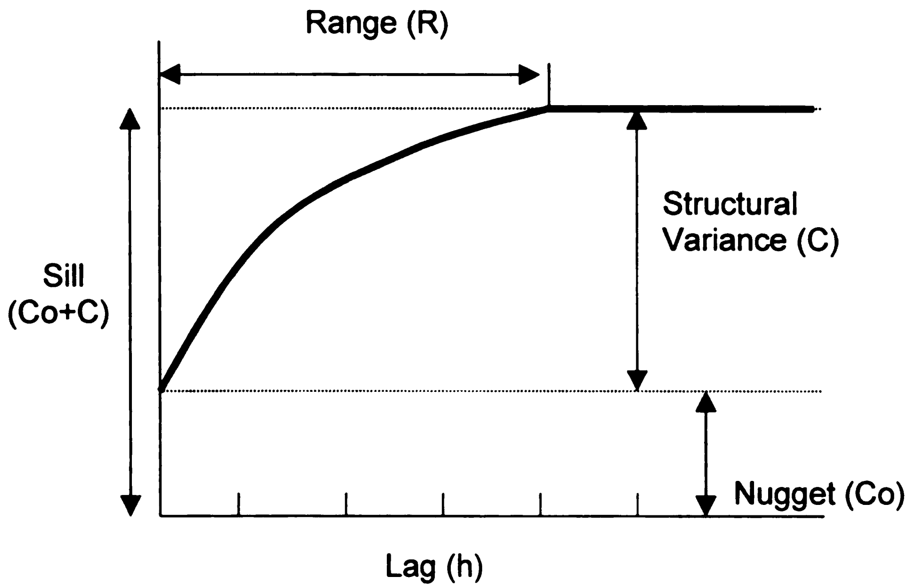

Figure 2.1. Hypothetical Semivariogram.

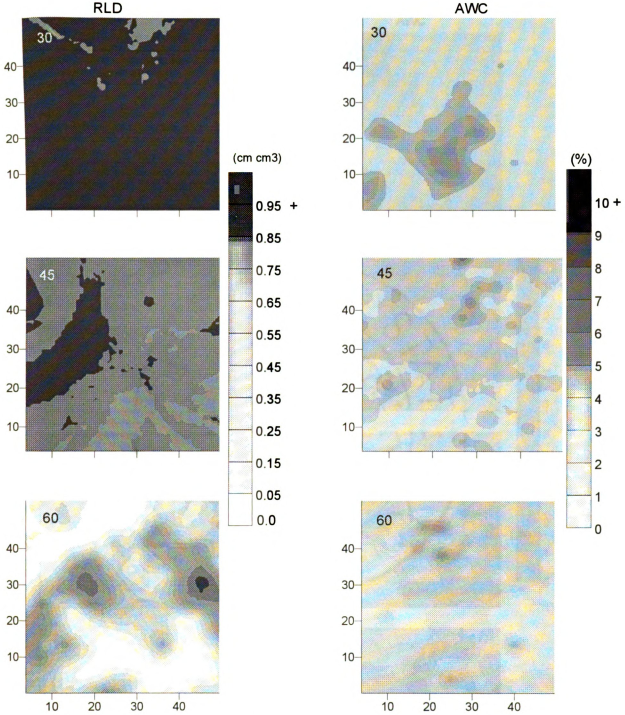

Figure 2.2. Root length density (RLD) (cm cm3) and available water content (AWC) within soil depths. (C1). Greenhouse experiment at Michigan State University, MI.

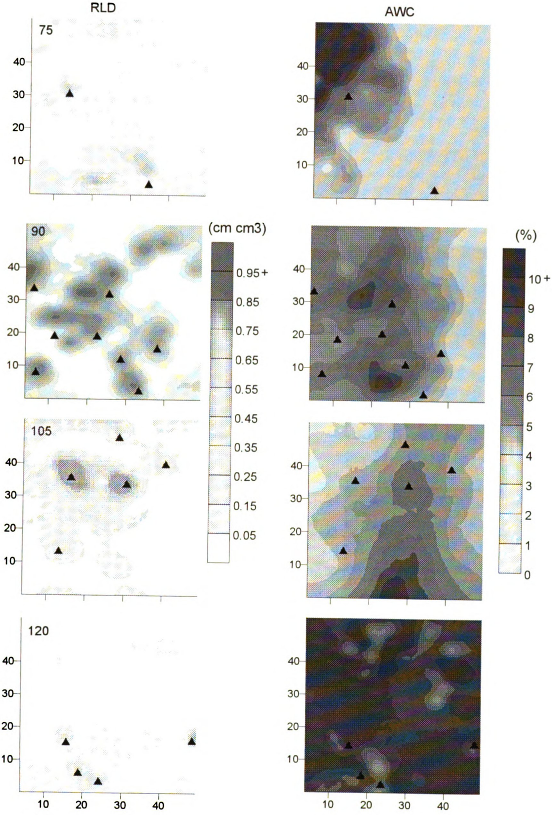

Figure 2.2. (Cont'd)

