8-1999

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Hou, Qingjiang, "Soil Moisture Within the Windbreak/Crop Interface and a Comparison of Three Types of Sensors for Measuring Soil Water Content" (1999). *Dissertations & Theses in Natural Resources*. 211.
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SOIL MOISTURE WITHIN THE WINDBREAK/CROP INTERFACE AND A COMPARISON OF THREE TYPES OF SENSORS FOR MEASURING SOIL WATER CONTENT

by

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A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Natural Resource Sciences

Under the Supervision of Professor James R. Brandle

Lincoln, Nebraska

August, 1999

SOIL MOISTURE WITHIN THE WINDBREAK/CROP INTERFACE AND A COMPARISON OF THREE TECHNIQUES FOR MEASURING SOIL WATER CONTENT

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University of Nebraska, 1999

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Root-pruning has long been recognized as one of the most effective ways for alleviating yield suppression at the windbreak/crop interface. Results from several latest studies on windbreak root-pruning indicated no differences between soil moisture levels in root-pruned and nonpruned plots. Other recent works in alley cropping studies suggest that light rather than soil moisture may play the major role in limiting crop production in this zone. For two consecutive years, we evaluated the effect of root-pruning on soil moisture in the windbreak competition zone under both cropped and noncropped conditions at the University of Nebraska-Lincoln Agricultural Research and Development Center near Mead, Nebraska.

In 1997, soil moisture in three windbreak systems cropped to soybean were systematically measured using a TDR Trase System (Soilmoisture Equipment Corp., Santa Barbara, CA) at two depths (30 cm and 45 cm) three distances (0.75H, 1.00H, and 1.25H, H represents windbreak height) in both the east and west exposures.

Under a noncropped condition in 1998, soil moisture in the south exposure of a windbreak was systematically measured at three depths (30 cm, 45 cm, and 60 cm), four distances (0.75H, 1.00H, 1.25H, and 1.50H), and in four replications using both gravimetric sampling method and the TDR Trase System.

From June to September 1997, seven rounds of measures were taken. Analyses of variances revealed that soil moisture in the top 30 cm at the east exposure averaged 2.3%(P=0.03) and 1.6%(P=0.12) higher at 0.75H and 1.00H in root-pruned plot. At 0.75H, moisture increase in the 45 cm profile of root-pruned plots was also significant (1.95%, P=0.06) compared to the nonpruned plots. In the west exposure, moisture

contents in root-pruned plots were consistently higher than the nonpruned plots but were not significantly different at any distance and depth.

In 1998, soil water contents were consistently higher in the 45 cm profile for up to 1.25H as a result of root-pruning (3.3% at 0.75H ($P=0.02$), 2.2% at 1.00H ($P=0.1$), and 1.0% at 1.25H). Gravimetric determinations at the corresponding time and locations showed the same moisture trend in respect to root-pruning, distances, and depths as the TDR method but the magnitude is smaller. The standard deviation for each set of gravimetric samples was higher than those of the corresponding TDR measures because the effective sensing volume for TDR is much larger than that of the gravimetric sampling. These results indicate that previous failure in detecting the soil moisture increase by root-pruning was probably caused by the large variation associated with the gravimetric sampling method as well as the concurrent water consumption by crops.

We evaluated the performance of TDR Trase System, CS615 Time Domain Reflectometers (Campbell Scientific, Inc., Logan, UT), and Hydra Soil Moisture Probe (Vitel, Inc., Chantilly, VA) under both greenhouse and field conditions. When intended for measuring the mean soil moisture in a 30 cm profile, the Trase gave the best result in terms of calibration, accuracy, variability, and interchangeability, followed by the CS615 and Hydra probe. The differences between sensor brands are related to the effective sensing volume. When measuring a vertical soil profile, the larger the sensor's effective sensing volume the smaller the effects of small scale heterogeneity and the better the sensor's approximation to the actual moisture value.

Acknowledgements

No words are strong enough to express my sincere appreciation to my advisor Dr. James R. Brandle for his leadership, step by step guidance, encouragement, and sustained trust throughout my graduate program. His direction and influence on me included both academic matters and other aspects of my life, both of which I value most for the benefit I derived. My sincere gratitude also goes to my co-advisor Dr. Michele M. Schoeneberger for her consistent support, participation, and tremendous effort in guiding me through the whole education process. I treasure her detailed instruction, critical review, and invaluable inputs that made my thesis writing a challenging but not less thoughtful, beneficial, and enjoyable experience. I appreciate Dr. Kenneth G. Hubbard for his continued attention, patience, and the most valuable consultation to me on a number of issues throughout the program. In addition, I am very grateful to my graduate committee for their recommendations and the board of NSA Graduate Student Research Award for recognition in 1998.

The research could not have been done without the generosity and assistance from so many people. Especially, Drs. David Marx and Linda Young for statistical analysis, Mr. Karl Blauveld for advice and helps in technical aspects, Mr. Richard Carman for data collection and liaison, and Mr. Bruce Bolander and Mr. Michael Ceislik for the convenience during field instrumentation. I would also like to acknowledge Mrs. Karma Larson for her help to my writings and contribution in editing this manuscript.

I certainly enjoyed and benefited a great deal from the warm, friendly atmosphere in the office. The convenient consultation and casual conversations with my fellow colleagues, Xinhua Zhou and Mark Mash, often inspired me so much and made office work more colorful and enjoyable.

Besides academic, I would like to express special thanks to Mrs. Carolyn Brandle for her kindness, hospitality, and warm reception on numerous occasions.

The sustained encouragement, love, and support from my wife Yuqin, daughter Wei, and son Young constitute, as always, my firm foundation. My most sincere appreciation goes to my wife for shouldering my responsibility taking care of our kids and letting me concentrate on study.

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Chapter 1

INTRODUCTION AND OBJECTIVES

1.1. Windbreaks and Sustainable Agricultural Systems

In terms of production, modern agriculture is tremendously successful, yet it is of growing concern whether this productivity is sustainable either economically or ecologically (Soule & Kiper, 1992). The fast growth in the global economy during the past few decades has to some extent been accomplished by or associated with excessive exploitation of natural resources, environmental deterioration, and damage to the natural ecosystem. The major ecological problems associated with modern agriculture are environment deterioration, soil and water erosion, depletion of energy, loss of genetic and biotic diversity, and chemical contamination. Industrialized agricultural practices and the prosperity they bring about cannot be sustained unless a sound ecological basis is maintained (Miller, 1996; Glissman, 1998).

On the other hand, the fast growth in world population is imposing ever-increasing demands for higher yields while environmental problems, climate change, frequent drought, soil and water erosion, land degradation, and even desertification pose their own threats. Human society must find a way to preserve the most fundamental resources such as soil and water and to stabilize the ecosystem in order to achieve adequate food supplies and sustainable development (Brown, 1998).

With a growing population and limited natural resources, the limits of agricultural land resources have already been reached in many parts of the world. Potentially or even previously marginal agricultural fields are now under intense production thanks to advances in agricultural technology. This means future demand for additional food supply cannot be satisfied by placing more land into production. The only way to meet the challenge will be to find alternatives that increase unit output from existing lands.

At present, scientists and policy makers around the world are searching for economically sound and environmentally sensitive alternatives to produce the food needed for a growing global population. One of the new approaches to solving agricultural problems and to establishing sustainable agriculture is to follow the model provided by the natural ecosystem (Miller, 1996). Natural ecosystems are ones that have evolved over a long period, such as natural grasslands. Their overall production is balanced by their ability to generate what is required. The community is bio-diversified and can maintain sustainability even with changing environmental conditions.

A sustainable system is one that sustains itself, especially its own capital — the living soil and functions over some specified time (Soule, 1992). Vernon et al. (1991) defined sustainable agriculture as "a system of whole-farm resource use balanced with whole-farm productivity". The overall level of productivity achieved is dependent upon the ability to coordinate and manage simultaneously soil, water, plant, and animal resources within climatic and economic limits.

Agroforestry and field windbreaks

As one of the more practical ways leading toward sustainability, agroforestry practices offer an alternative to the less sustainable monocropping systems (Bagley, 1988; Francis, 1998). Agroforestry is a collective name for land-use systems and technologies where woody perennials are deliberately used on the same land-management units as agricultural crops and/or animals in some form of spatial arrangement or temporal sequence. In agroforestry systems there are both ecological and economical interactions between the different components (Lundgren and Raintree, 1982). Within this decade, the science and practice of agroforestry has entered a phase of wide spread interest based on the potential for agroforestry to simultaneously address the economic, environmental, and social needs of people on their private lands (Ehrenrich et al., 1995; Rietveld, 1995; Rietveld et al., 1997). In the United States, Rietveld and Francis (1998) estimated that agroforestry can potentially address sustainability issues on nearly two-thirds of the Nation's lands, especially in agricultural regions.

Windbreaks and sustainable agriculture

Windbreaks are barriers used to reduce and redirect wind. They usually consist of trees and shrubs, but may also be perennial or annual crops and grasses, fences, or other materials (Brandle et al., 1991). Field windbreaks normally consist of woody species and are oriented perpendicular to the most damaging winds. The range of effective protection extends up to 20-30 times the height of the windbreak to the lee depending on the structure of the windbreak. The reduction in wind speed behind a windbreak modifies the environmental conditions or microclimate in the sheltered zone. These changes in microclimate can be used to create desirable environments for growing crops, raising livestock, and protecting the living and working areas (Frank et al., 1974; Rosenberg, 1974; Black et al., 1988; McNaughton, 1988; Brandle et al., 1988).

As one of the most widely used and well-studied practices in agroforestry systems, windbreaks are an effective way to establish a sustainable agricultural system in a variety of field conditions all over the world (Bagley, 1988; Burel, 1996). "Windbreaks used alone or in combination with other practices can effectively control wind erosion and may allow for efficient food production on otherwise marginal agricultural land" (Brandle & Hintz, 1988).

1.2. Major Benefits of Field Windbreaks

Windbreaks improve overall yield production

A wide spectrum of literature exists concerning the effect of field windbreaks on crop yields. Although the general hypothesis that field windbreaks cause a net increase in crop yields is still questioned by some, there is overwhelming evidence showing that shelterbelts benefit field and forage crop production (Frank et al., 1974; Brandle et al., 1987; Baldwin, 1988; Kort, 1988).

Field windbreaks reduce soil loss due to wind erosion and preserve soil and water resources by controlling runoff. Brandle et al.(1984 and 1992) estimated that a typical field could be protected with as little as 5 to 6 percent of the land base devoted to shelterbelts. They also indicated that yield increases as low as 6 to 7 percent would more than offset the costs associated with the establishment and maintenance of shelterbelts and the yield loss associated with the land removed from production.

Windbreak increases water use efficiency

Under dryland or rain dependent agriculture, the limiting factor in yield production is most often available water. Rainfall does not occur at the right time, frequency and/or in adequate amounts for optimum yield. Windbreaks can increase water use efficiency by suppressing evaporation and by changing the microclimate, thus altering the rate of crop transpiration (Dickey, 1988; Brown and Rosenberg, 1969). Enhanced humidity and vapor pressure gradients in sheltered fields contribute to better plant water relations and a subsequent improvement in crop growth performance than in the open fields (Rosenberg et al., 1983; Davis & Norman, 1988).

Another influence of windbreaks on plant growth involves the redistribution and conservation of soil water, particularly under temperate or semiarid and arid conditions. Under these conditions where snow composes a larger proportion of the overall annual precipitation, field windbreaks benefit crops by collecting more snow and thereby preserving more moisture in the early growing season (Steppuhn, 1982-1983; Shaw, 1988). A properly designed windbreak can aid in uniformly distributing snow and thus improve the supply of soil moisture to crops in spring.

Some other benefits of field windbreaks

Besides creating a more favorable environment for crop growth and preserving soil and water in the shelter, field windbreaks may also provide special forest products and help reduce below ground water pollution due to fertilizers and pesticides. By direct sheltering and enriching biodiversity in the rural landscapes, field windbreaks provide critical habitat for wildlife, hence increasing recreational opportunities (Schoeneberger & Dosskey, 1995; Johnson & Beck, 1988). Unfortunately, under the market-driven economy, people tend to pay more attention to the immediate results and judge the performance of any practice on a short-term basis rather than on its long-term potential.

The limited adoption of windbreaks can be traced to this thinking. The protective effects of windbreaks on crops are often overlooked or dismissed due to the yield loss immediately adjacent to the windbreak. Although this reduction caused by competition for resources at the tree/crop interface is offset by the overall yield increase in the open field, it is more readily observed and thus influential in determining landowner's perception of windbreak value.

1.3. Some Adverse Effects of Field Windbreaks

Adverse aspects associated with field windbreaks include competition for moisture and nutrients, occupation of space, and excessive shading. These negative effects and subsequent yield reduction at the windbreak/crop interface have attracted attention (Ong, 1996). Studies that have documented this interface yield loss are available for soybean (Rasmussen, 1990; Nieto, 1997); millet (Ong et al., 1991; Onyewotu, 1995); sorghum (Korwar & Radder, 1994); oat (Lenotievsky, 1934; Kort, 1988); winter wheat (Lyles et al., 1984); and spring wheat (Kowalchuk and Jong, 1995). Reasons for the yield suppression in the windbreak/crop interface include a variety of direct and indirect interactions. These physical and environmental interactions are multidimensional, including both above and below ground factors.

1.4. Tree/Crop Interactive Relationships in Agroforestry Systems

In agroforestry systems a number of direct and indirect interactions between trees and crops take place (Ong, 1991). These interactions can improve productivity (Ong, 1991); increase soil fertility (Kang et al., 1990); enhance nutrient cycling (Szott et al., 1991); preserve soil (Lal, 1989); ameliorate microclimate (Monteith et al. 1991); induce competition (Ong et al., 1991) and allelopathy (Tian and Kang, 1994); and alter pest, disease (Zhao, 1991), and weed dynamics (Rizvi, 1991). While the majority of these findings came from alley cropping studies, the principles of tree/crop interactions can be extrapolated to windbreak/crop situations. In alley cropping systems, trees occupy a larger portion of the field than in windbreaks and are often managed for some tangible output such as fuel, timber, specialty products, and green manure along with their microclimate benefits. The major management objectives for field windbreaks are improved crop growth and erosion control. Hence, windbreaks often comprise larger tree species and occupy a significantly smaller portion of the field than in alley cropping systems.

Like in alley cropping systems, interactions between windbreak trees and the crops at the interface are complex. The majority of evidence pertaining to the benefits and drawbacks of windbreaks are qualitative and indirect. A major task for research is to see how the mixture of different kinds of plant components can be made to interact optimally so as to fulfill their individual as well as their combined yield potential. For field windbreaks, the problem is how to maintain maximum protection in the sheltered areas while reducing or limiting the competitive yield loss at the interface.

Above and below ground interactions in agroforestry system

Ecological interactions between trees and crops at their interface are classified in terms of above- and belowground utilization of physical resources (Ong, 1991). Above-ground interactions are due to shade effects and subsequent changes in temperature, humidity, and precipitation and are especially influential in tropical or humid regions where water is abundant. In these regions, tree induced shading rather than competition for moisture is regarded as the dominant factor in yield suppression at the tree/crop interface. For example, Neumann et al.(1985) studied light and water availability in fields with and without trees in tropical Rwanda where the annual rainfall is about 1000 to 1200 mm. They concluded that tree shading effects on neighboring crops were the dominant factor in determining yield at the interface, because well-maintained tree rows (E-W direction) growing in crop fields had no effect on the humidity of the soil as measured by tensiometers. Ong et al.(1991) studied the above- and belowground interactions in a semiarid agroforestry system in India. They concluded that atmospheric interactions in alley cropping systems are positive but of minor importance when compared with belowground competition.

Whenever space is limited, trees and crops actively interact in the "hidden half"-the belowground, most probably competing for water and nutrients. Such interactions for belowground resources can be as important as those for light and space aboveground (Anderson and Sinclair, 1993). The complexity of below ground interactions is related to the form and nature of the system as a whole and to the possibility and extent that each and every component offers for sharing or not sharing space as well as limited below ground resources. In a windbreak system, trees have an advantage over annual crops because they already have an established rooting system at the start of each growing season. Therefore, unless the roots of the crop components fill unoccupied spaces, or there are phenological differences in root growth and activity, a high level of below ground competition is inevitable (Huxley, 1996). Our ability to observe and measure what is happening at the tree/crop interface is obviously crucial to our understanding of the governing principles regarding below ground competition, and the use of this information to create ecologically sound and economically viable management guidelines.

Root systems at the tree/crop interface

Tree root system

Traditionally, tree roots were thought to spread deep into the ground and extend to the branch tips (dripline) with fine roots concentrated at the dripline. Tree/crop competition was thought to be confined within that zone and therefore of minimal importance. Later studies indicated, however, that trees often develop higher concentrations of fine roots within the top layer of the soil profile (Yeager, 1953; Kort, 1988; Jonsson et al., 1988; Noordwijk et al., 1991). Tree root concentration is strongly related to the specific site conditions such as soil texture, underground water table, and available resources of soil moisture and mineral nutrients. Windbreak tree root distribution is closely related to the groundwater table. Using isotopes of oxygen as a tracer, Smith et al.(1996) found that trees obtained a larger portion of their water from the surface layers of the soil only after rain events and accessed deeper water when precipitation was not available. Thus, during dry periods, the trees extracted deeper reserves of soil water while the millet crop extracted water in the upper soil profile. When groundwater was unavailable both trees and crop obtained water from the top 2 to 3 meters of the soil throughout the year. Under these conditions, utilization of water by windbreak and crops is complementary only if groundwater is accessible to the trees.

In his studies of tree root systems growing in clay soils near Fargo, North Dakota, Yeager (1953) found that 97 percent of tree roots were in the top 1.2 meters of the soil. Ong (1991) reported that roots of *Leucaena leucocephala* (Lam.) de Wit are abundant in the top 30 cm of the soil and the presence of a root barrier is effective in restricting lateral movement of the roots. Five common agroforestry tree species grown in a maize intercrop were found to have the majority of their fine roots (less than 2 mm in diameter) occurred in the top layers of the soil (Jonsson et al., 1988). This has also been found with trees in rangeland (Belsky et al. 1989) and temperate agroforestry systems (Kort, 1988). It would seem one of the primary reason for tree roots to concentrate in the upper layer of the soil profile is to receive and compete for soil moisture from rainfall when belowground water supplies are not available.

In addition, tree root systems have been found to actively redistribute soil water in the vertical profile through hydraulic lifting and "hydraulic redistribution". While such phenomenon may bring benefits to the shallow-rooted companion plants through water lifting when groundwater is available, it may also intensify water stress for the crops nearby if precipitation comprises the only source of water supply (Burgess et al., 1998).