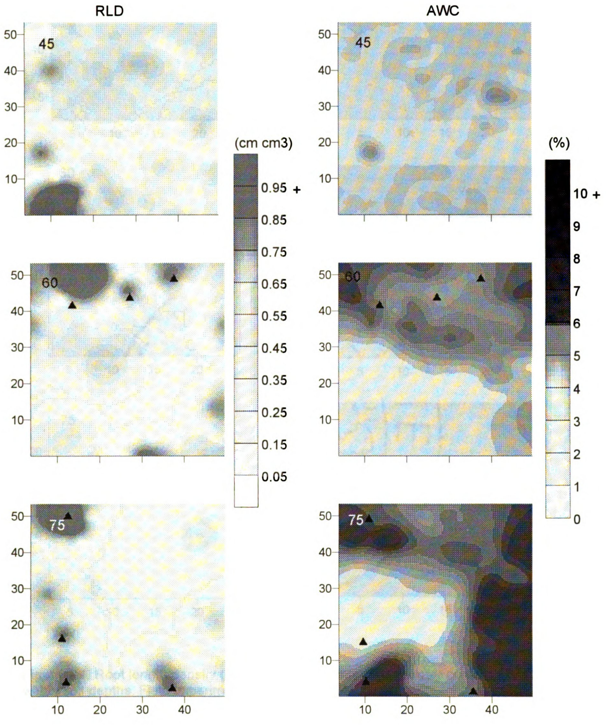

Figure 2.3. Root length density (RLD)(cm cm3) and available water content (AWC) within soil depths. Greenhouse experiment (C2) at Michigan State University, MI.

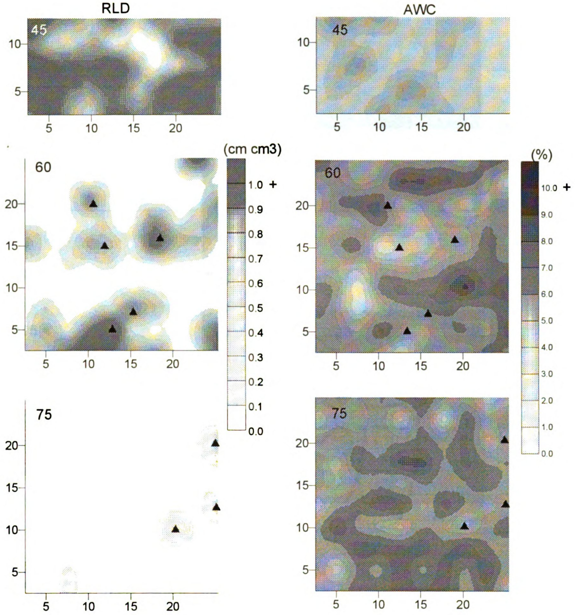

Figure 2.4. Root length density (RLD) (cm cm3)and available water content (AWC) within soil depths. Field experiment at Maricopa, AZ.

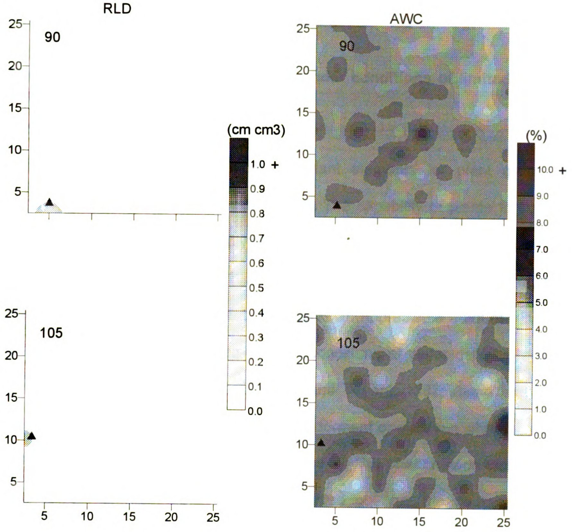

Figure 2.4. (Cont'd)

Chapter 3

Root water extraction by corn plants under conditions of limited supply of water.

Introduction

Water is one of the most important elements for plant growth and development in conditions of water deficit. The capability of plants to survive in limited conditions of water supply will largely depend on the uniformity and depth of its root system (Kozlowski, 1968; Passioura, 1983; Kramer and Boyer, 1995). Data in literature show that plants can leave an appreciable amount of water in the soil without being extracted even in conditions of water deficit (Passioura, 1983; Robertson et al., 1993a; Hamblin and Tenant, 1987; Bland and Dugas, 1989). This means that plants will become dormant or die even when a supply of water still available in the soil. The reasons for this phenomenon were not fully understood, and several researchers pointed out that the causes would be related to: (i) root clumping (Passioura, 1983; Tardieu, 1988), (ii) uneven root distribution of roots in the soil profile (Robertson et al., 1993b), (iii) onset of the crop maturity before roots make use of the deep water in the soil (Passioura, 1983; Robertson et al, 1993a), or (iv) low root density at deep layers (Passioura, 1983). It is argued that if roots are not present in some regions of the soil, these regions will not be adequately explored and an incomplete extraction of water may occur (Ritchie, 1986).