Root systems at tree/crop interface

At the tree/crop interface, the root systems are generally distributed in a non-random manner because of the spatial heterogeneity underground (Ong, 1996). Factors that influence rooting depth and density include soil texture, content and distribution of water, nutrient level, and oxygen availability. Noordwijk et al. (1991) implied that in a mixed cropping system, root length densities which would be sufficient for efficient resource use in a monoculture may not be sufficient in a competitive situation. If water or nutrients are in short supply within the plant, the root system will get a larger share of the carbohydrate supply within the plant and will increase in size relative to the shoot. Consequently, root systems are more likely to increase and be concentrated at the tree/crop interface because both the tree and crops need to invest larger portions of their photosynthetic accumulation in roots in order to increase their ability of capturing more soil moisture. This is especially true in areas where rainfall provides the dominant water input.

Plant water extraction from the soil

The depth of the soil profile and its extractable water content determines the maximum quantity of water available to plants in an area. The available soil water is generally defined as the quantity of water held by the soil matrix at tensions between field capacity and the permanent wilting point (Kramer, 1988). The actual quantity of available water in a given field depends on its soil characteristics, especially soil texture. In terms of volumetric water content, the available water may range from 7% in very light, sandy soils to 40% in soils with a high organic or clay content; values for loams and clay loams are typically 20% to 25%.

Absorption of water by plants is proportional to the water potential gradient established between the roots and the surrounding soil created by transpirational water losses from the canopy. As the soil dries it becomes increasingly difficult for the plant to extract the next unit of water from the near vicinity of the root surface. Therefore, the rate of absorption and hence water status depends critically on both soil moisture content and rooting depth and density. The most effective way for plants to maintain absorption and hence transpiration in drying soils is through sustained root and/or mycorrizal proliferation. As a result, plants growing in soil conditions of lower moisture content tend to form more abundant root systems than those of similar size growing under more favorable moisture levels.

1.5. Water Balance at the Tree/Crop Interface

If no irrigation is applied at the tree/crop interface, the water balance can be described by the following equation (Ong, 1996):

$$T_t + T_c = P - I - r - R - D - S \qquad (1)$$

where T_t and T_c denote transpiration by the tree and crop components, respectively; P, I, and D represent precipitation, interception, and deep drainage beyond the rooting zone, respectively; S is direct soil evaporation, *r* is runoff, and R represents the residual moisture left following harvest.

Ong (1991) estimated that most annual cropping systems use only 30–35% of the total rainfall in arid and semi-arid regions because much of the water is lost through soil evaporation (S). The presence of a windbreak suppresses the evaporative loss of soil moisture as a whole especially at places where periods of strong sensible heat advection are common (Rosenberg et al., 1983). However, at a windbreak/crop interface the partitions among various components expressed in (1) are dramatically different from that of the whole field depending on windbreak and crop species and site specific conditions.

Without irrigation, the maximum available soil water at a tree/crop interface is limited by the total precipitation (P) and the capacity of the soil to hold it, excluding crown interception (I), surface runoff (r), and deep percolation beyond the rooting zone (D). Under a tree/crop competitive scenario, the total available soil water for plant transpiration is shared between T_t and T_c. An increase in either term will inevitably result in a decrease for the other.

Soil water content at a certain time and space represents a measurement of the residual (R). Subjected to all the other terms in equation (1), it also depends on soil as well as plant properties. While the permanent wilting point is soil as well as plant dependent, most plants under relatively water-stressed conditions have the ability to deplete the soil of moisture to similar level in terms of percentage water content. Although there exist a larger difference between plant species in terms of water potentials of roots at the permanent wilting point (-10 to- 30 bar), these differences correspond to relatively small changes in soil water content, often small enough to be within the range of measurement error (Slavik, 1974; Kramer, 1983). In this sense, the limit below which plants can not extract more available water is largely set by the permanent wilting point of the soil and less dependent on plant species. At the windbreak/crop interface, the water supply is generally not enough to meet the demand, and trees and crops are frequently under water stress. As a result, soil water will be maintained at low levels for a significant portion of the growing season. Any treatment effect on soil moisture may or may not be detectable depending on general soil water conditions, vegetation growth, as well as the measurement technique employed.

On the other hand, soil moisture tends to change dramatically even within short distances, depending upon microtopography and soil properties, particularly clay content. It is difficult to obtain reliable estimates of changes in soil water in the entire root zone, because of the large vertical and horizontal variability in soil water distribution in the field. This is caused to some extent by irregularities in root distribution and thus water uptake. Because of this variability, considerable replication of sampling is required in order to yield meaningful results. Intensive direct sampling often disturbs site conditions, causes vegetation damage, is labor intensive and very costly. On the other hand, direct sampling suffers from large variation because it is impractical to collect large volumes of soil per sample and to make repeated measurements at the same location. As a consequence, indirect methods for which a variety of sensors are available are becoming more appealing and gaining in use. The major concerns with indirect methods are each sensor accuracy, precision, calibration, stability, interchangeability, cost and ease of operation. In order to obtain reliable results with indirect techniques, it is necessary to understand sensor's technical characteristics under controlled conditions as well as their performance and effectiveness under field situations.

Based on a thorough evaluation of studies on the interactive relationship of trees and crops in agroforestry systems, below ground interactions have emerged as one of the most important issues that need to be investigated in order to fully understand and successfully manipulate agroforestry plant associations (Huxley, 1991). Competition for limited resources is obvious when plants are grown in close proximity, but the extent of such competition for a single growth resource, such as soil water, is often confounded by other factors and difficult to partition among all the components. More rigorous experimental designs and precautions are necessary to ensure that the assessment of moisture competition is free from interference by factors other than treatments.

Significant efforts have been made to evaluate the competitive effects of trees on crop yield in a variety of agroforestry systems around the world. In general, competition is limited to the area within 1 to 1.5 H (H is the average height of the woody species) of the windbreaks. In some cases, competition may extend up to 3H from the tree/crop interface (Greb and Black, 1961; Stoeckeler, 1962).

1.6. Techniques Used for Restricting Tree Root Competition

Tree/crop competition for soil moisture at the interface has been perceived as one of the most important factors causing yield suppression, especially in arid and semiarid regions. Various methods that put a constraint on tree root or shoot growth at the start of crop growing season have been tried to eliminate or at least reduce the negative effects. Root pruning is the cutting of the lateral tree (or other woody species) root system to a certain depth to restrict their root exploitation of soil profile beyond the pruning line. Root pruning techniques include: trenching along the edge of the windbreak; installation of a belowground barrier between the windbreak and the crop; and the cutting of lateral tree roots using machinery (Lyles, 1984; Singh, 1989; Ong, 1991; Korwar, 1994; Onyewotu, 1995). Shoot pruning was reported as having the same effect as root pruning (Jones and Sinclair, 1998).

Trenching

Digging deep trenches along the windbreak and severing tree roots can greatly reduce water extraction by trees from the adjacent crop field. The trenches are usually back-filled with soil. This is not a permanent solution and must be repeated frequently. Tree roots have been reported to grow more than 2 meters a year can reinvade the adjacent field in a relatively short time. The trenches can be left unfilled to prevent recurring root growth, however, open trenches capture rain and runoff as well as snow and cause a redistribution of soil moisture input. Open trenches also increase surface area for evaporation and can lead to excessive water loss if dry weather persists. Other drawbacks to open trenches include inconvenience to field operations, intensive labor, and the creation of a barrier with the excavated soil.

Below ground barrier

A modified version of trenching is the root barrier technique (Singh, 1989). After the trench is dug, a barrier, usually a polyethylene sheet, is installed and the trench is refilled. This technique prolongs the trenching effect and overcomes some of the disadvantages associated with open trenches. Like trenching, it is labor intensive and costly, and effects may or may not last as long as expected depending on the property of the material.

Cutting of lateral tree roots

Another technique often used by researchers as well as producers is the cutting of lateral tree roots. It is similar to trenching but in this case a blade is pulled through the soil by a tractor. Pruning depth is flexible and can be repeated at the desired frequency and location. The method is less labor intensive, causing minimal interference with field operation, and considerably cheaper.

Pruning the tree root system can reduce competition for soil moisture between the windbreak and the adjacent crop when the soil water supply is limited or inadequate (Lyles et al, 1984; Ong, 1991; Rasmussen, 1990). If applied after the windbreak has reached its protective maturity, tree root pruning allows the windbreak to exert microclimate advantages at its full capacity while reducing the yield loss caused by competition.

In several studies, the effectiveness of root pruning in the interface was evaluated by examining soil water content through direct soil sampling. Many of these studies found no significant differences in soil moisture between root-pruned and nonpruned treatments (Rasmussen, 1988; Larwanou (Final report unpublished), 1996; Nieto, 1998). Significant biomass and crop yield increases in the tree/crop competition zone were, however, consistently observed as a result of root pruning techniques (Panfilov, 1932; Stoeckeler, 1962; Lindquist, 1971; Naughton, 1982; Lyles, 1984; Nieto, 1998).

It seems logical that root pruning the windbreak will result in a repartitioning of the available soil moisture between the crop and the windbreak. The water freed up by pruning is used by the crop, resulting in a larger plant biomass that in turn consumes a greater amount of soil moisture than the crop in the nonpruned zones. The result is depletion of soil moisture to similar levels in both pruned and nonpruned areas. Consequently, it is inappropriate to interpret the effect of soil water competition by using only soil moisture differences observed under cropped situations.

Due to the distribution characteristic of tree root systems in windbreaks as well as the presence and availability of soil water, it is unlikely that root pruning produces a uniform effect on soil moisture at different depths and distances from the pruning line. To elucidate soil moisture competition at the windbreak/crop interface requires systematic measurement of soil moisture at various layers of the soil profile, at various distances from the windbreak, and a separation of crop evapotranspiration from that of the windbreak vegetation.

The lack of trends between enhanced crop performance due to windbreak root pruning and the companioning soil moisture measurements suggests that concurrent soil moisture will have little vitality. The confounding effect of tree/crop water consumption must be separated before reaching any conclusion on how, and to what extend soil moisture changes resulting from tree root pruning contribute to yield improvement of the adjacent crop.

1.7. Experimental Consideration

We predict root pruning at the tree/crop interface will reduce the windbreak extraction of soil water from the interface. The increase in available soil water to the adjacent crops through tree root pruning is the dominant factor responsible for the increase in crop biomass and yield in the interface. To date, the reported failure to detect soil moisture differences between root pruning treatments does not imply that it does not exist, rather that we have not been measuring the system appropriately. It seems logical that tree root pruning makes a larger portion of soil water available to the adjacent crops which, as a result, will result in a higher crop biomass under conditions when moisture is limiting. The elevated crop biomass in turn increases the amount of water consumption and consequently reduces soil water differences.

To test this idea, we designed an experiment for the 1998 growing season using a bare soil situation which would remove the confounding effects of crop water consumption. By excluding the crop vegetation, it is possible to observe the moisture dynamics in the soil profile at both root-pruned and nonpruned plots for the duration of a drying cycle initiated by a rain event, and an entire growing season. This allowed us to single out the effect of soil water on crop yield and evaluate the importance of moisture competition at the windbreak crop interface.

By comparing soil moisture in root-pruned and nonpruned plots under a no-crop situation, soil moisture differences created by severing the tree roots can be evaluated free from the damping effect of crop transpiration. Continuous measurement and data integration will offer a better understanding of water extraction by the windbreak during each rain event. The integration of each period can yield the whole picture for a growing season, and allow for further evaluation of the role and extent that soil moisture stress plays in determining crop yield behavior at the tree/crop interface.

1.8. Major Objectives of the Study

The major goals for this study were: 1) to quantify root-pruning effects on soil moisture at the windbreak/crop interface under cropped and noncropped situations; 2) to compare the results of direct sampling with those by TDR Trase System (Model 6050X1, Soilmoisture Equipment Corp., Santa Barbara, CA); and 3) to evaluate and contrast the ability of three kinds of instruments for estimating a 30 cm vertical soil profile under both greenhouse and field conditions. The instruments were TDR Trase System, CS615 Time Domain Reflectometer (Campbell Scientific Inc., Logan, UT), and Hydra Soil Moisture Probe (Vitel, Inc., Chantilly, VA).

The specific objectives of this study

1. To determine the temporal as well as spatial dynamics of soil moisture at the windbreak/soybean interface as it is affected by tree root pruning in a mature field

windbreak.

2. To determine the spatial and temporal soil moisture pattern at the interface of a mature field windbreak as it is affected by root-pruning under a noncropped situation.

3. To compare the ability of the three techniques for measuring volumetric soil moisture content in a 30cm soil profile and their intra- and inter-unit variability under both controlled (greenhouse) and field conditions.

Chapter 2

ROOT-PRUNING ALTERS SOIL MOISTURE AT THE WINDBREAK/CROP INTERFACE

Abstract

Yield suppression in the area adjacent to windbreaks is a major factor for producers considering planting a field windbreak. Conventional wisdom attributes this suppression to competition for soil moisture and recommends root-pruning as an appropriate treatment to reduce the level of competition. Several recent studies of windbreak root-pruning indicated no differences between soil moisture levels in pruned and nonpruned plots. Other recent works in alley cropping studies suggest that light may also play a major role in limiting crop production in this zone. We think that failure to detect the expected increase in soil moisture as a result of root-pruning was caused by the confounding effect of concurrent crop water consumption plus the large variation associated with gravimetric determinations. For two consecutive years, we evaluated root-pruning effects on soil moisture at the windbreak/ crop interface under both cropped and noncropped conditions. When soybean was grown in 1997, volumetric soil moistures in three windbreak systems were systematically measured using Time Domain Reflectometry (TDR) at two depths, three distances, and three replications in both the east and west exposures. SAS mixed procedure (SAS Institute, 1996) was used for testing the fixed effects of root-pruning, distance, depth, and their interactions. The overall differences in soil moisture between root-pruned and nonpruned plots in crops were smaller in magnitude at all distances in both the west and the east exposures, compared

with the noncropped condition in the south exposure. Nevertheless, soil moisture in the east exposure with crop averaged 2.3% higher (P=0.03) in the top 30 cm profile at 0.75H (H= windbreak height) in contrast to 1.6% (P=0.12) at 1.0H throughout the growing season as a result of root-pruning. Moisture increase due to root-pruning was also significant (P=0.06) in the top 45 cm profile at 0.75H. The corresponding differences in the west exposure, however, were undetectable at various distances and depths. Enhancement in soybean yield due to root-pruning corresponded well with the observed differences in soil moisture at various distances, especially in the east exposure. Under a noncropped condition in 1998, soil moisture at the south exposure of a mature windbreak was systematically measured using TDR at three depths, four distances, and four replications. Statistical analysis indicated that throughout the measuring period soil water content was significantly higher in the top 45 cm profile for up to 1.00H from the windbreak as a result of root-pruning. At 0.75H, moisture increase averaged 3.29% (P=0.02) compared with 2.19% (P=0.116) at 1.00H. Beyond 1.00H the enhancement declined to about 1% and was statistically nonsignificant. These results agree with the previously reported range of crop yield suppression near the windbreak, indicating that soil moisture competition between the crops and windbreak is highly related to and at least partially responsible for the reported yield suppression within the windbreak competition zone.

2.1. Introduction

Field windbreaks are an important component of sustainable cropping systems around the world. With the ever-increasing demand for food production, the limitation on arable land resources, the global change in climate, and deterioration of the environment, windbreak technology provides a vital tool for the creation and maintenance of sustainable agricultural systems (Bagley, 1988; Burel, 1996). This is especially true in arid and semi-arid agricultural regions and in developing countries where agriculture dominates the overall economy and population growth imposes a constant pressure on land exploitation. Even in the United States, nearly two-thirds of the nation's agricultural land resources call for the protection from environmentally sound and ecologically balanced practices, such as field windbreaks, in order to sustain grain production (Francis et.al, 1998).

Field windbreaks function by reducing wind speed in the protected zone. As a result, the potential threat of soil and water erosion is reduced, microclimate conditions for crop production are enhanced, and biodiversity of landscapes are enriched. Besides direct protection against potentially adverse natural events, windbreaks provide various benefits to crop growth and development, depending on the crop, the type of soil, and the local climate (Eimern, 1964; Rosenberg, 1979; McNaughton, 1988). These benefits include earlier germination of seeds due to the enhancement of air temperature and a more favorable plant water relation by the suppression of vapor pressure deficit.

While a windbreak takes a portion of the land out of crop production and entails an initial investment for establishment, there is wide spread research and overwhelming evidence that it leads to a net increase in total crop yield and crop quality (Stockeler, 1962; Brandle, 1984; Kort, 1988; Baldwin, 1988). As a result, the net economic return is positive, input costs are reduced, and environmental conditions are improved (Brandle, 1992).

Although the vast majority of crop studies have indicated a positive response to shelter, there appears to be a general ignorance of these results in many parts of the world. This is especially true in areas where environment conditions are favorable to crop production and the benefits of windbreaks are less obvious, and where land resources have been exploited to the limit and people's very survival depends on putting every piece of land into food production. In these areas landowners are reluctant to divert even a small proportion of their field to shelterbelts. One reason for this reluctance comes from the variable yield reports in the literature. Another reason is related to the competition at the interface between the windbreak and the crop (Ong, 1991; Huxley, 1991). Although yield suppression due to competition exists only within one to one and one-half times the height of the windbreak (Kort, 1988), and yield increases beyond that more than compensate for the suppression (Brandle et al., 1984), farmers still cite competition as a primary reason not to include windbreaks in their farming system (Rasmussen et al., 1990).

2.2. Literature Review

Yield suppression at the tree/crop interface remains a major obstacle to adoption of windbreak technology and has attracted great attention from researchers in many parts of the world. Tree root-pruning is effective in alleviating yield suppression in both alley cropping and field windbreak systems over a wide range of geographical regions (Panfilov, 1931; Stockeler, 1962; Linquist, 1971; Naughton, 1982; Ong, 1991).

After a three year study of the windbreak effect on crop yield in 15 fields cropped to spring wheat in south central Canada (near Saskatoon), Kowalchuk and Jong (1995) concluded that competition for soil water, rather than nutrients, constituted the major reason for crop yield suppression in the interface area. Their data indicated that when moisture conditions during the growing season were below average, competition by the windbreak suppressed crop yield about 10 meters into the field, but when soil water was abundant the competition effect was barely noticeable.

Lyles et al. (1984) compared the effects of root-pruning various types (species) of single-row field windbreaks in Kansas. They concluded that there were significant differences in soil moisture adjacent to different windbreak species and these differences were more consistent during fallow years. They also found significant differences in soil moisture between pruned and nonpruned treatments during fallow periods. Winter wheat yield data showed a 60% increase following root-pruning.

Ssekabembe et al. (1994) reported that black locust (*Robina pseudoacacia* L) hedgerows decreased soil moisture between rows by 8% and 32% depending on soil types. In contrast, no major differences in soil moisture were detected if tree rows were separated with underground partitions from the crop area.

Rasmussen et al.(1988) studied the effect of windbreak root-pruning on corn and soybean production. They reported that the number of soybean branches with more than one pod increased by 0.5 branches/plant and plant biomass increased by 26% at 20 meters from the windbreak as a result of root-pruning. Final soybean yield increased

32% at 7.5 meter from the windbreak when all root-pruned treatments were compared with that of the nonpruned plots. Corn yield improved an average of 18% for all root-pruning treatments. Soil sampling for gravimetric water content at various distances from the windbreaks revealed no differences among treatments at three sampling depths and three distances perpendicular to the windbreak. They attributed the lack of differences to the above normal precipitation.

Root-pruning of *Leucaena* hedgerows in the semi-arid tropics of India increased grain and stover of the alley-cropped rabi sorghum by 33% and 17%, respectively (Korwar & Radder, 1994). Observations indicated that soil moisture competition between crops and hedgerows was considerably reduced by root-pruning at different developmental stages of sorghum. The authors suggested that the competition between hedgerows and arable crops could be reduced considerably by root-pruning and frequent top removal of the hedgerow.

A 1996 preliminary study examined three exposures (east, west, and north) of a 30-year-old windbreak system with soybeans in an attempt to describe the water relations within the zone of competition. No significant differences in soil moisture between root-pruned and nonpruned plots were found by TDR measurement despite an obvious enhancement in crop yield as a result of root-pruning (Larwanou, 1996; Nieto, 1998). A concurrent study in the same experimental plots showed similar soil moisture results by gravimetric determination compared to the indirect determinations (Nieto, 1998).

There exists a common agreement that windbreaks induce yield suppression within one to one and a half tree height depending on windbreak species and site conditions (Kort, 1988). Water stress due to tree root competition is believed to be the primary reason for these yield suppression (Lyles, 1984; Ong, 1991; Kowalchuk & Jong, 1995). We suspect the wide range of results on soil moisture as affected by pruning windbreaks (Lyles, 1984; Rasmussen, 1988; Korwar & Radder, 1994; Larwanou, 1996; Nieto, 1998) could have resulted from the confounding effect caused by concurrent crop transpiration, sampling time, frequency and number of samples, as well as measurement methodology.

Gravimetric sampling was the dominant soil moisture method used in these previous studies. While direct soil sampling is one of the most accurate methods there are some obvious limitations, such as the limited effective sampling volume per sample, difficulty to operate with large sample numbers, soil disturbance, and the impossibility of repeated measurements. These limitations make this method problematic for use in experiments that require frequent and daily measurements. For these reasons, most previous studies have drawn conclusions based on only a few rounds of gravimetric measures (Lyles et al., 1984, Rasmussen et al, 1990; and Korwar & Radder, 1994).

In recent years, Time Domain Reflectometry (TDR) has developed into one of the more reliable methods for indirect measurement of soil moisture (Pearcy, 1989). Both its working principles and field applications are well-documented (Dasberg, and Dalton, 1985, Dasberg and Nadler, 1987; Topp, 1981,1984, 1985; Dalton, 1984,1987; Richardson, 1992). By comparing the TDR-measured values with values obtained by a gravimetric determination on a variety of soil types and soil water contents using hand probes (1984), Topp et al. concluded that TDR-measured values were as accurate and precise as those from gravimetric samples. They found that the standard deviations of differences between TDR and gravimetric values were ± 0.02 m^3 m^{-3} when measured locations were the same but no more than ± 0.06 m^3 m^{-3} when measured locations were different.

2.3. Hypothesis and Objectives of the Study

We hypothesize that tree root-pruning will increase the amount of soil moisture available to the crop within the windbreak competition zone and consequently enhance crop biomass and yield, which in return will damper the augment in soil moisture caused by restricting windbreak root extraction. The lack of soil moisture differences in previous studies may be related to the confounding effect caused by the concurrent crop water consumption as well as to the limited effective sampling volume and large spatial variations associated with the direct sampling method.

The objectives of this study were to determine the temporal as well as spatial distributions of soil moisture at the windbreak/crop interface as it is affected by tree root-pruning and to contrast the results under cropped with noncropped conditions.

2.4. Materials and Experimental Design

2.4.1 Field conditions and experimental layout for 1997

The study was conducted at the University of Nebraska-Lincoln Agricultural Research and Development Center (ARDC) near Mead, Nebraska (41° 29′ N, 96° 30′ W, and 354 m above sea level). The soil was a typical Argiudoll (Sharpsburg silty clay loam), recently reclassified in the Aksarben series (USDA, 1997). The experiment fields are essentially flat with slopes less than 2%.

In 1997, three similar windbreak systems planted in 1966 were used as replications. All three systems had windbreaks on the east, west, and south sides while the north side was open. Each windbreak consisted of two rows of green ash (*Fraxinus pennsylvanica* L.), Austrian pine (*Pinus nigra* Arnold), and eastern redcedar (*Juniperus virginiana* L.) in alternating pairs. The windbreak systems were on an average 12 meters high and 60% in density. On May 9, 1997 (day of the year 129), a soybean crop [Glysine max (L) Merr., variety 'Iroquois'] was planted in 76 cm rows parallel to the windbreaks. Neither irrigation nor fertilizer was applied during the entire growing season. Specific windbreak parameters and the relative distances for all soil moisture sampling locations are given in Appendix Table 1.

Within each windbreak system the north-south oriented shelterbelts on the east and west sides were selected for treatment application. There were 24 treatment combinations resulting from two exposures (East vs. West) × two treatments (Pruning vs. Nonpruned) × three distances (0.75H, 1.00H, and 1.25H)(H = windbreak height) × two soil depths (30 cm vs. 45 cm).

A strip-split-plot design was used with root-pruning and distance from the tree line as the whole plot and split-plot factors, respectively. Tree/crop interfaces at the east and west exposures were subdivided into four pairs of 2 blocks perpendicular to the windbreak. One block from each of the four pairs was randomly selected and root-pruned with a single 0.75 meter long ripper knife at 0.6H from the nearest tree row to a depth of 75 cm. Within each block, soil moisture sampling locations were systematically arranged along the central line perpendicular to the windbreak at 0.50H (in only one replication within each exposure), 0.75H, 1.00H, and 1.25H (Appendix Fig. 5). At each sampling location two pairs (30 cm and 45 cm) of TDR waveguides were vertically installed from the soil surface. A total of 120 pairs for each of the two lengths were used in the three windbreak systems. In order to avoid air pockets due to poor contact with the surrounding soil, a special pilot tool was used during waveguide installation. A portable Time Domain Reflectometry (TDR) Trase system (Model 6050X1, Soil Moisture Equipment Corp., CA) was used for nondestructive, repeated measurements on a roughly biweekly interval throughout the growing season.

2.4.2 Field conditions and experimental layout for 1998

In 1998, we redesigned the experiment using only the south exposure in a noncropped condition so that the confounding factor of crop water usage was removed. An east-west oriented two-row windbreak was used for arranging treatments and microclimate instrumentation. There were 30 treatment combinations resulting from two treatments (Pruning vs. Nonpruned) × five distance (0.5H, 0.75H, 1.00H, 1.25H, 1.50H) × three measuring depths (30 cm, 45 cm, and 60 cm). Soil moisture was systematically measured using both TDR and gravimetric sampling methods.

Planted in 1966, the windbreak was 11 meters high and 240 meters long with a density approaching 70%. Trees in the south row were eastern redcedar (*Juniperus virginiana* L.) alternated with Scotch pine (*Pinus sylvestris* L.) while those on the north row were eastern redcedar. To exclude plant evapotranspiration, a 40 meter wide strip to the south of the windbreak was kept free from any vegetation during the entire period of soil moisture measurement. By leaving a 30 meter section at each end the rest of the strip was subdivided into four paired blocks as replications. Within each replication, one block was randomly selected for root-pruning while the other served as a control (nonpruned). Windbreak sections within the four selected blocks were root-pruned to a depth of 0.75 meter at 6.0 meter (0.6H) from the south tree row. In each of the eight blocks, TDR moisture probes of different lengths (30 cm, 45 cm, and 60 cm) were installed at five locations along the central line perpendicular to the windbreak at 0.5H, 0.75H, 1.0H, 1.25H, and 1.5H respectively (Appendix Fig. 6). Both 30 cm and 45 cm rods were installed at each of the 40 locations while the 60 cm probes were used only in the first two replications. Once proper contact with the soil was assured all the probes were left in the field for the whole growing season. Two portable TDR Trase systems (the same model as in the previous year) were used for measuring on a systematic basis. A total of 32 rounds of TDR measurements were taken from June to September.

2.4.3 Linear model for the variance analysis

With soil moisture as the responding variable, root-pruning, distance from the tree line, and depth of the soil profile at each measuring location were assumed to have fixed effects.

Under these assumptions, the linear model for the variance analysis for both years within each exposure can be expressed as:

$$Y_{ijkl} = \mu + R_l + P_i + RP_{il} + S_j + PS_{ij} + RPS_{ijl} + D_k + PD_{ik} + SD_{jk} + PSD_{ijk} + \sum \varepsilon_{ijkl}$$

Where, μ, R, P, S, and D represent overall mean of the dependent variable (volumetric soil moisture content), replication (block), pruning (major treatment factor), distance from the windbreak (split-plot factor), and depth of the soil profile at each distance. Y_{ijkl}

represents the observation on the Rth replication, Pth pruning, Sth distance from the windbreak, and Dth depth level of the soil profile. RP_{il} and RPS_{ijl} represent the whole-plot and split-plot error terms respectively. The SAS Mixed procedure was used for the computation of least square means and the separation of differences between treatment components and their interactions. Degrees of freedom associated with each mean were approximated using Satterthwaite's approach.

In 1997, seven rounds of TDR measurements were taken from June 4 to September 12. Because of the obvious difference caused by windbreak orientation, the main effect of exposure was first examined using SAS Mixed procedure, in which the three windbreak systems and their interaction with exposure were designated as random factors (Table 2.1 A and B).

Given the large moisture differences associated with windbreak orientation, separate statistical analyses were conducted on an exposure basis for both the 1997 and 1998 seasons. When soybean crop was involved in 1997, data from the three windbreak systems were pooled because no significant differences were found between windbreaks in respect to exposures. Under the SAS Mixed procedure, replications and their interactions with pruning and distance within each exposure were assumed as having random effects. Root-pruning, distance from the windbreak, and depth of the soil profile along with their interactions were examined for the fixed effects (Table 2.2). The mean for each treatment factor (pruning, distance, and depth) as well as their high level interactions at specific level (0.75H and 1.00H) were separated using t-test by selecting the Diff option with the Lsmeans statement. Degrees of freedom for each least square mean were approximated using Satterthwait's procedure (Table 2.3).

The same statistical procedures were used for analyzing treatment effects on soil moisture under the 1998 test conditions (Table 2.5 A and B). Since root-pruning caused significant soil moisture differences in the top 45 cm profile at locations closer to the windbreak for all dates combined, statistical analysis on a daily basis for the top 45 cm profile at 0.75H, 1.00H, and 1.25H were given in Table 2.6.

2.4.4 Environmental instrumentation

In 1998, precipitation was measured with plastic rain gauges (Forestry Supplier, Inc.) at each of the five distances corresponding to soil moisture sampling points in four replications (Appendix Fig.6). A total of 22 rainfalls were recorded from June to October. SAS Mixed procedure was used with replications and their interactions with distances designated as random terms for testing the fixed effect by distance from the windbreak. Since no apparent differences was observed among measuring locations beyond 1.00H, the average recording of 1.00H, 1.25H, and 1.50H was used as reference for comparing precipitation reduction at 0.5H and 0.75H.

Other microclimate variables were measured at three distances from the windbreak (dataloggers located at 0.75H, 1.25H, and 1.50H) in two replications. Two net radiometers (Q-7.1, Campbell Scientific Inc., Logan, UT) were used for monitoring differences in net radiation among distances from the windbreak at the first replication. As a reference, one of the net radiometer was maintained at 25 meters from the nearest tree row, where the windbreak's shading effect was considered negligible. The other was shifted among distances of 0.5H, 0.75H, 1.0H, and 1.5H. Wind speed was measured with cup anemometers (Model 12102, R. M. Young Traverse City, MI) at 1 m and 2 m above the surface at each data logger location. Wind direction was measured at 2 meter high at 1.5H and 1.0H. Soil temperature was determined with averaging soil thermocouples probes (TCAV, Campbell Scientific, Inc.) at 15 cm and 20 cm deep from the surface at all datalogger locations. Each of the six dataloggers (CR10, Campbell Scientific, Inc.) was programmed for taking measurements every minute and logging the data as 30 minute averages. Rain gauges were manually checked and recorded for each rain event. Statistical analyses for all measured microclimate variables were made after checking out abnormal recordings against some quality control criteria described by Hubbard (1988).

2.4.5 Sensor calibration

Before field installation, all temperature and relative humidity sensors (Model XN217, Model HMP35 and Model CS500, all by Campbell Scientific, Inc., Logan, UT) were calibrated. The manufacturer provided calibration parameters for the net radiometers.

Because of maintenance requirements for the original unit, a different TDR Trase system of the same model was used starting in early August 1998. Measurements from probes of different length (30 cm, 45 cm, and 60 cm) were calibrated in the test field. During calibration, a series of measurements for each probe length were taken over a wide range of moisture conditions from different layers of the soil profile and various distances from the windbreak. Corresponding gravimetric soil samples were taken from between each pair of probes soon after a TDR reading was recorded. A soil bulk density for each pair of TDR and gravimetric samples was determined from the same soil profile at the nearest location. Calibration parameters and linear regressions for each probe length were determined using SAS regression procedure (Fig. 2.1).

2.5. Results and Discussion for 1997

When soybean was involved in 1997, soil moisture content in the west exposure was consistently higher than in the east exposure. For all seven rounds of measurements the mean volumetric soil moisture content averaged 2.3% higher in the west exposure ($P = 0.08$). Dates of measurement had a significant effect ($P < 0.001$) but no significant interaction was found between measuring date and exposure ($P = 0.5572$) (Table 2.1).

Exposure-based statistical analysis indicated that sampling date had a significant effect ($P < 0.0001$) because the temporal variation in soil moisture was closely related to both stages of crop development and the prevailing weather conditions during the time of sampling. For the first round of measurements in early June, the overall soil water content was high because water storage accumulated during the off-season was still available and younger plants were yet becoming the major sink. With crop development, leaf area index increased and crop water usage went up as evidenced by the decline of mean soil moisture in corresponding rounds of measurements in July and early August. By mid- to late-September soybean plant vegetative growth and pod-fill had ceased and water consumption was reduced. Subsequent precipitation recharged the soil profile resulting in an overall increase in soil water content.

Another temporal trend for both exposures was the consistently higher water content in the deeper soil profile ($P < 0.0001$). In the west exposure, soil water content for the top 30 cm profile averaged 26.4% in contrast to 29.5% for the top 45 cm layer.

Correspondingly, mean soil water contents for the two depths on the east exposure were 24.6% and 26.7%. While the mean soil moisture in the 45 cm profile reflected soybean water extraction patterns at different stages of development, more temporal fluctuations were observed for the 30 cm profile, most likely due to a strong influence of both root distribution and rainfall penetration. This is because the majority of plant fine roots are concentrated in the top 30 cm soil profile (Casper and Jackson, 1997) and most rains will recharge the top layer, making it more frequently wetted and readily depleted of the moisture storage during rain intervals. While either soybean root extraction or direct soil water evaporation could dominate water consumption depending on the biomass and weather conditions, it was more likely that their combined effects made moisture content consistently higher in the top 45 cm than in the 30 cm profile.

As illustrated in Figure 2.2 and Figure 2.3 the most obvious moisture increase induced by root-pruning occurred in the 30 cm soil profile at 0.75H and 1.00H in the east exposure. Reasons for the significant moisture difference between root-pruned and nonpruned plots in the 30 cm rather than in the 45 cm profile under cropped conditions can be twofold. Firstly, tree/soybean competition for soil water might be more intense within the top 30 cm profile caused either by higher concentration of root systems and/or by a strong direct soil evaporation. Another possibility is related to the effective depth of root-pruning. It is logical for the soil water content to be different in the shallower horizon if pruning only severed tree root systems at the shallow depth level, i.e. the upper 30 cm profile.

2.5.1 Root-pruning effects on soil moisture in different exposures

Root-pruning caused different effects on soil moisture in the two exposures under the cropped conditions in 1997. In the west exposure, no significant moisture increase was found at any distance or depth in root-pruned plots compared to corresponding locations in the nonpruned plots throughout the season. Overall soil water contents for both root-pruned and nonpruned plots were almost identical (P=0.75) (Table 2.2). Although soil moisture at 0.75H for root-pruned plots averaged 1.2% and 0.3% higher in the 30 cm and 45 cm soil profiles than that of the control plots, neither were statistically significant (P equal 0.14 and 0.7, respectively) (Table 2.3). At 1.00H and 1.25H the effect of root-pruning was even less clear at either measuring depth (Fig. 2. 2). Distance from the windbreak had more effect (P = 0.03) than did root-pruning. For all measuring dates soil moistures always increased with distance from the tree line in both root-pruned and nonpruned plots. If the spatial moisture gradient in the nonpruned plots was a result of both tree root extraction and the variation in microclimate variables, such differences with distance in root-pruned plots, however, may be more likely a result of aboveground microclimate variables, most probably shading and crown effects on precipitation distribution.

The east exposure had soil moisture patterns similar to the west exposure in terms of distance, depth, and measuring date, but root-pruning effects were more complicated. Both pruning by depth and pruning by distance interactions were much higher compared to those in the west exposure (P values 0.27 and 0.07, respectively). As a result of the high level two-term interactions among pruning, distance, and depth, pruning by distance by depth interaction (P value equal 0.18) deserves the most attention. At 0.75H, mean soil moistures in root-pruned plots for the top 30 cm and 45 cm profiles were 2.3% and 2.0% higher than that of the control plots. By t-test, their associated probability levels are 0.03 and 0.06 respectively, both are highly significant. At 1.00H and 1.25H, the corresponding differences dropped to 1.6% and -0.6% for the 30 cm profile compared to 0.2% and 0.7% for 45 cm profiles. None of which was statistically significant at the 10% level (Fig. 2.3).