Simulation of water extraction is the extreme importance in water models to determine the amount of water extracted by plants (Ahuja and Nielsen, 1990).

Most of these models are based on the relationship between the amount of roots present and water extraction by roots (Molz, 1981; Hector, 1993); however, the importance of using roots as a parameter in such models has being questioned by several researchers (Hamblin, 1985; Bland and Dugas, 1989; Dardanelli, 1997).

The reason is that these models assume roots as being uniformly distributed in the soil or decreasing exponentially with root depth in the soil (Dwyer, 1988; Klepper, 1990). Nevertheless, due to the heterogeneity of the soil environment (Russel, 1977; Hamblin, 1985; Zobel, 1996), to the intrinsic plant factors that determines root growth, and to the interaction among soil-root, the assumption of uniform root distribution is not adequate. The validity of using roots to explain water depletion from the soil may be inappropriate (McIntyre et al., 1995; Lacape et al., 1998).

The adequate solution would be the development and use of water extraction models that are not root based to describe the pattern of water depletion by plants (McIntyre, 1995). A functional model of water extraction was proposed by Ritchie et al. (1999). This model assumes that roots reached a threshold in each soil layer, that water demand is higher than supply and that lower limit was precisely measured or estimated. Its simulates water depletion in a soil profile in a daily basis. An empirical constant K, was included in this model, and represents the fraction of extractable water in a specific soil layer per day.

The objectives of this work were: (i) to estimate from soil water depletion curves the empirical constant K for corn plants growing in water deficit conditions, (ii) to determine the beginning of the maximum water extraction rate at each soil layer and, (iii) to simulate water extraction by using the functional model proposed by Ritchie et al. (1999).

Material and Methods

This experiment was conducted from DOY 336 in 1997 to DOY 81 and 96 in 1998. Two steel cylinders with dimensions of 60cm in diameter, 180 cm in high and 0.6 cm of wall thickness were pushed into the soil to obtain undisturbed soil samples. The soil was collected at Michigan State Research Farm, MSU, East Lansing and is classified as Metea B (Loamy, mixed, mesic Arenic Hapludalfs), according to USDA, Soil Conservation Service. More details are given in chapter one of this thesis.

The cylinders with contained soil were removed and placed in greenhouse at Pesticide Research Center, Michigan State University, East Lansing, and covered with plastic to maintain the initial moisture content. Three corn seedlings (variety Cargill 333), with 4 leaves were transplanted on DOY 336 in 1997 in C1 and 20 days later in C2. Plants in each cylinder were fertilized with a NPK formula (19-19-19) at rate of 500 kg ha^{-1} at transplanting day and side fertilized with nitrogen (100 kg ha^{-1}) 20 days later after transplanting. After transplanting, plants were watered daily until DOY15 in 1998, and water was withheld afterwards.

Daily minimum and maximum temperatures were obtained from a minimum data set recorder (Model LI-1200, Li-cor, Lincoln, NE) located inside the greenhouse. Temperature data from DOY 23 in 1998 to DOY 91 in 1998 are shown in Figure 1.2.

Soil water content was measured by using neutron scattering technique (CPN, Model 503 DR) during the plant growth period in limited supply of water. One access tube (aluminum, 50 mm i.d.) was seated in the center of each cylinder. Readings were made using a 32 s count at 15 cm intervals up to a depth of 1.20 m, every 48 hours during the drying cycle.

The neutron probe was calibrated by using two steel barrels containing soil. An equation fitted to the neutron-probe readings in these two barrels, one with dry soil and the other one with wet soil, was used to calculate the volumetric water content in this experiment. Although the soil used in these barrels is not the same soil used in this experiment, it was considered that the slope found in this equation was constant for the neutron-probe and that only the intercept varied as function of the soil type where the probe was being used. By keeping this slope fixed, a new intercept for the calibration equation was found by using the last neutron-probe readings and the data of volumetric water content obtained from the TDR readings. This was the methodology used to determine the volumetric water content considering that there was not a specific neutron probe calibration where the experiment was performed.

A model that does not take into account root length density (RLD) (cm cm^{-3}), but generalizations from measured soil water content changes, was used to simulate the rate of water extraction by corn plants. The model proposed by Ritchie et al. (1999), assumes that roots reached a minimum density for each soil layer to extract water at a minimum rate. Also it assumes that the demand of water by transpiration is greater than the water supply in the root zone, and that the lower limit of water content can be precisely measured or estimated. The equation that produces the daily change in water content is:

$$\theta_d = \theta_{d-1} - (\theta_{d-1} - \theta_{LL}) * K \quad (1)$$

where, θ_d is the volumetric water content in a given day (cm^3cm^{-3}); θ_{d-1} = volumetric water content in the previous day (cm^3cm^{-3}); θ_{LL} = volumetric water content at lower limit (cm^3cm^{-3}); and K(day^{-1}) = an empirical constant that represents the maximum fraction of available water extraction within one day. For most crop situations this K constant is assumed to be approximately 0.1 (Ritchie et al., 1999). Based on data found in the literature this model is the only one at present time that does not depend on the amount of roots, that is why it was used in this experiment.