2.5.2 On soil moisture differences between exposures

The large differences in soil water content between exposures may have resulted from windbreak shading and the subsequent differences in leaf area index and crop biomass. In the west exposure, both the total biomass and leaf area index at different development stages, as well as the final yield, were lower than that of the east exposure (Table 2.4). Consequently, more soil water was consumed through crop transpiration, resulting in lower soil water content in the east exposure throughout the growing season. Compared to the west exposure, the better soybean growth performance in the east exposure possibly resulted from a more favorable growing condition created by different shading patterns at various times throughout the day. When air temperature causes less moisture stress in the early morning, shading is most intensive in the west exposure. With favorable light and temperature conditions during that time, plants in the east exposure were able to use available soil water for biomass accumulation. As shading diminishes in the west exposure starting from late morning, air temperatures would rise and most likely plant moisture stress would then occur. Consequently, plants close to the windbreak in the west exposure could not take advantage of more available soil water for effective carbohydrate accumulation in the early morning due to shading. Lower crop production in the west exposure means lower water consumption which can then translate into higher soil water content all season long.

2.5.3 Root-pruning and soybean yield

Overall, soybean growth differences were readily apparent between root-pruned and nonpruned plots in both the east and west exposures. Differences in soybean biomass, leaf area index, and final yield in respect to root-pruning, exposure, and distance were reported by Nieto (1998). As a result of root-pruning, the overall soybean yield increased 81 kg ha^{-1} and 154 kg ha^{-1} in the west and east exposures, compared to that of the nonpruned plots (Table 2.4). At 0.75H, root-pruning enhanced soybean yield by 192 and 874 kg ha^{-1}, corresponding to 12.2% and 40.8% compared with the nonpruned plots, in the west and east exposures, respectively. Beyond 0.75H yield increases in both exposures were less clear. These soybean yield enhancements were well reflected by the observed soil moisture patterns in respect to root-pruning, distance from the tree line, and windbreak orientation (Table 2.3, Figure 2.2 & 2.3). The agreement between soil moisture and soybean yield demonstrated that soil water extraction by trees is responsible for the crop yield suppression at the windbreak /crop interface. It also indicated that the degree of tree/crop competition for soil water was a function of windbreak orientation as well as the relative distance from the windbreak. In this particular study, soil moisture reduction due to windbreak extraction was most severe within 1.00H and such reduction was more prominent in the east than in the west exposures.

2.6. Results and Discussion for 1998

2.6.1 Distribution of precipitation at the interface

Daily rainfall distributions by distance for the 22 rain events recorded from June to October are plotted in Figure 2.4. Single degree freedom contrasts with the SAS Mixed procedure indicated that the cumulative rainfall at both 0.5H ($P<0.001$) and 0.75H ($P<0.05$) were significantly less than the reference. The overall accumulative rainfalls at 0.5H and 0.75H are 14 % and 2.9% less than that of the average of 1.00H, 1.25H, and 1.5H.

Out of the 22 rain events, the mean rainfall at 0.5H was significantly less than the average of 1.25H and 1.50H for 10 times at the 5% level and 2 times at the10% level with the rest having no significant difference between distances. Correspondingly, only two rain events induced significant reduction at 0.75H at the 5% level. The varied results with rain events may be a reflection of tree canopy interception and wind direction during the rains. Darnhofer (1989) has suggested that rainfall modification by a windbreak usually occur within 1H of the windbreak depending on wind directions during the rain.

In this study, fewer differences in accumulative rainfall between distances were observed with rains during a southerly wind (windward) than if a rain came with a northerly wind (leeward). With leeward rains, sampling points closer to the windbreak tended to receive less precipitation than further distances. The majority of the rains during this study occurred in southwest or southeast winds, resulting in a less significant effect on the south-facing interfaces. Since 0.5H was located inside the pruning line and usually does not account for yield production, precipitation was considered to play a marginal, if not insignificant, role in soil moisture at various distances during the 1998 field experiment. Nevertheless, the windbreak edge effect on precipitation could intensify and extend deep into the field depending on the windbreak orientation in respect to the dominant wind directions during rains.

2.6.2 Soil moisture in pruned and nonpruned plots

From June to September the mean soil moistures for both pruned and nonpruned plots followed a similar trend at all measuring depths but deep layers always had higher moisture content than the shallower one for all rounds of measurements. Obviously, such spatial soil moisture patterns were related to or driven by bare soil evaporation, because direct evaporation comprised the major nonsoil sink for available water under the noncropped conditions used in this study. On the other hand, the mean soil moisture content for pruned plots were consistently higher than nonpruned plots for all rounds of measurements at both the 45 cm and 30 cm depths taken with both TDR Trase systems (Fig. 2.5).

Soil Moistures for the Top 30 cm Profile Pruned vs. Nonpruned

Statistical analysis using SAS Mixed procedure suggests no significant differences in soil water content in the top 30 cm profile at the 5% level (Fig. 2.6) although the soil moisture averaged higher in root-pruned plots than in nonpruned plots. This result differed from what was observed in the 1997 study and was most likely due to differences in windbreak orientation, species composition, and especially soybean crop involvement. Other possibilities for this difference include: 1) annual plowing practice in 98 trial field reduced or eliminated the presence of tree root system from the top 30 cm profile; 2) direct soil evaporation was so overwhelmingly strong that it dampened the effect caused by the presence of tree root system in nonpruned plots. Observation on fine root densities via access pits in the field indicated there were greater concentrations in the 30 - 45 cm layer than in the top 30 cm profile. This trend would lend support to the first argument.

Soil Moistures for the Top 45 cm Profile Pruned vs. Nonpruned

Mean soil moisture content for the top 45 cm profile of the root-pruned plots were consistently higher than the nonpruned plots for all rounds of sampling at 0.75H and 1.0H. The contour graphs (Fig. 2.7 & Fig. 2.8) readily illustrate the similarity of mean soil water contents at 0.5H and 1.5H were almost identical for the root-pruned and nonpruned plots. These results suggest that root-pruning does not affect soil moisture dynamics beyond 1.50H or inside the prune line (0.5H). However, starting from around 0.75H to 1.50H the moisture gradient in root-pruned plots dropped nearly 3% more than the corresponding distances in the nonpruned plots. As a result, for the majority of dates soil water content in root-pruned plots at 0.75H were similar to levels at 1.25H in the nonpruned plots. The all date soil water content average (11 round of measurements) at 0.75H for root-pruned plots was 3.3% higher than nonpruned plots ($P<0.05$). At 1.00H the difference declined to 2.2% ($P<0.1$). Beyond the range of one tree height the differences were smaller and not significantly different at the 10% level (Table 2.5). These suggest that the root-pruning effect on soil moisture in this study was confined to the 1.00H zone near the windbreak. It also implies that the root system for the windbreak studied may be more concentrated within one tree height into the field at the south exposure. The greater moisture difference between treatments in the top 45 cm compared to the 30 cm layer also means more active water extraction by tree roots from the horizon between 30 cm and 45 cm in the soil profile. Perhaps, annual field cultivation prevented a concentration of tree roots within the top 30 cm and consequently promoted an accumulation of fine roots just below it.

Soil moisture data throughout the season indicated that windbreak trees were actively extracting soil water from below the top 30 cm profile within the range of one tree height and that root-pruning was effective in suppressing water extraction by the tree root systems. Looking at the 45 cm profile data, the largest increase in soil water content as a consequence of root-pruning always occurred at 0.75H (Table 2.6). Of the seven sampling dates in August and significant differences in soil moisture were observed for 3 days and 2 days at the 1% and 5% levels, respectively, with the mean ranging from 2% to 4.1%. As illustrated in Figure 2.9 (August 12), soil moisture enhancement through root-pruning was most prominent in the top 45 cm layer and within a distance of one tree height from the windbreak.

2.7. Soil Moisture Profiles Cropped vs. Noncropped

Under the cropped conditions in 1997, no significant differences in soil moisture were detected between the pruning treatments in the top 45 cm profile for all measuring locations except 0.75H in the east exposure. Under the noncropped situation in 1998, however, soil moisture in the top 45 cm profile for root-pruned plots increased 3.3% ($P<0.03$) at 0.75H and 2.2% ($P = 0.12$) at 1.0H, compared to the corresponding nonpruned sampling points.. At 1.25H the mean difference was 1% but statistically nonsignificant. This implies that an average of 3%, 2%, and 1% more available soil water would become available at 0.75H, 1.00H, and 1.25H should crops be present in the root-pruned plots. Beyond the range of 1.25H the tree root systems were less aggressive in extracting soil water in the south exposure of the specific windbreak studied in 1998.

When soybean was grown in 1997, both the crop and the windbreak extract available soil water from the nonpruned plots. In the root-pruned plots, however, the soil moisture previously consumed by the windbreak was available to the crop resulting in enhanced biomass and concomitant water consumption by crop. Consequently, soil moisture was reduced to similar levels in both pruned and nonpruned plots, particularly in the deeper horizon (45 cm). Since rains recharge the soil from the top layer down and a higher leaf area index suppresses soil evaporation rates, soil water content in the top 30 cm vs. 45 cm profile tends to fluctuate more. This fluctuation is influenced by the overall water supply, the specific weather conditions, and the crop developmental stage. Deeper in the soil profile, available soil water is consumed either by crops alone as in the root-pruned area or by windbreak plus crops as in the nonpruned plots, resulting in similar moisture levels regardless of the presence of tree root systems. The moisture difference between treatments in the 45 cm profile becomes even small as the crop leaf area index increases and the water demand becomes greater than the slower off-season water recharge in the deeper soil profile. Therefore, root-pruning effects are more evident in the 30 cm profile than in the 45 cm when soybean crop was present in 1997.

Without crop coverage in 1998, bare soil evaporation constituted the dominant nonsoil sink for available soil water. Consequently, weather conditions and dates measurement rather than root-pruning treatment were more likely to dominate water content in the shallower (30cm) soil profile. This effect was evidenced by the consistently non-significant differences between root-pruned and nonpruned plots in the top 30 cm profile under the noncropped conditions.

Data from our two-year study, which included both cropped and noncropped conditions, indicate that severe competition for soil moisture exists in the interfaces between windbreaks and the adjacent crops. The competition for soil moisture contributed to the suppression of crop biomass and yield within an area up to 1.25H from the windbreak. Root-pruning proved to be an effective way for diverting soil water from windbreak to crop usage which in turn lead to a significant increase in crop biomass and yield. Previous studies showing no difference in soil moisture between root-pruned and nonpruned plots might have resulted from the larger variation associated with gravimetric soil sampling method as well as the confounding effects caused by the concurrent crop transpiration.

2.8. Suggestions

Due to resource constraints we concentrated our field observation in 1998 only in the south exposure of a single windbreak. Windbreak species composition have been shown to influence soil moisture competition at the tree/crop interface (Lyles, 1984). Further studies should take this into account in the design of experiments. Water balance investigation or parallel experiments with both cropped and noncropped conditions are necessary in order to begin qualifying the interactions between trees and crops in agroforestry systems. Understanding these interaction will enable the development of better management guidelines to enhance agroforestry benefits.

Root-pruning did improve soil moisture conditions in the top 45 cm profile on the south side of the windbreak. Without crop coverage soil moisture was consistently higher in the root-pruned zone to a range up to 1.25 times tree height than in the control plots. However, root-pruning did not completely eliminate differences in soil moisture with distance from the windbreak (Fig. 2.8), suggesting other factors besides tree competition may also be involved, i.e. rainfall distribution and aboveground microclimate. The redistribution of precipitation by windbreaks is influenced by crown interception. This influence varies with the relative distance from a windbreak and the wind direction during a rain event. Depending on windbreak orientation and wind direction, the windbreak edge effect could constitute one of the major factors inducing lower soil moisture near the tree line as previously described.

Microclimate data for 1998 showed some interesting trends with distance from the windbreak. Mean air temperature during 11:00am to 16:00pm was 1.35 °C higher at 0.75H than at 1.50H. Mean soil temperatures at both 15 cm and 20 cm below the surface were likewise higher at 0.75H than at 1.50H (1.69 °C and 1.58 °C, respectively). Averaged wind speeds (above 1 meter/second) at 0.75H were lower than at 1.50H. From June 25 to August 3, net radiation at 0.75H averaged 12.4 Watts/m^2 s lower than at 1.5H with a standard deviation of 5.3Watts/ m^2 s (Table 2.7). These indicate aboveground microclimate factors vary with distance from the windbreak, even at the south exposure where the shading effect is the most minimized. The variations in microclimate parameters may collectively induce a higher rate of evaporation near the windbreak and contribute to the soil moisture gradient with distance from the windbreak consistently observed throughout the season in both root-pruned and nonpruned plots. Most probably, changes in microclimate aggravated soil moisture competition between trees and the adjacent crops and were at least partially responsible for the well-documented yield suppression at the windbreak/crop interfaces.

Table 2.1

A. Statistical analysis for the fixed effects on soil moisture by exposures (east and west) and sampling dates in 1997. East exposure refers to the windbreak/crop interface to the east of a windbreak while west exposure represents the windbreak/crop interface to the west of a windbreak.

Sources	NDF	DDF	Type III F Values	Pr > F
Exposure	1	4	5.46	0.0795*
Date	6	24.6	67.91	0.0001**
Exposure * Date	6	24.6	0.83	0.5572

NDF = Degree of freedom of numerator.
DDF = Degree of freedom of denominator.

B. Soil moisture mean separation by the Diff option with the Lsmeans statement of the SAS Mixed procedure.

Exposure	Lsmean %	SE	Difference %	Pr> | t |
East	25.57	0.684	2.22	0.0795
West	27.83	0.683		

SE = Standard Error.

Table 2.2 Analysis of variances for the fixed effects on soil moisture by pruning, distance, depth, and their interactions in the East and West exposures in 1997. East exposure refers to the windbreak/crop interface to the east of a windbreak while west exposure represents the windbreak/crop interface to the west of a windbreak. Distances include 0.75H, 1.00H, and 1.25H. H represents windbreak height. Depths include 30 cm and 45 cm from the soil surface. Pruning refers to pruned and nonpruned.

Sources		East Exposure		West Exposure	
	NDF	Type III F	Pr > F	Type III F	Pr > F
Pruning (P)	1	1.93	0.2004	0.80	0.4144
Distance (D)	2	9.98	0.004**	6.95	0.0108**
P * Distance	2	3.33	0.0772*	0.29	0.7524
Depth	1	53.5	0.0001**	120.	0.0001**
P * Depth	1	1.27	0.2767	0.00	0.9603
D* Depth	2	0.10	0.9025	1.11	0.3532
P * D * Depth	2	1.89	0.1823*	0.82	0.4578

NDF = Degrees of freedom of numerator.

** Highly significant.

* Strong interaction.

Table2.3 Differences in mean soil moisture percentage between root-pruned and nonpruned plots and the associated probability levels by SAS Mixed procedure (the Diff option with the Lsmeans statement) in 1997.

		West Exposure				East Exposure			
Depth	Dist	Diff	SE	T	Pr >| t |	Diff	SE	T	Pr>| t |
	0.75H	1.19	0.79	1.50	0.14	2.30	1.01	2.30	0.03**
30 cm	1.00H	0.20	0.79	0.26	0.80	1.62	1.00	1.63	0.12
	1.25H	-0.3	0.78	-0.39	0.70	0.20	0.99	0.20	0.84
	0.75H	0.31	0.79	0.39	0.70	1.97	1.01	1.95	0.06*
45 cm	1.00H	0.04	0.79	0.05	0.96	-0.56	1.01	-0.56	0.58
	1.25H	0.70	0.79	0.89	0.38	0.74	1.00	0.74	0.46

Diff = Mean differences in moisture percentage.
SE = Standard error.
Dist = Distance from the windbreak.
** Significant at 5% level.
* Significant at 10% level.

Table 2.4 Soybean leaf area index (LAI), biomass at two development stages (V6 and R7), and final yield as a function of windbreak orientation and distance for root-pruned plots in 1997. H represents windbreak height. (After Nieto, Carlos. 1998).

Exposure/distance	LAI	V6 (t/ha)	R7(t/ha)	Yield (kg/ha)
West-0.50H	0.81**	0.28**	1.90**	462.20**
West-0.75H	1.73	0.76	4.25	1571.1
West-1.50H	2.97	1.28	7.25	3235.8
West-3.00H	2.41	1.20	6.93	3368.6
East-0.50H	1.02**	0.32**	2.10**	612.70**
East-0.75H	2.21	0.80	4.66	2142.6
East-1.50H	3.51	1.40	7.40	2764.6
East-3.00H	3.30	1.52	6.60	2327.4
Standard error	0.22	0.10	0.63	249.2

** Significant linear trend for effect of distance ($P<1\%$).

V6 represents soybean phenological stage of sixth node.

R7 represents soybean physiological maturity.

Table 2.5

A. Analysis of variance for the fixed effects on soil moisture by pruning, distance, depth, and their interactions in the south exposure in 1998. Pruning includes pruned and nonpruned plots. Distances include 0.75H, 1.00H, 1.25H, and 1.50H (H represents windbreak height). Depth include 30 cm and 45 cm from the surface.

Sources	NDF	DDF	Type III F	Pr > F
Pruning (P)	1	6	2.51	0.1643
Distance (D)	3	18	11.71	0.0002
P * Distance	3	18	1.00	0.4159
Depth	1	6	10.31	0.0183
P * Depth	1	6	2.67	0.1536
D* Depth	3	18	0.45	0.7216
P * D * Depth	3	18	0.05	0.9846

NDF = Degrees of freedom of numerator.
DDF= Degrees of freedom of denominator.

B. Differences in soil moisture % between pruned and nonpruned plots by the Diff option with the Lsmeans statement of the SAS Mixed procedure.

	30 cm Profile			
Distance	Difference	SE	t	Pr >| t |
0.75H	1.23	1.324	0.93	0.3643
1.00H	0.05	1.324	0.04	0.9690
1.25H	-0.48	1.324	-0.36	0.7214

	45 cm Profile			
Distance	Difference	SE	t	Pr >| t |
0.75H	3.92	1.324	2.48	0.0231*
1.00H	2.19	1.324	1.65	0.1158
1.25H	1.01	1.324	0.77	0.4539

Diff = Mean differences in moisture percentage.
SE= Standard error.
* Significant at 5% level.

Table 2.6 Comparison of daily mean soil moisture percentage and the associated probability levels between root-pruned and nonpruned plots in the top 45 cm profile at various distances from the windbreak. H represents windbreak height.

Date	Distance	Nonpruned	Pruned	Difference	SE	DF	T	Pr >| t |
12-Aug	0.75H	26.84	29.44	2.59	1.72	45.9	1.51	0.1382
	1.00H	28.66	31.19	2.53	1.72	45.9	1.47	0.1483
	1.25H	29.86	31.10	1.24	1.72	45.9	0.72	0.4739
13-Aug	0.75H	26.77	29.86	3.09	1.82	47.7	1.69	0.0968*
	1.00H	28.81	31.28	2.46	1.82	47.8	1.35	0.1825
	1.25H	30.13	31.68	1.55	1.82	47.8	0.85	0.3979
14-Aug	0.75H	26.62	28.66	2.04	1.62	41.5	1.26	0.2136
	1.00H	29.63	32.10	2.46	1.62	41.5	1.52	0.1351
	1.25H	29.53	32.23	2.71	1.62	41.5	1.68	0.1014
15-Aug	0.75H	26.79	29.73	2.93	1.71	43.7	1.72	0.0927*
	1.00H	28.88	31.24	2.35	1.71	43.7	1.38	0.1745
	1.25H	31.61	33.08	1.46	1.71	43.7	0.86	0.3948
11-Sep	0.75H	26.04	29.88	3.84	1.23	38.7	3.12	0.004***
	1.00H	28.42	29.95	1.53	1.23	38.7	1.25	0.2204
	1.25H	30.68	32.07	1.39	1.23	38.7	1.14	0.2624
12-Sep	0.75H	25.93	29.99	4.06	1.24	40.7	3.28	0.002***
	1.00H	28.84	30.72	1.88	1.24	40.7	1.52	0.1356
	1.25H	30.72	31.68	0.95	1.24	40.7	0.77	0.4456
13-Sep	0.75H	26.15	29.77	3.62	1.34	42.5	2.70	0.01***
	1.00H	28.73	31.44	2.71	1.34	42.5	2.02	0.0498**
	1.25H	31.97	32.36	0.40	1.34	42.5	0.22	0.8306

* Significant at 10% level; ** Significant at 5% level; *** Significant at 1% level.
SE= Standard error. DF = Degrees of freedom.

Table 2.7 Microclimate variables measured at 0.75H from the windbreak and at the control point (1.5H). Data come from June 25 to August 3. (11:00am~ 16:00pm). Differences equal measured values at 1.5H minus those at 0.75H with the respective standard deviations. H represents windbreak height (11meters).

Parameters	0.75H	1.50H	Difference	Reasons
Long wave↓	High	Low	N/A	Tree emission
Short wave↓	High	Low	N/A	Tree reflectance
Long wave↑	High	Low	N/A	Higher surface T
Short wave↑	Same	Same	N/A	Same albedo
Net radiation	Low	High	~12.4 ±5.3 W/S	Strong effect by T
Air temperature(T)	High	Low	~ -1.35 ±0.47 °C	Less turbulence
Wind speed	Low	High	~0.2 ±0.3 M/S	Above 1.0m/s
Relative humidity	High	Low	~ -1.2 ±2.69%	Less turbulence
Soil temperature	High	Low	~ -1.58 ±0.83 °C	High air T at 20cm
Precipitation	Less	More	~ -3% less	Edge effect

↓ Represents incoming radiation. ↑ Represents outgoing radiation.

N/A : Not available. T = Temperature.

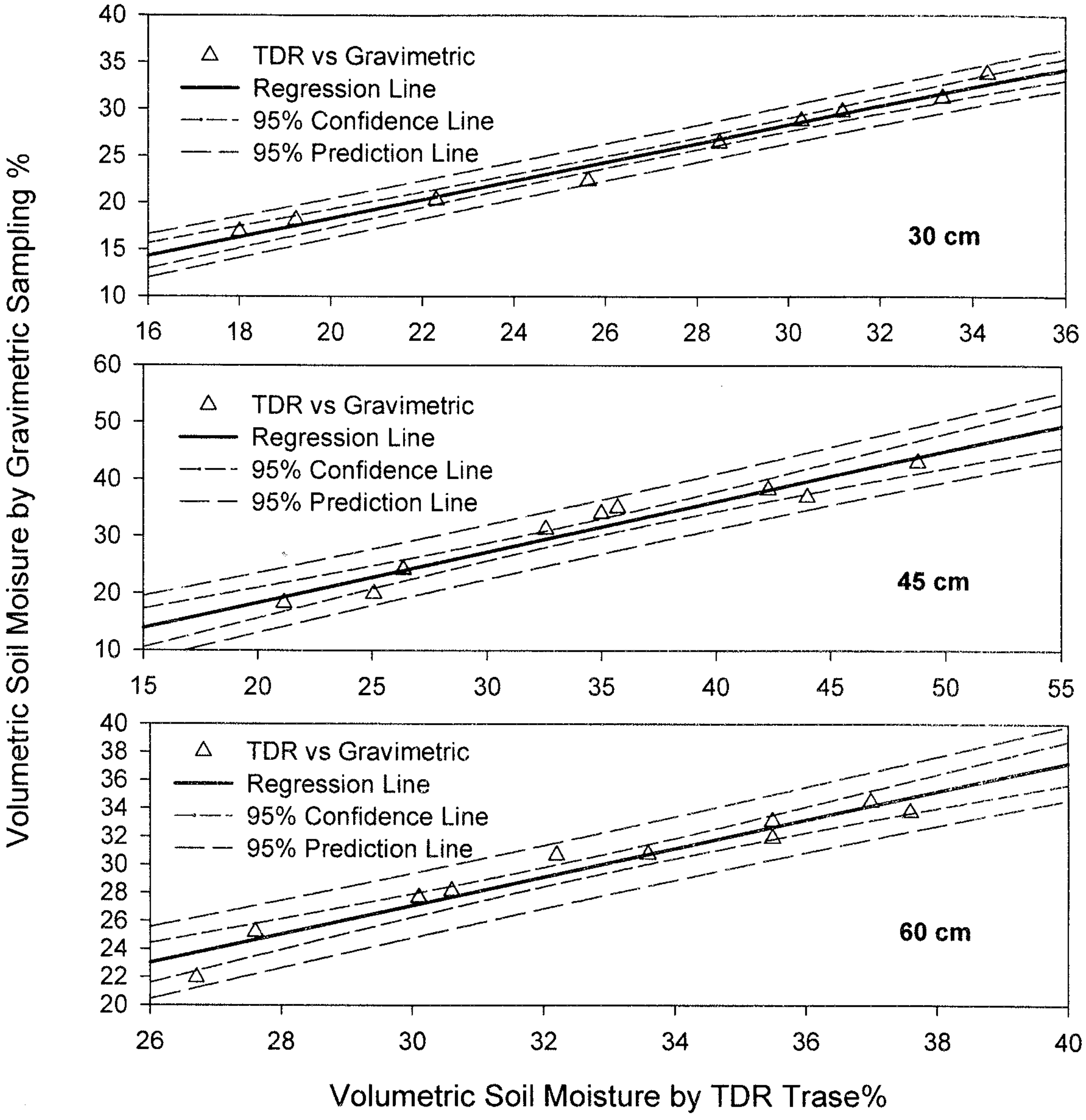

Figure 2.1 TDR Trase measurements on the 30 cm, 45 cm, and 60 cm waveguides regressed against gravimetric measurements.

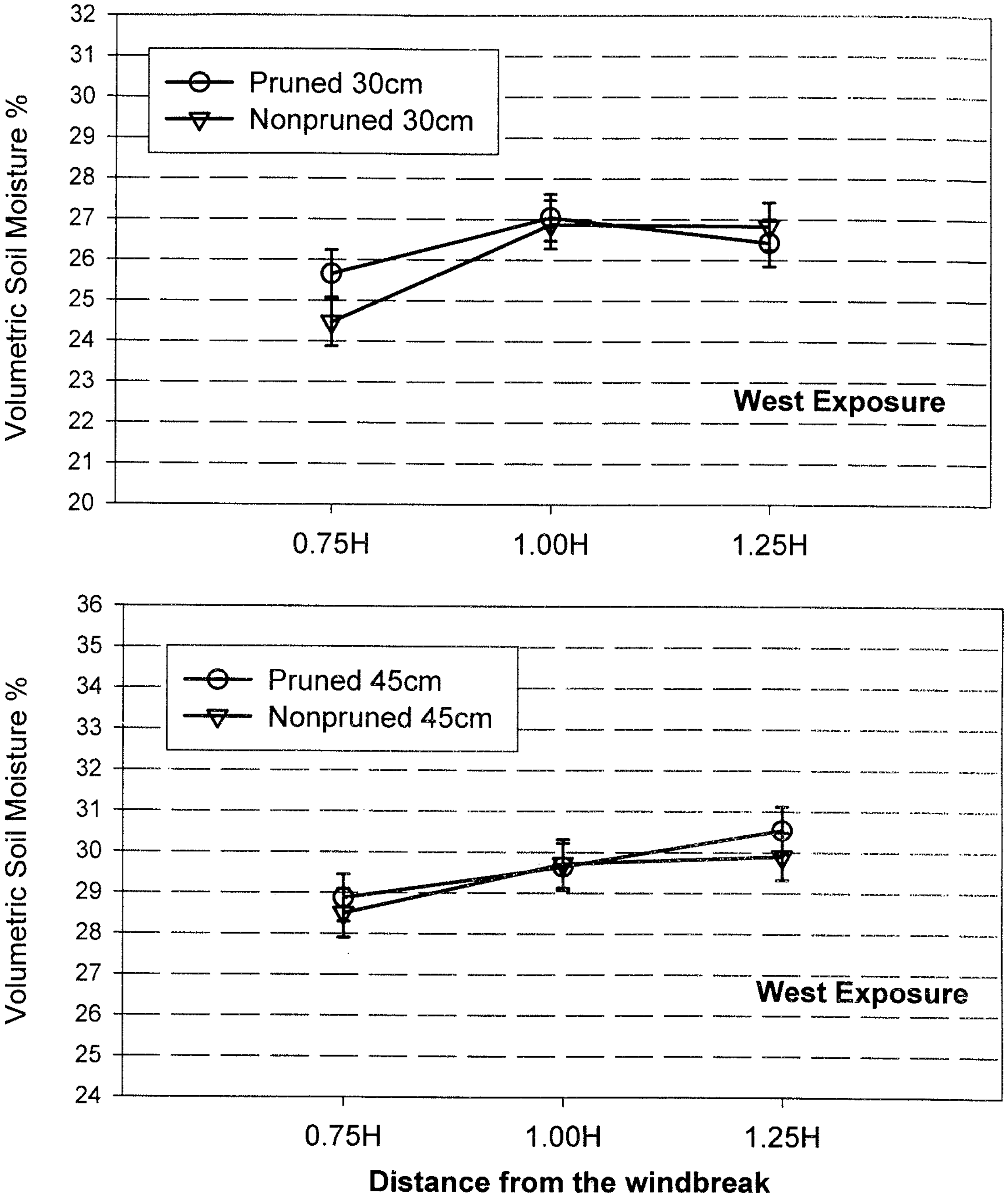

Figure 2.2 Mean soil moisture as function of pruning, distance from the windbreak, and depth of the soil profile in the west in 1997 when soybean was growth at the windbreak/crop interface. Data come from all seven round of measurement. H represents windbreak height. Error bars stand for standard errors.

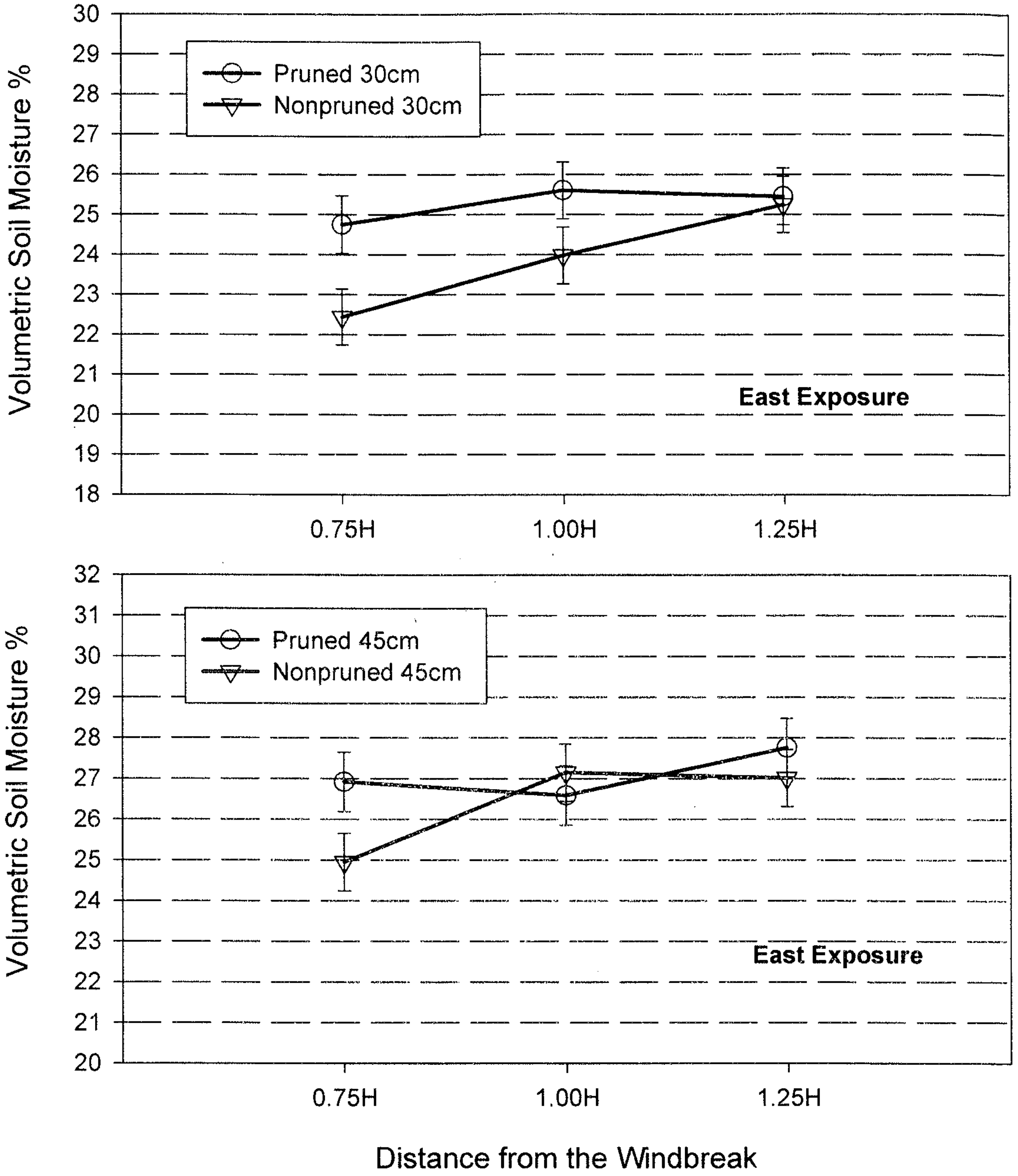

Figure 2.3 Mean soil moisture as a function of pruning, distance from the windbreak, and depth of the soil profile at the east exposure when soybean was grown at the interface in1997. Data come from seven rounds of measurements from June to September. H represents windbreak height.

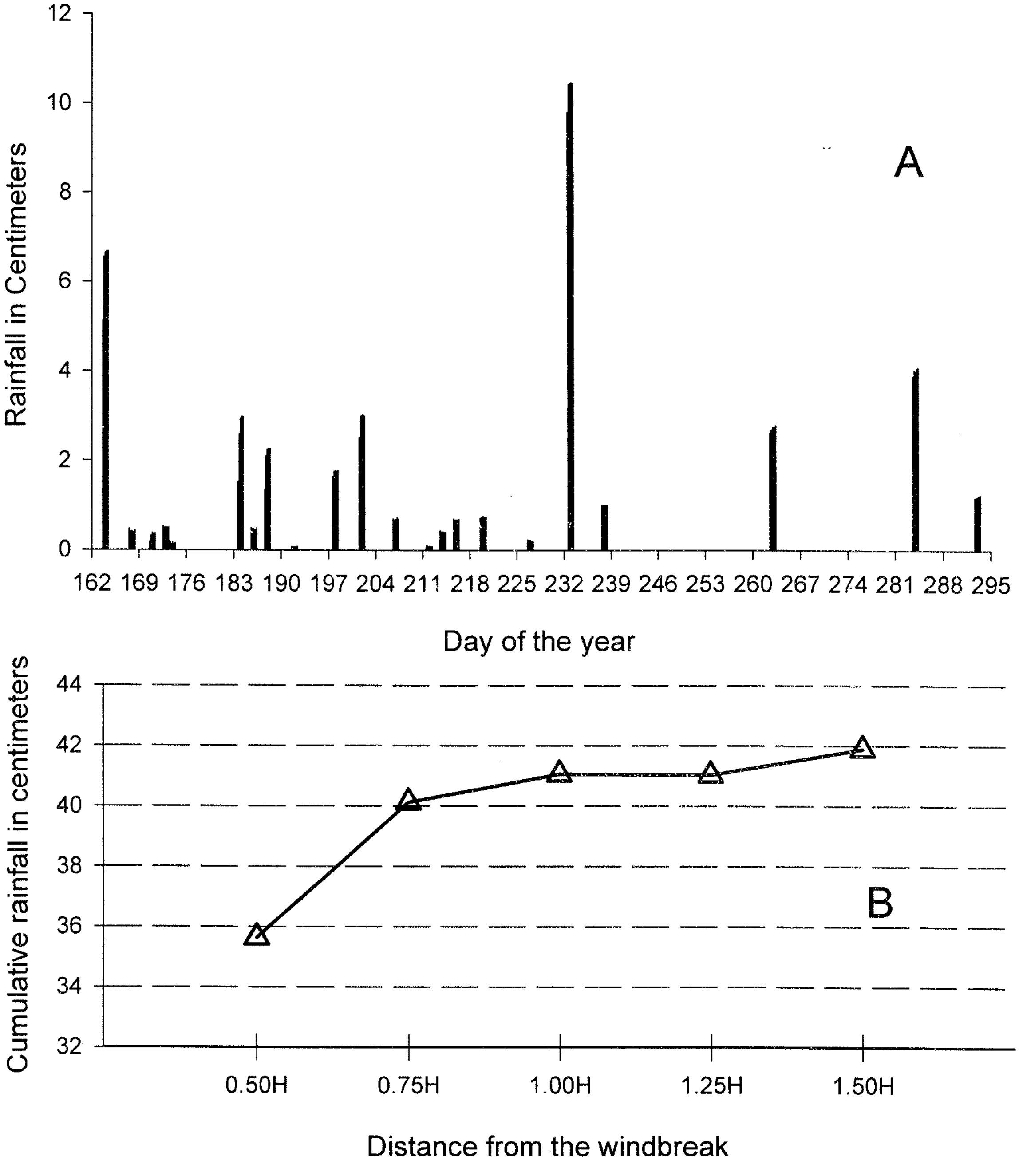

Figure 2.4 Rainfall distribution as measured at the south exposure during the trial (A). Accumulative precipitation at different distances from the windbreak from June 12 to October 24,1998 (B).
H represents windbreak height.