The measured soil water content obtained with the neutron probe gauge was used to determine the constant K for all soil layers in both cylinders. This value was obtained by curve fitting the logarithm of the difference between volumetric water content and the lower limit for each soil layer.

For the upper layers, LL was considered equal to the lowest value of VWC obtained with the neutron probe in these layers. A relationship between VWC and clay content observed at upper layers was established, and the resulting equation from this relationship was used to estimate LL at deep layers in both cylinders (Figure 1.11).

The condition in the model that water demand be greater than the water supply in the root zone can be confirmed by the daily evapotranspitration ($mmday^{-1}$) values in Figure 1.7.

Results and Discussions

The time course for changes in VWC (cm^3cm^{-3}) used to determine K for all soil layers in both cylinders (C1 and C2) is depicted on Figures 3.1 and 3.2. The data showed that there was an exponential decay in water change in the upper layers from 15 to 75 cm in C1; however, below that, this exponential decay was not so evident. Results also showed that some water extraction was occurring at deep layers but at low rates. Below 75 cm depth the change in water content was not so steep. In both cases, a low density of roots at deep layers or a bypassing of some soil regions may have contributed to the low water extraction observed below 75 cm.

The log transformation of the difference between AWC and LL for each soil layer as a function of time for water extraction is presented in Figures 3.3. Curves with different slopes fit quite well the measured data during rapid extraction when the time of measurement for each time was biased to the date when water decay became exponential. As mentioned by Ritchie et al. (1999) this bias time is related to the time when roots obtain sufficient density and uniformity to extract water at it is maximum rate during the period of limited supply. The slopes, K, determined here (Table 3.1) at the upper layers are very close to the value of K=0.1 mentioned in the functional model proposed by Ritchie et al. (1999).

In the upper layers, the K values ranged from 0.07 to 0.09 for C1 and C2. These values are approximately similar to those values obtained for cotton (Bland and Dugas, 1989; Lacape et al.,1998), pearl millet (McIntyre et al. 1995), soybean, sunflower, maize and peanut (Dardanelli, 1997). However, for deep layers K values were lower than 0.07. K values as low as 0.03 was found in C1, and K value ranging from 0.008 to 0.025 was found in C2 (Table 3.1). Ritchie et al. (1999), attributed values of K less than 0.1 to root clumping. Soil constraints, such as high clay content would cause cracks or fissures where roots could grow clumped. Once roots are clumped, a considerable bypassing by the root system in the soil volume can occur which would lead to an incomplete water extraction and consequently causing K to be low. Another possible reason for low K values is the low root density at deep layers, when further downward root growth ceased (Ritchie, et al., 1999).

In the chapter 2 of this thesis, it was observed that roots were clumped and bypassing soil regions. This bypassing was confirmed here by the low values of K observed at deep layers.

The maximum water extraction rate in soil layers below 45 cm depth occurred after DOY 45 in C1 (Table 3.2). This means that when the period of water deficit began in DOY 45 (Figures 1.4, 1.5 and 1.6) corn plants had already extracted water at the maximum rate they could at 30 cm but this rate decreased with soil depth. It is most likely that roots were present in these layers before plants had been affected by water deficit on DOY 45, but the maximum rate of water extraction began with only few days of difference within each other at these layers. The time interval when maximum water extraction began in these layers varied from 1 to 3 days in C1, and about 9 days in C2. Plants could not extract water at same rate below 45 cm because roots were clumped and also because the low root densities at deep layers. As a consequence an incomplete water extraction from deep layers occurred.

In C2, it was not possible to get information about the amount of roots present in the first 30cm depth. Nevertheless, considering the K value of 0.09 (Table 3.1), water extraction was at the maximum rate in this layer (Figure 3.3). This means that this soil layer was probably fully colonized by roots and that almost all existent water was extracted. Based on the graphs of water depletion (Figure 3.2), the beginning of water extraction is not clear; but the maximum rate of extraction began by DOY 50. For soil depth from 45 to 75 cm, the maximum water extraction rate began around DOY 59 (Figure 3.4), almost the same period when water deficit began affecting plants in C2 (Figure 1.5 and 1.7). Also, it was noticed that the beginning of water extraction for these layers began around DOY 27, thus taking almost 30 days for roots colonizing these layers. However, based on the Table 3.1 and Figure 3.2, this colonization was not complete and K values for these layers were 0.065. In this situation it is probable that the low root density caused the incomplete water extraction. For soil depth from 90 to 120 cm, some water extraction was verified after DOY 65; however, K was consistently low, and the probable cause was the low root density. The severe water deficit effects on these plants impaired root growth and at an appreciable rate and density to fully extract water from deep layers.

The data presented until now show that the rate of water extraction was at its maximum for upper layers when root density was high enough to allow that. For deep layers, K values, were consistently lower than 0.01, as previously suggested by Ritchie et al. (1999). For both cylinders, the causes of K being low, seems to be associated to a low root density, root clumping and also to root system bypassing soil regions.

Using the K values found and the time indicated in Table 3.2 for C1 and C2, simulations of water extraction were performed for some selected soil layers. The water extraction simulations performed for soil layers at 30, 90 and 120 cm depth for both cylinders indicated that the model proposed by Ritchie et al. (1999) was adequate to describe water extraction by roots (Figure 3.4). In this study, K value at 30 cm depth was around 0.09 for C1 and C2, but different at deep layers. At 90 cm depth, K was equal to 0.07 in C1 and equal to 0.025 in C2. These differences may have been caused by the low root density observed in C2 and by the clumped roots found at C1. At 120 cm in both cylinders, K reached values as low as 0.03 and 0.008 for C1 and C2 respectively, and the reasons for such low K values may be related to a low root density found in both cylinders. As proposed by Ritchie et al. (1999), the K value equal to 0.1 can be used to describe the daily fraction of water extracted by plants; although, to correctly describe the water extraction in conditions of restricted water supply, K values different than 0.1 were used in the simulations performed here. These different values are correct, when it is assumed that K varies as function of the amount and distribution of roots for each soil layer as proposed by Ritchie et al. (1999). In this study K decreased with soil depth to account for the bypassing and low root density.

Summary and Conclusions

When measurements of volumetric water content are accurate and periodically obtained, it is possible to simulate water extraction by plants without knowing the amount of roots for each soil layer. This means that it is possible to simulate water extraction based on the model proposed by Ritchie et al. (1999) and based on K values for each soil layer. If K is not calculated, a value of 0.1 may be used to predict water extraction. However, in this case, a clear exponential decay in water content for soil layers along the time must be observed before assuming K equal to 0.1. In case no clear exponential decay is observed different values of K must be used for each soil layer to accommodate the correct water extraction by plants.

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Table 3.1. K values for different soil layers in C1 and C2. Greenhouse experiment at Michigan State University.

Depth (cm)	K	
	C1	C2
0-30	0.080	0.090
30-45	0.080	0.065
45-60	0.075	0.065
60-75	0.075	0.065
75-90	0.070	0.025
90-105	0.070	0.010
105-120	0.030	0.008

Table 3.2. Day of the year (DOY) for water extraction within soil layers for C1 and C2. Greenhouse experiment at Michigan State University, MI.

Michigan	Depth(cm)	DOY	
		Maximum	Interval
C1	0-30	24	-
	30-45	45	21
	45-60	46	1
	60-75	47	1
	75-90	50	3
	90-105	53	3
	105-120	55	2
C2	0-30	50	-
	45-75	59	9
	75-90	63	4
	90-105	65	0
	105-120	70	5