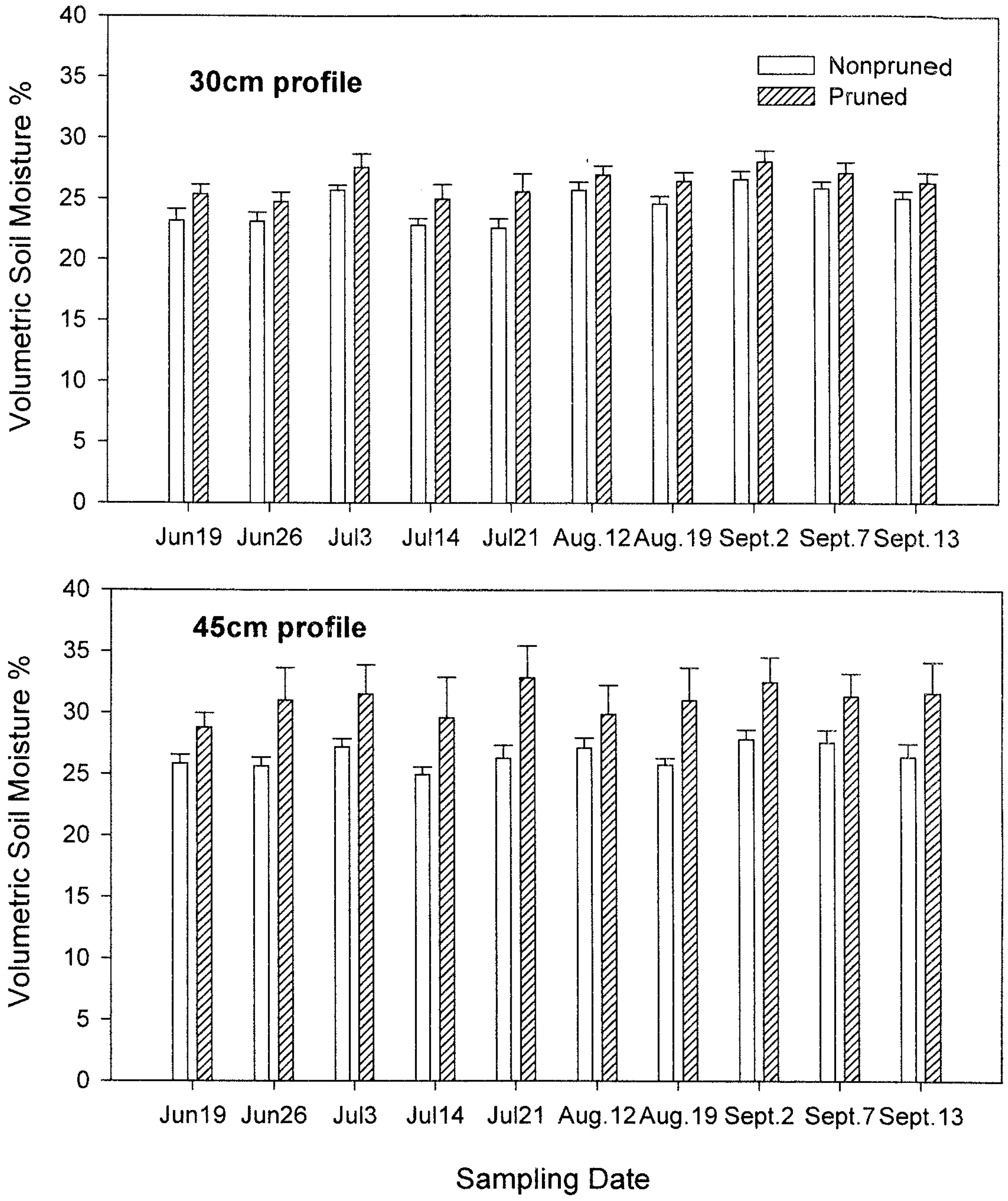

Figure 2.5 1998 soil moisture for different sampling depths.

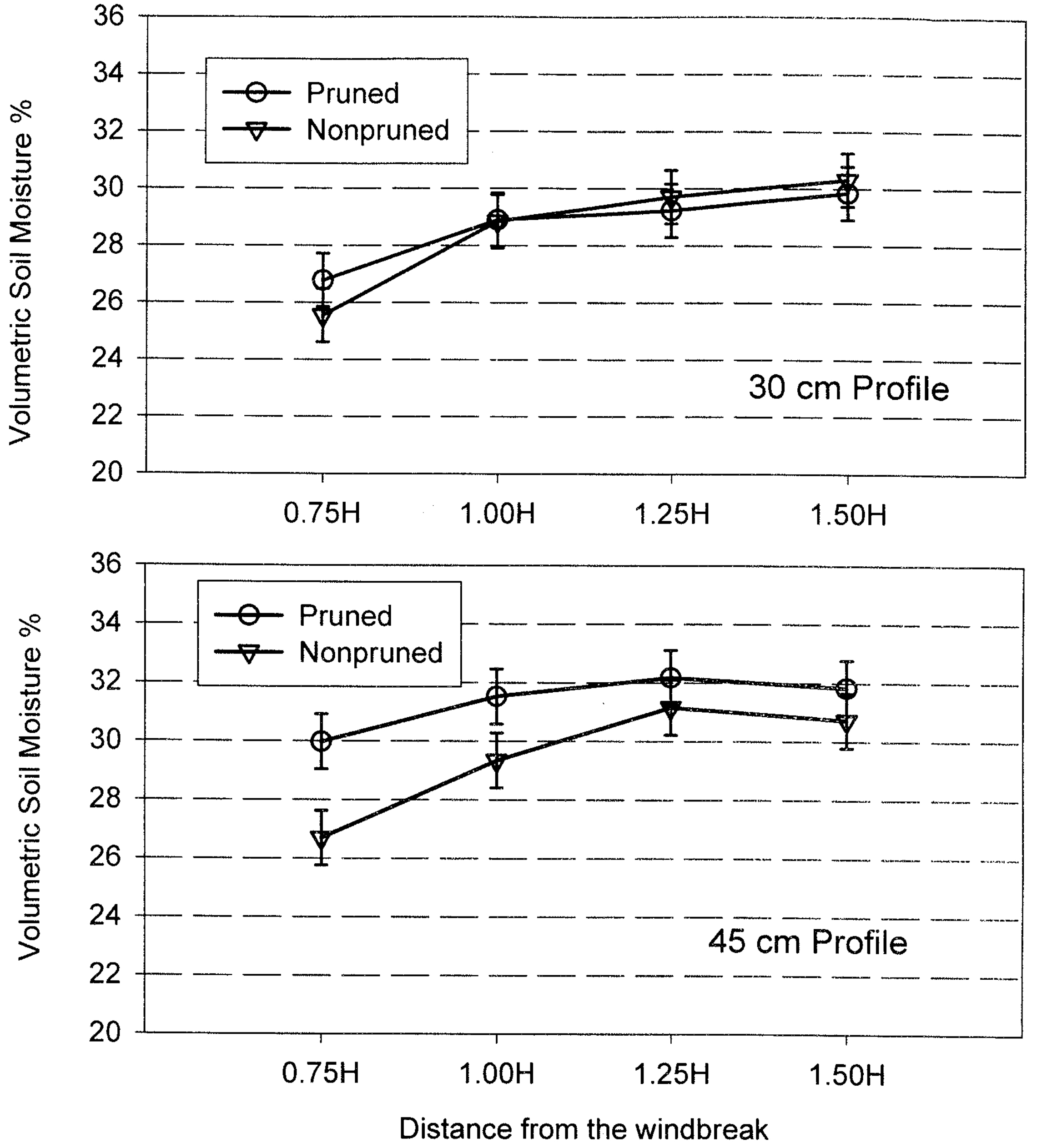

Figure 2.6 Mean soil moisture as a function of pruning, distance, and depth in the south exposure in 1998. Means calculated by SAS mixed procedure. Error bars stand for standard errors.
H represents windbreak height

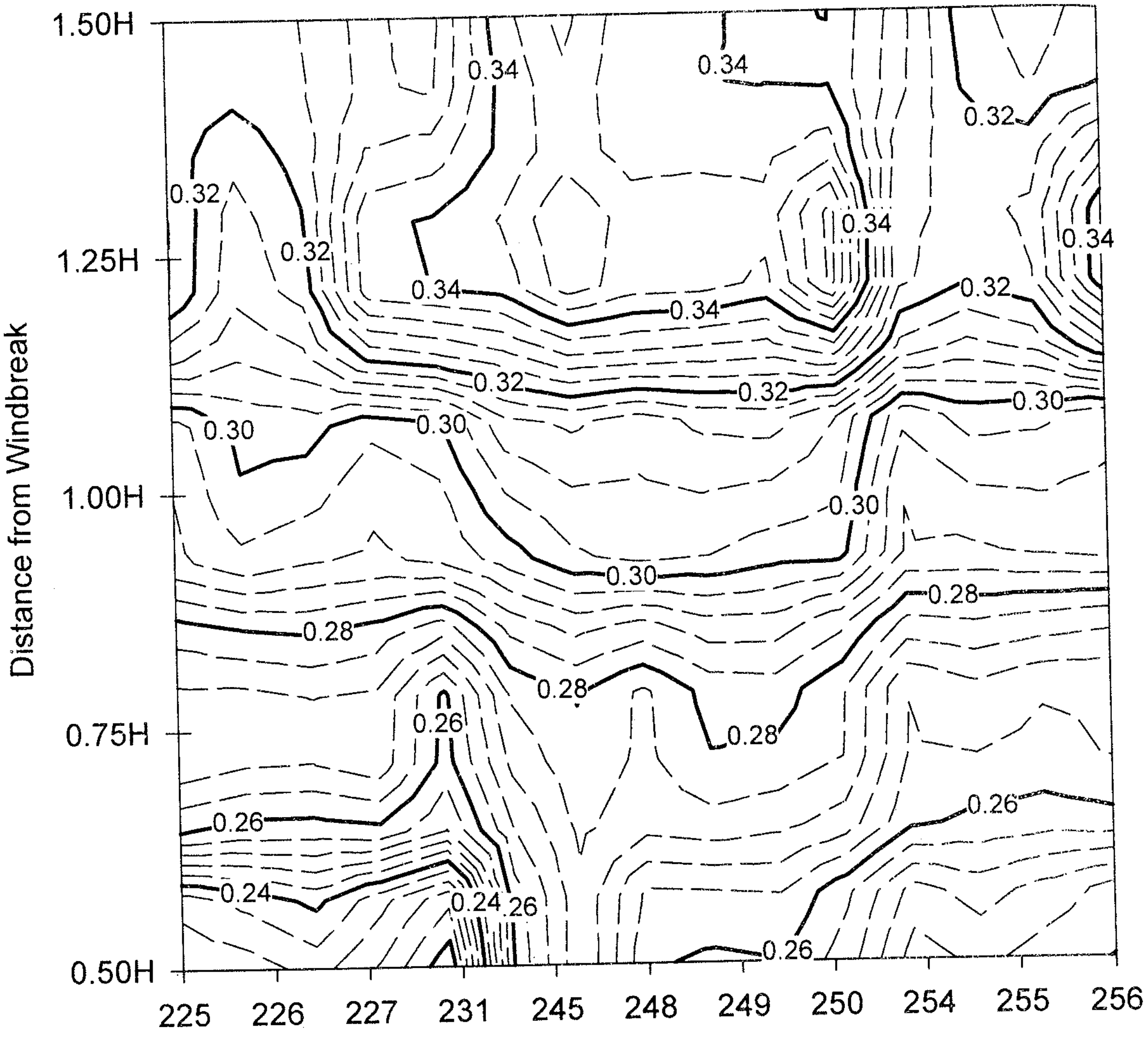

Figure 2.7 Average soil moisture as a function of distance in the top 45 cm profile of the nonpruned plots as measured on consecutive days.
H represents windbreak height.

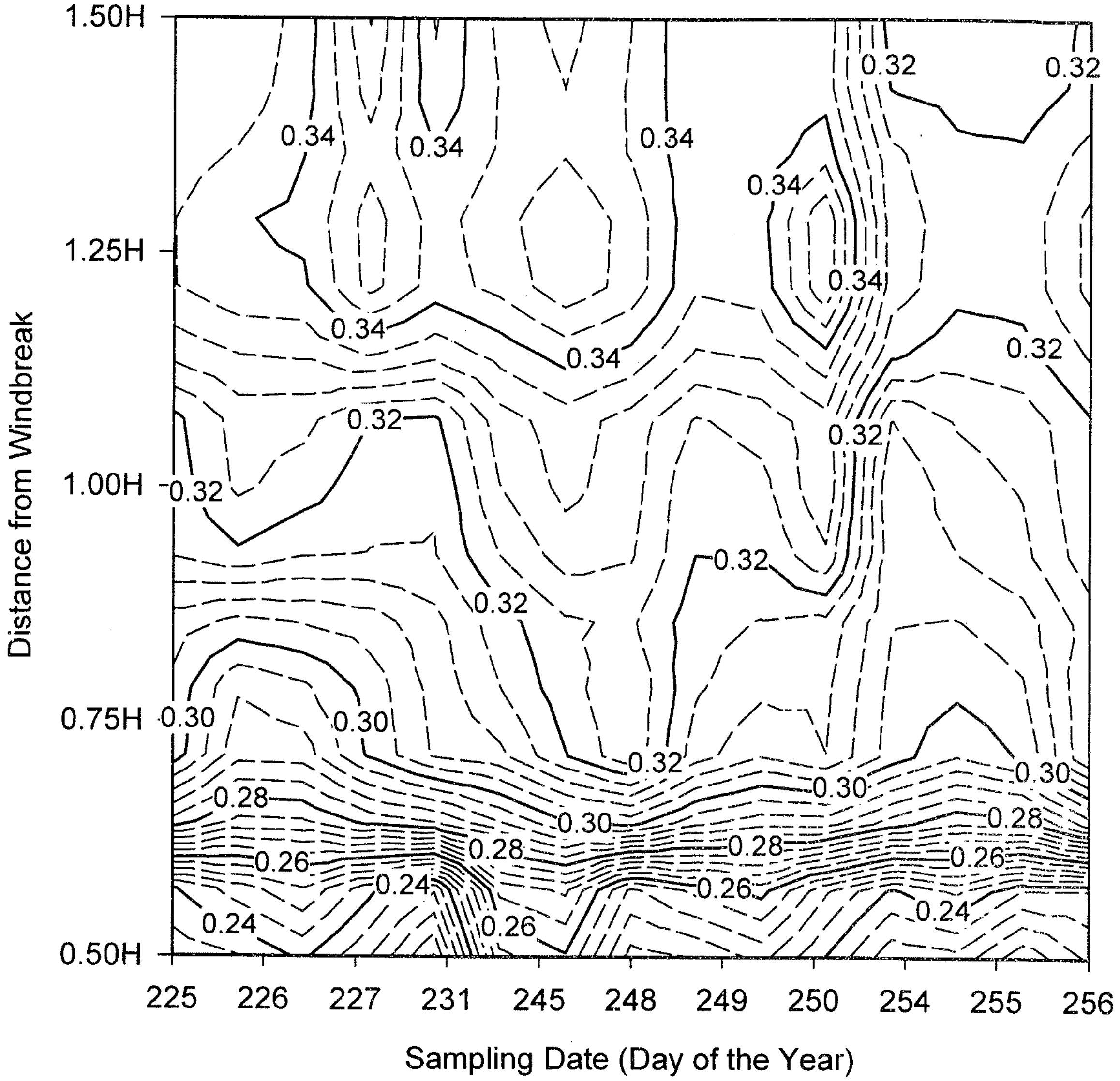

Figure 2.8 Average soil moisture as a function of distance in the top 45 cm profile of the pruned plots as measured on consecutive days.
H represents windbreak height. Pruning line was at 0.6H.

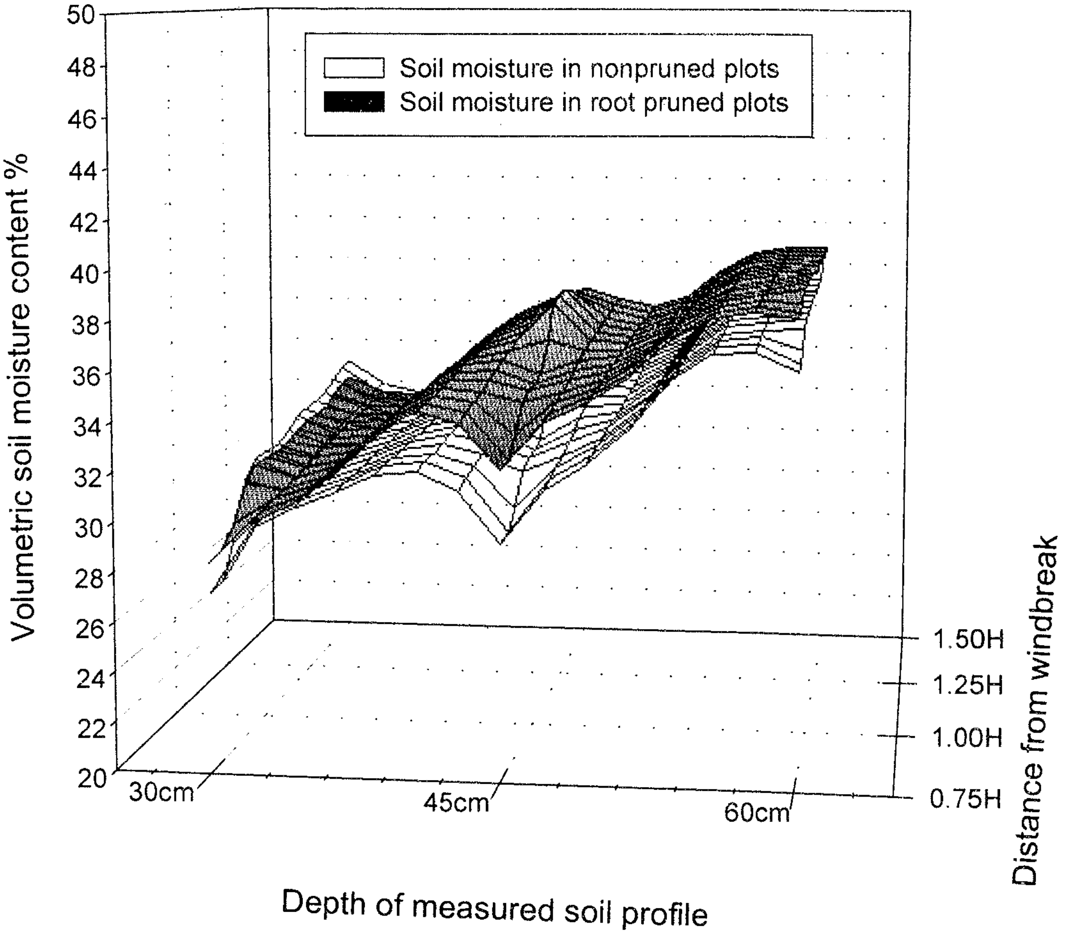

Figure 2.9 Spatial distribution of volumetric soil water percentage in root pruned and nonpruned plots as measured on August 12, 1998.
H represents windbreak height.