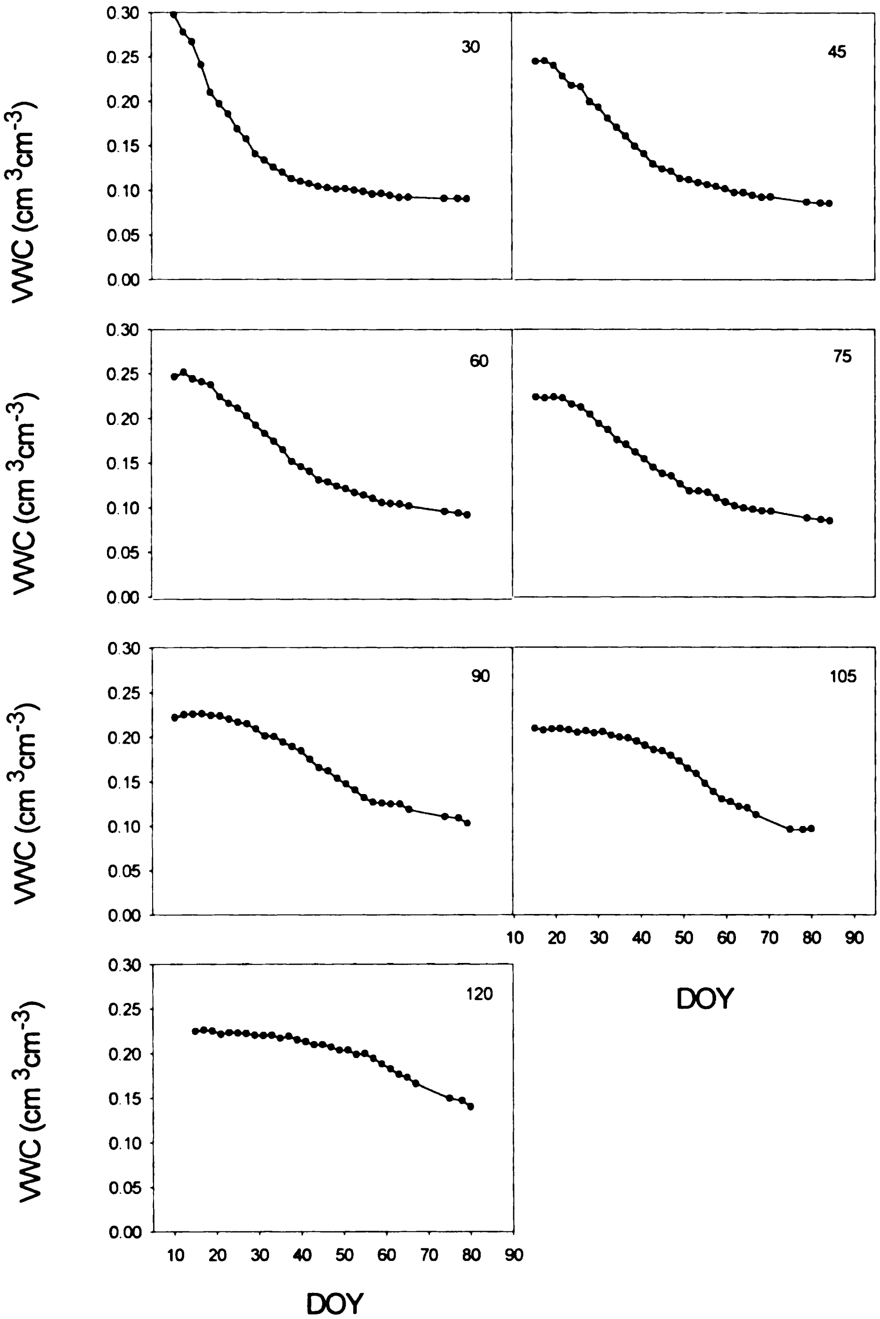

Figure 3.1. Volumetric water content (VWC)(cm^{3}cm^{-3}) within different soil depths (cm) as function of the day of year (DOY). Data for C1 in the greenhouse experiment at Michigan State University, MI.