Chapter 3

COMPARING TDR WITH GRAVIMETRIC METHOD FOR MEASURING SOIL MOISTURE UNDER FIELD CONDITIONS

Abstract

Studies indicate that Time Domain Reflectometry (TDR) is a reliable and time-efficient method of measuring soil moisture. Limited soil disturbance, flexibility for large field application, and the capability for repeated measurements are major advantages of TDR. In a two-year root-pruning study conducted in the windbreak/crop interface, we compared the performance of TDR Trase with gravimetric determinations. Based on a dozen rounds of site-paired measurements over a large field, Pearson correlation between TDR Trase and gravimetric samplings was 0.61, indicating some differences existed between the two methods. The standard deviation for the TDR trase measurements ranged from 1.2 to 1.8% in volumetric water content in contrast to 1.7 to 3.4% for the corresponding gravimetric determinations. Under both cropped and noncropped conditions at the windbreak/crop interface, the TDR Trase data revealed a significant increase in soil water content as a result of windbreak root-pruning, but the gravimetric method did not. When a soybean crop was involved in 1997, the observed moisture differences by TDR Trase in respect to root-pruning and distance from the windbreak were well reflected by the corresponding soybean biomass and yield data. Under a noncropped condition in 1998, the TDR Trase data revealed a soil moisture enhancement pattern in the root-pruning plots that agrees with the previously reported range of yield suppression at windbreak /crop interfaces. While the corresponding

gravimetric determinations showed a similar trend as the Trase data, the magnitude of moisture differences and the significant levels were smaller between treatments. Part of the difference between the two methods was caused by the spatial variation in terms of water content and soil bulk density. Another major reason for the discrepancy lies in the different effective volumes sampled by each method. The TDR measurement, which corresponds to a cylinder of 1.5 times the space between the paired waveguides in diameter, senses a soil volume much larger than a gravimetric sample. Consequently, a larger sample would be required for the gravimetric method than for the TDR determination if the same level of measurement accuracy is to be obtained. These suggest that the TDR method is more sensitive than the gravimetric determination and thus suitable for use in a large field study where repeated measures are required.

3.1. Introduction

The gravimetric method for measuring soil moisture has some limitations (Chapter 2, 4) despite its accuracy and cheap equipment costs. Time Domain Reflectometry offers some advantages over direct soil sampling, but its overall performance under field conditions requires further evaluation. In order to compare the two methods on a large field data basis, a series of corresponding measurements were taken in the study on competition for soil moisture at the windbreak/crop interface described in Chapter 2.

3.2. Objective of the Study

The objective of this study was to compare the performance of the TDR Trase System I

(Soilmoisture Equipment Corp., Santa Barbara, CA) with the gravimetric sampling method under field conditions.

3.3. Data Collection and Statistical Analysis

Soil moisture was systematically measured using TDR at three distances, two depths, and three replications in the east and west exposures of three windbreak systems for both root-pruned and nonpruned treatments in 1997 (site conditions and experimental layout are described in Chapter 2, Appendix Fig. 5). As part of a companion study, volumetric soil moistures were gravimetrically determined for the same three windbreak systems in similar spatial patterns throughout the growing season (Nieto, 1998).

Along with 32 rounds of TDR measurements taken from June to September (1998) using two sets of TDR Trase System I (see Chapter 2 for sampling scheme), nine rounds of gravimetric measurements were taken at nearby locations corresponding to each TDR waveguide location (Appendix Fig. 6). A new TDR Trase unit (the same model) was used starting from early August till mid-September because of maintenance for the original machine, and with the new Trase unit twelve rounds of measurements were recorded. In a companion with measurements by the new Trase unit, three rounds of gravimetric samples were collected. All gravimetric samples were taken at least three meters away but within five meters from the TDR waveguide locations in order to minimize site variation and sampling interference. Each round of gravimetric measurement consisted of forty samples for each sampling depth (30 cm and 45 cm) for a total of 80 samples. Soil samples were dried under a constant oven temperature of 110°C until constant weight was achieved at which time the dry weights were recorded.

Soil bulk densities were determined throughout the field by three depth levels at 30 cm, 45 cm, and 60 cm in order to convert gravimetric data to a volumetric basis. A total of 35 bulk density samples were collected in conjunction with moisture sensor calibration. The samples covered different moisture conditions and a range of distances from the windbreak throughout the 35 meter strip along the windbreak. Site specific conditions are discussed in Chapter 2.

For the nine rounds of gravimetrically determined soil moisture data under noncropped conditions, the same statistical procedures, SAS Mixed model (SAS Institute, 1990) as described in Chapter 2, were used for analysis of variance and testing of fixed effects.

3.4. Results

Soil Bulk Density

As expected, soil bulk density varied significantly with depth ($P< 0.001$) but less so with distance from the windbreak. Mean bulk density for the top 30 cm, 45 cm, and 60 cm profiles were 1.20, 1.36, and 1.27 with standard deviations of 0.08, 0.07, and 0.02, respectively.

Sampling Variation with TDR Trase and Gravimetric Methods

Data analysis in Chapter 2 indicated that soil moisture in the top 30 cm profile in the 1998 experimental field showed no significant differences between root-pruned and nonpruned plots, especially at 1.00H, 1.25H, and 1.50H (H = windbreak height). Data from these three sampling locations in both root-pruned and nonpruned plots were used for contrasting sampling variations associated with each method on a daily basis. The standard deviations for a number of data sets, each consisting of 24 gravimetric samples from the top 30 cm profile in four replications, ranged from 1.7 to 3.4% while those for the TDR Trase 30 cm waveguides were from 1.2 to 1.8% (Table 3.1 & 3.2). On August 12, 13, and 19, when both gravimetric soil samples and TDR measurements were taken, the standard deviations for the TDR Trase data were 1.5, 1.8, and 1.4%, in contrast to 2.1, 2.5, and 2.2% for the gravimetric determinations, respectively.

Using the 1998 field data and with the TDR recordings as the dependent variable, linear regression on the corresponding gravimetric data (30 cm and 45 cm) produced the overall coefficients of 0.52 (slope) and 17.9 %(intercept) with the adjusted R^2 (square of the Pearson correlation coefficient) of 0.36. The 30 cm waveguides had a larger slope and R^2 values than those for the 45 cm (Fig. 3.1 & 3.2). Based on 190 pairs of data from both 30 cm and 45 cm profiles, the Pearson correlation coefficient between gravimetric and TDR was 0.61.

Statistical analysis for the nine rounds of gravimetric data in 1998 indicates that measuring date, distance from the windbreak, and depth in the soil profile all had significant effects on soil moisture ($P<0.001$). Also, windbreak root-pruning showed strong interactions with both depth of soil profile and date of measurement ($P = 0.04$ and 0.02, respectively) (Table 3.3 A and B).

3.5. Discussions

Soil bulk density measurement is required for comparing the gravimetric-based measures with the volumetric-based measures of TDR. It is very difficult to readily obtain soil bulk density data and accuracy is sacrificed by using mean values because of its large spatial variation. Suppose the mean soil moisture is 30% by weight, the conversion into volumetric water content using the above measured bulk density values would produce 0.08×1.96×30% = 4.7% or 0.07×1.96×30% = 4.2% error at the 95% confident level for the 30 cm or 45 cm soil profiles, respectively. In this study, significant differences in soil bulk density were revealed between depths of the soil profile but less so with distance from the windbreak (Table 3.3). The higher soil bulk densities in the top 45 cm profile may be the result of a plowing-induced hardpan layer formed between 30 and 45 cm. Variations associated with soil bulk density may have comprised one of the factors resulting in the low correlation with the TDR Trase data.

The large variation associated with each set of gravimetric samples also can account for the discrepancies between the two methods. With the maximum standard deviation of 3.4% for the gravimetric determination and 1.8% for the TDR measurement at the same set of sampling locations (Table 4.1), it would take 44 or 11 samples for the gravimetric determination to approximate soil moisture within 1% or 2% error limits, respectively, with 95% confidence. Correspondingly, only 13 or 4 pairs of TDR waveguides would be needed to achieve a similar level of estimation accuracy.

Because of the spatial gradient in soil moisture and bulk density, the larger variation with each set of gravimetric samples could be, or at least partially, caused by site variation since each round of gravimetric samples were taken from different locations while the TDR Trase measurements were not. The effect of spatial variation is also confounded with the effective sensing volume for each method in respect to the variance associated with each set of samples. Gravimetric samples on August 12, 13, and 19 indicated that variation for the standard deviations (2.1, 2.5, and 2.2% on daily basis) was 0.25% while that for the corresponding TDR measurements was 0.21% (1.53, 1.79, and

1.37%). This means site variation for both TDR and gravimetric determinations were in the same magnitude, indicating the small sensing volume is more responsible than the spatial variation for the observed variation within each set of samples.

3.5.1 Discrepancy and similarity between TDR and gravimetric determinations under cropped conditions in 1997

The 1997 soil moisture data measured with TDR showed the same trend as those by gravimetric determinations in respect to exposures and stages of crop development, despite the effect of multi-locations (three windbreak systems), study-specific measuring scheme, and different approaches by two independent studies (Nieto, 1998) (Fig. 3. 3). The general compliance implies that TDR and gravimetric determinations generally depict the same trend on a large field data basis.

Nevertheless, TDR data for the east exposure showed a highly significant difference in soil moisture as a result of root-pruning in both the 30 cm and 45 cm profiles at 0.75H and in 30 cm at 1.00H (Chapter 2) while gravimetric data did not. Soybean crop biomass and yield measurements correlated well with the soil moisture pattern revealed by TDR data with respect to exposure, root-pruning, and distance within the windbreak/crop competition zone (Chapter 2). The discrepancy between TDR Trase and gravimetric sampling may be related to the differences in the working principle pertaining to each method and the size of samples taken with each method. The effective sampling volume for each pair of TDR waveguides (a cylinder with a diameter approximately 1.5 times the space between the parallel waveguides (Topp et.al, 1984)) is nearly 20 times larger than that collected by a standard soil sampling probes (usually 2 cm in diameter). Because of its time efficiency and flexibility for use in large fields, each round of measurements with the TDR Trase method consisted of 204 measuring points at two depths (30 cm and 45 cm) compared to only 48 samples at one depth with the gravimetric sampling method. Larger number of samples provided the TDR method greater power than the gravimetric determination for detecting treatment effects on soil moisture.

The TDR technique as used with a Trase unit does have some problems that must be dealt with in field experiments. Our experience involved a few missleading outputs on the 45 cm rods due to soil shrinkage when the soil was dry. At some spots readings generated by the Trase processor were consistently higher than those from neighboring locations. Quality control procedures, such as setting the upper limit of individual recordings or making adjustment according to neighboring spots, need to be invoked before data analysis is conducted.

3.5.2 Discrepancy and similarity between TDR and gravimetric determinations under non-cropped conditions in 1998

Under the noncropped conditions used in 1998, gravimetric determinations revealed a generally similar trend to TDR Trase data but also showed some disagreement with what has been discussed in Chapter 2. Like the TDR Trase method, the gravimetric determination also found a greater moisture difference in the 45 cm profile than in the 30 cm layer as a result of root-pruning but the differences between pruned and nonpruned plots were smaller in magnitude.

On one hand, gravimetric data did reveal that soil moisture in the 45 cm profile increased for about 2% at 0.75H and 1.25H as a result of root-pruning on some dates (day of the year 196,202, 223, and 225) (Fig. 3.4 & Fig. 3.5). On the other hand, for the combined data of all dates no significant differences were present in a SAS Mixed procedure between root-pruned and nonpruned plots at any distance, depth, and distance by depth interaction. These results differ from what has been discussed for the corresponding TDR Trase data in Chapter 2.

Despite the fact that gravimetric determination did not show as large a difference as by Trase, statistical analyses suggest some important relationships in regard to the effects by treatments and their combinations (Table 3.4). These relationships are similar to what have been explained for the TDR data in Chapter 2. First of all, soil moisture was dominantly affected by date of measurement (P value = 0.0001) and date of measurement also showed significant interactions with root-pruning, distance, and depth of the soil profile (P values equal 0.0257, 0.0001, and 0.0008 respectively). Interactions among pruning, distance, and date were also highly significant (0.0139). Regarding treatment by date interaction, root-pruning increased soil water content when overall soil moisture was moderately high (on June 30, July 14 and 15, August 11 and 13). On those dates, treatment by distance interactions were also higher and pruning increased soil water content at all measured distances, though the magnitude was not consistent. On some dates the increase at 0.75H was higher than for other locations (August 11 and 13, July 14) while on other dates the opposite was true (June 30 and July 15). However, when soil moisture was low like on June 21 and July 21 the favorable soil moisture conditions created by root-pruning were not sustained or detectable. The dominant effect by sampling date was easy to understand because weather conditions determine both water supply from rain events and water consumption via bare soil evaporation under no crop situation. Without vegetation, direct evaporation dominated the soil water extraction. Root-pruning changed water consumption within a certain range of soil moisture conditions, which was set by the overall relationship of supply and demand. When soil water content was moderately high, demand by direct evaporation and tree root extraction at the control plots could well exceed bare soil evaporation alone in root-pruned plots, thus making a difference between treatments detectable. Similarly, when the overall soil moisture was low the majority, if not all, of available soil water in both root-pruned and nonpruned plots could have been exhausted therefore making the root- pruning effect undetectable.

Despite the general agreement between TDR and gravimetric determinations in respect to impacts of windbreak orientation, distance from the windbreak, and depth of the soil profile on soil water, the TDR method is more sensitive to treatment effects. This makes the TDR Trase method more suitable for this type of, especially because it allows a nondestructive measurement over large areas at a relatively fast speed and with large replications.

Overall, the TDR and gravimetric data show a positive correlation throughout the 1998 measuring period. Reasons for their discrepancy can be complicated. Small scale spatial heterogeneity may be a major contributing factor since all gravimetric samples were taken at least two meters away from the TDR probe locations in order to reduce the possibility of interaction between the two methods. Figure 3.6 and 3.7 demonstrate this difference between TDR and gravimetric determinations, based on equal numbers of measurements from the same set of sampling locations. For the same reason, the correlation for consecutive rounds of measurements in respect to each sampling location was much lower for the gravimetric determination compared to the corresponding TDR determinations (Fig. 3.8 & Fig. 3.9). Also, the two methods differs in measuring unit because TDR readings correspond to volumetric water content of the soil profile, while direct soil samples give soil water content on a weight basis. Whenever weight-based soil water content was translated into volumetric basis it inevitably introduced an additional error associated with soil bulk density estimation.

Nevertheless, statistical analysis for the TDR data sets collected at corresponding locations showed a significantly higher soil water content in the top 45 cm profile as a result of root-pruning. A 3-4% soil moisture increase was consistently observed within a range of one tree height from the windbreak in the root-pruned plots throughout the growing season (Chapter 2). Such soil moisture differences in respect to distance from the windbreak and root-pruning treatment agree well with the previously reported crop yield response and the well-recognized range of windbreak/crop competition in similar studies (Kort, 1988).

3.6. Conclusions

Field application indicated that the TDR Trase System is reliable for determining volumetric soil water content. Its working principle permits timely, nondestructive, and repeated measurements on a large field basis. Compared to gravimetric determination, TDR Trase has a larger effective sensing volume per sample, thus making it less vulnerable to the large spatial variation and small scale heterogeneity in soil water contents. Unlike gravimetric determination TDR does not require site specific measurement of soil bulk density, which tends to change in both the horizontal and vertical directions and constitute one of the major factors for reducing the accuracy for measuring the volumetric soil water content by the direct soil sampling method. Timeliness, flexibility for using over multiple locations, and the capability of sensing a large soil volume made the TDR Trase system a sensitive way to detect treatment induced soil moisture differences on a large filed basis under both cropped and noncropped conditions.

Table 3.1 Standard deviations and the volumetric soil moisture ranges associated with gravimetric samples in the top 30 cm soil profile in the south exposure in 1998.

Date	Sample Number	Mean	Standard Deviation	Maximum	Minimum
June17	24	34.6	1.67	38.7	32.6
June 21	24	21.9	3.38	36.7	19.3
June 30	24	35.1	2.05	38.3	31.8
July 14	24	34.3	2.05	40.2	30.9
July 15	24	34.0	1.77	37.1	30.7
June 21	24	26.8	3.71	30.8	10.7
August 12	24	34.1	2.04	40.4	31.7
August 13	24	34.5	2.53	40.5	30.2
August 19	24	32.9	2.18	36.6	29.8

Samples were taken at 1.00H, 1.25H, and 1.50H.
H represents windbreak height.

Table 3.2 Standard deviations and the volumetric soil moisture ranges associated TDR Trase measurements on the 30 cm waveguides vertically inserted from the surface at 1.00H, 1.25H, and 1.50H in the south exposure in 1998.

Date	Sample Number	Mean	Standard Deviation	Maximum	Minimum
August 12	24	30.2	1.53	32.5	26.5
August 13	24	29.9	1.79	32.2	25.3
August 14	24	30.0	1.47	32.5	27.0
August 15	24	30.2	1.55	32.8	27.2
August 19	24	29.2	1.37	31.6	26.4
Sept. 2	24	30.1	1.53	32.7	27.4
Sept. 5	24	29.4	1.47	31.9	26.9
Sept. 6	24	29.8	1.32	31.9	27.2
Sept. 7	24	29.7	1.36	31.8	27.0
Sept. 11	24	28.6	1.17	30.7	26.4
Sept. 12	24	28.5	1.16	30.9	26.3
Sept. 13	24	28.8	1.18	31.1	26.6

H represents windbreak height.

Table 3.3

A. Analysis of variance for soil bulk density. Depth levels include 30 cm, 45 cm, and 60cm from the surface.

Source	DF	SS	MS	F value	Pr > F
Depth	2	0.121	0.06	6.75	0.0039
Distance	1	0.001	0.001	0.11	0.7403
Depth×Distance	2	0.0035	0.0017	1.97	0.1575

DF = Degrees of freedom.

B. Mean soil bulk density by profile.

Depth	Mean BK kg / cm^3	Standard deviation
30 cm	1.20	0.008
45 cm	1.36	0.007
60 cm	1.32	0.142

Table 3.4 Analysis of variance for the fixed treatment effects on soil moisture measured with gravimetric soil sampling method in 1998. Pruning includes root-pruned and nonpruned. Distances: 0.75H, 1.00H, 1.25H, and 1.50H. Depths: 30 cm and 45 cm. Dates: June 17, June 21, June 30, July 14, July 15, July 21, August 12, August 13, and August 19.