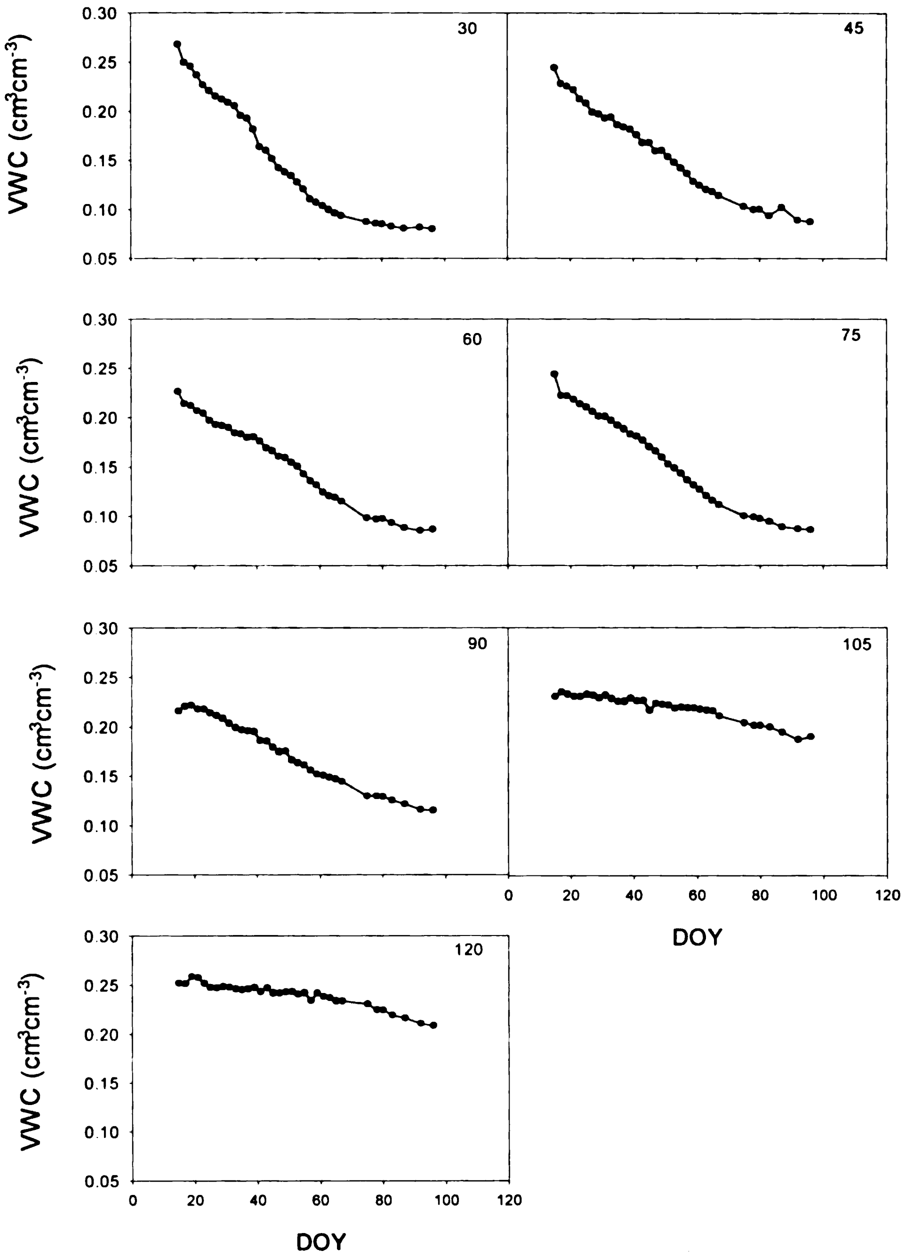

Figure 3.2. Volumetric water content (VWC)(cm^{3}cm^{-3}) within different soil depths (cm) as function of the day of year (DOY). Data for C2 in the greenhouse experiment at Michigan State University,MI.

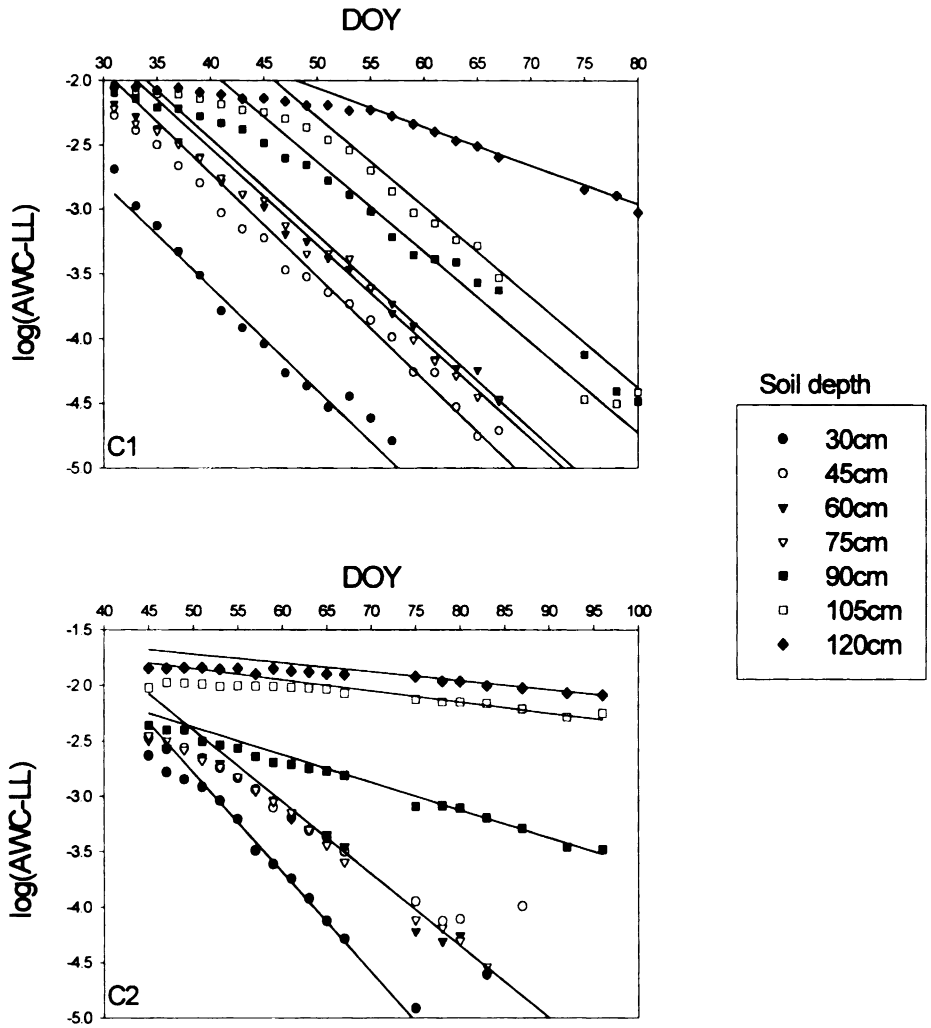

Fig ure 3.3. Logarithm of the difference between AWC and LL as function of DOY. The slope of straight lines represents K value for each soil depth. Data for C1 and C2 at greenhouse experiment at Michigan State University, MI.

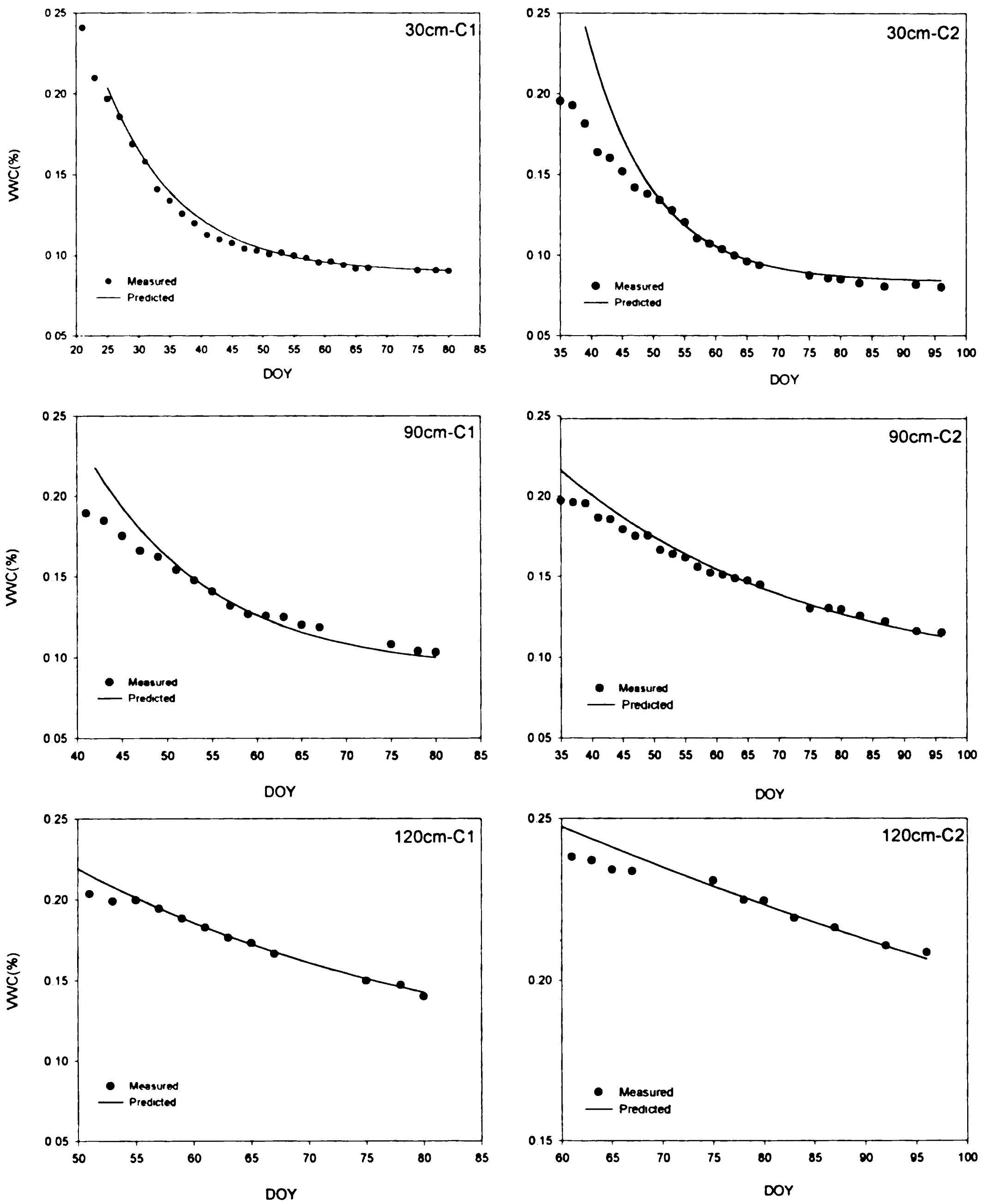

Figure 3.4. Measured and simulated VWC (%) at different soil depths for C1 and C2 in the greenhouse experiment at Michigan State University,MI.

General Conclusions

The main objective of this dissertation was to demonstrate that plants growing in limited supply of water could leave an appreciable amount of water in the soil without being extracted by roots. To confirm the hypothesis that roots bypassed soil regions in detriment of others, which caused the incomplete water extraction, this study aimed to verify the spatial variability of root distribution, water content and soil texture in soil samples collected in a grid pattern in two different locations.

Based on the krigged maps for both locations, it was confirmed that not only roots but also soil water content were spatially distributed in soil layers. The uneven distribution of roots and the spatial variability of soil water content for each soil layer studied confirmed the hypothesis of root bypassing.

Also, it was verified that classical statistics was not adequate to describe spatial variability. This kind of statistics does not take into account the distance among samples. Considering the scale, the spatial dependence among soil samples and the objectives of this study, geostatistics approach proved to be more adequate to describe the micro-scale spatial variability.

The functional model used to simulate soil water extraction in this study closely predicted the water extraction for soil layers observed in both cylinders (C1 and C2) in the greenhouse experiment at Michigan State University, MI. The constant value, K, in the functional model, must be defined for each soil layer if roots are not fully occupying a specific soil layer.