Source	NDF	DDF	F value	Pr > F
Pruning (P)	1	6	0.25	0.636
Distance	3	18	14.78	0.0001
P×Distance	3	18	0.72	0.552
Depth(D)	1	24	847.9	0.0001
P×D	1	24	4.55	0.0432
Distance×D	3	24	0.91	0.4506
P×D×Distance	3	24	1.18	0.3397
P×Date	8	24	266.3	0.0001
P×Date	8	359	2.34	0.0186

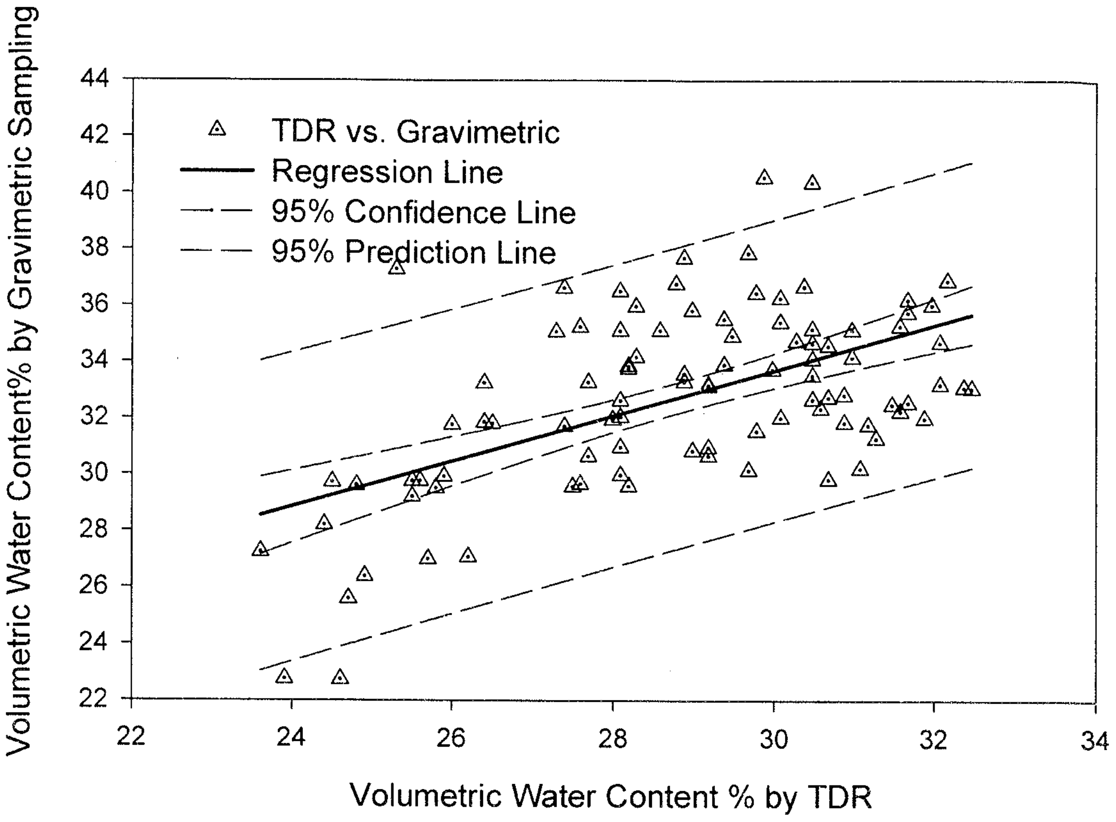

Figure 3.1 Linear regression and confidence interval of soil moistures measured with TDR Trase System on those by gravimetric soil sampling method for the top 30 cm profile. Data are from August 12, 13, and 19, 1998.

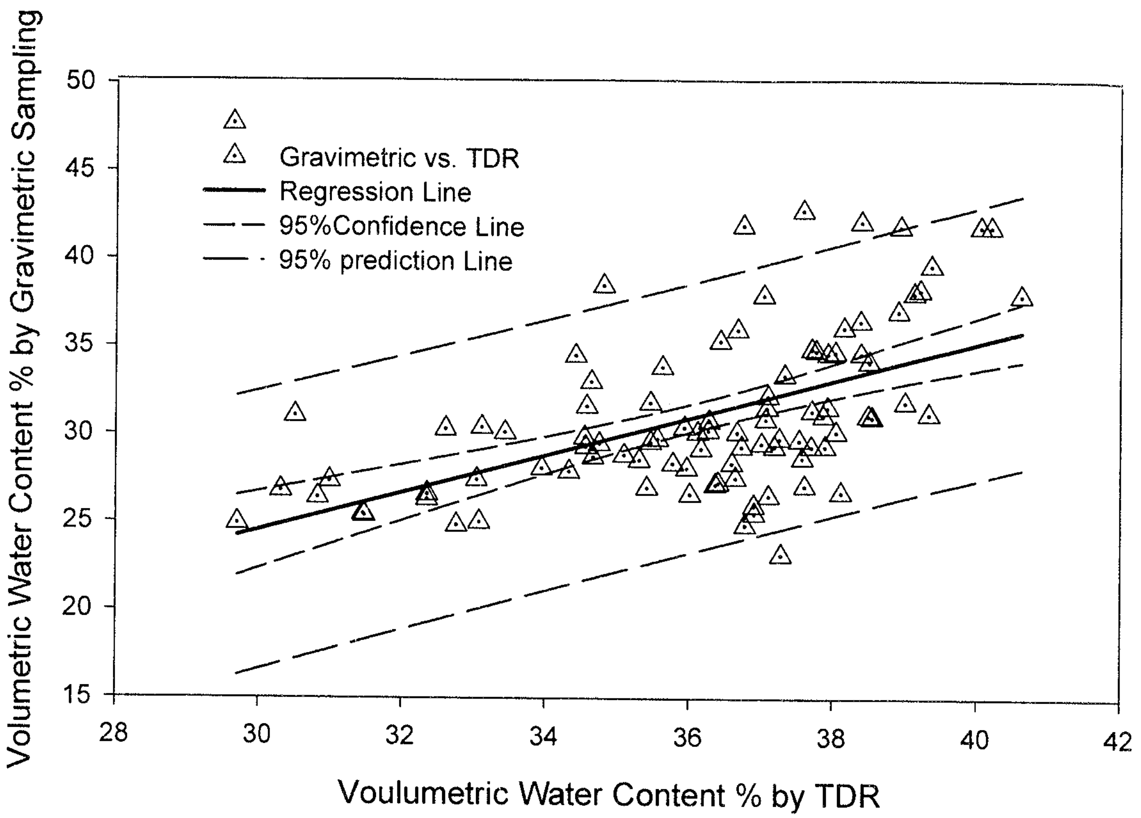

Figure 3.2 Linear regression and confidence interval of soil moistures measured withTDR Trase System on those by gravimetric soil samples for the top 45 cm profile. Data are from August 11, 13, and 19, 1998.

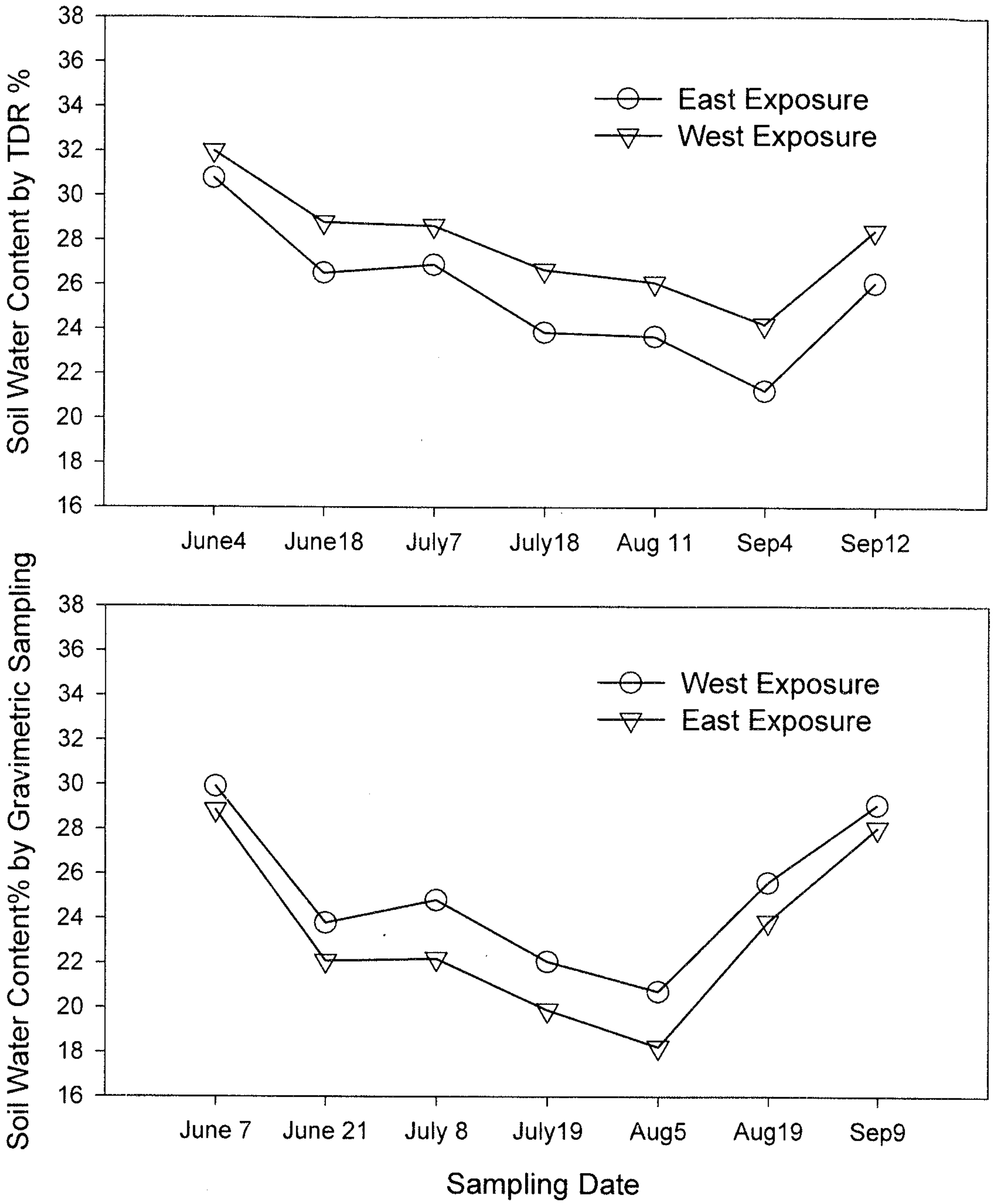

Figure 3.3 Volumetric soil water contents as a function of date and windbreak orientation at the East and West exposures as measured by TDR Trase and by gravimetric methods in the1997 growing season (gravimetric data after Nieto, Carlos).

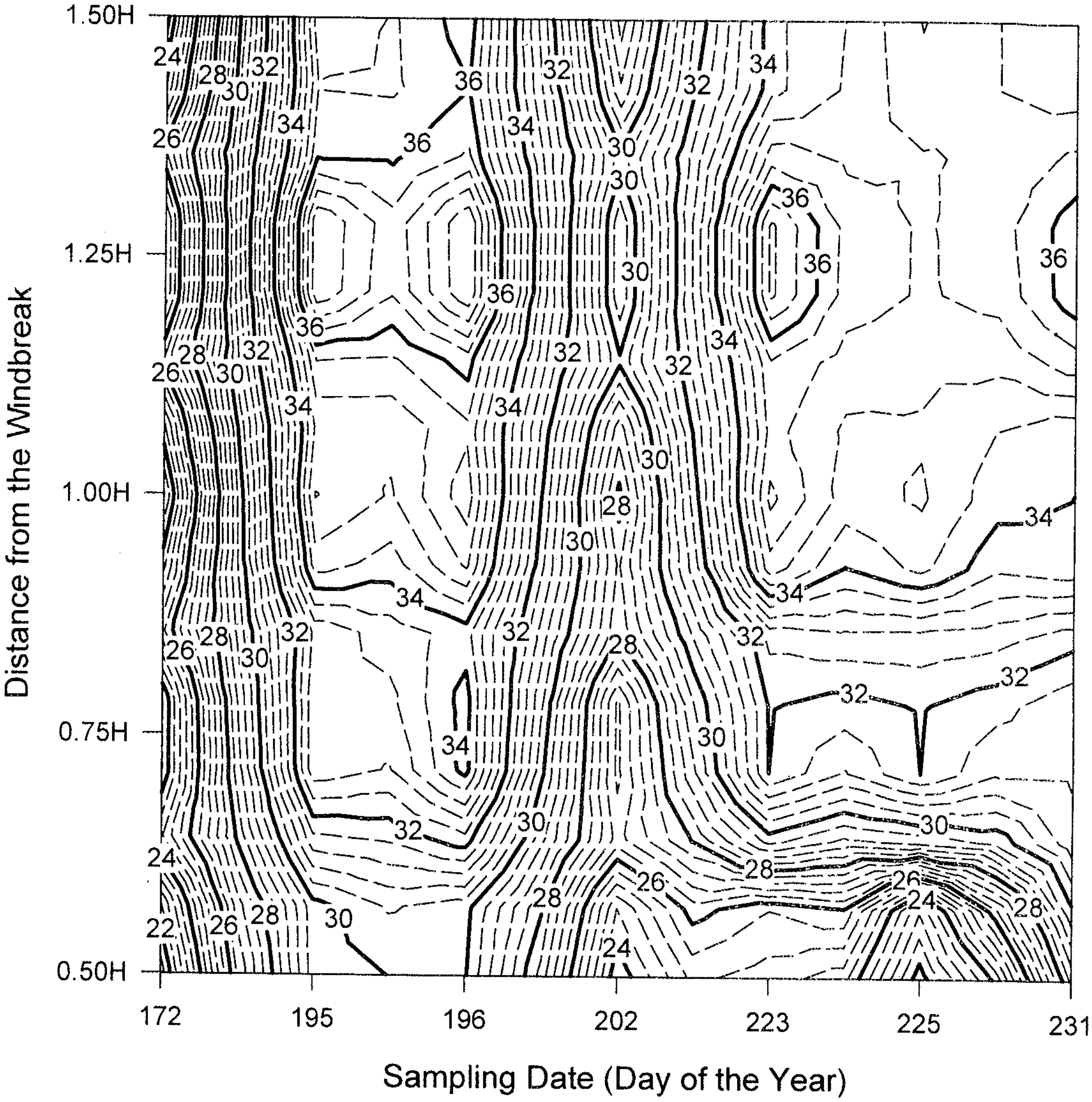

Figure 3.4 Soil moisture in the top 45 cm profile of nonpruned plots measured by gravimetric sampling method in 1998. H represents windbreak height.

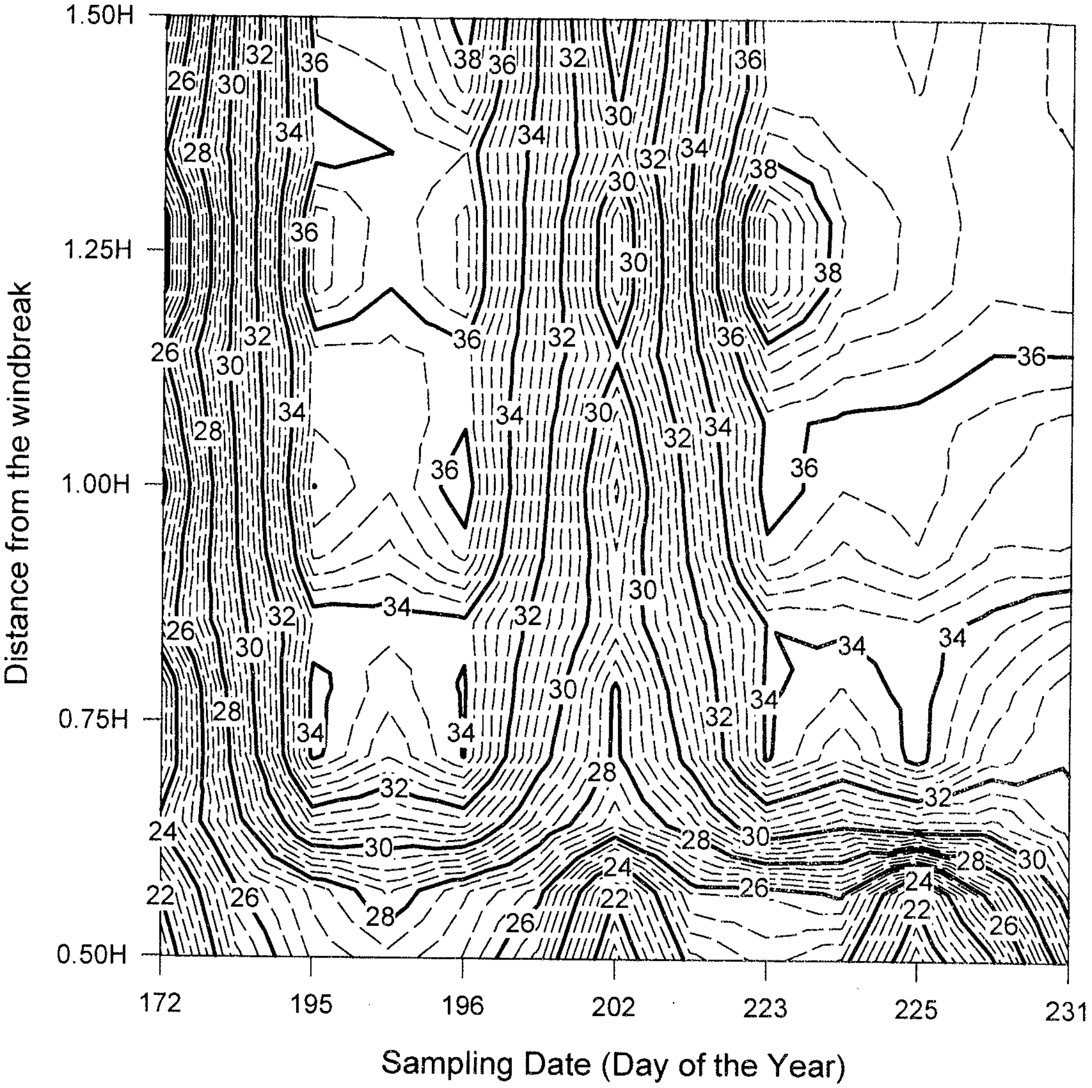

Figure 3.5 Soil moisture in the top 45 cm profile of pruned plots measured by gravimetric sampling method in 1998.
H represents windbreak height.

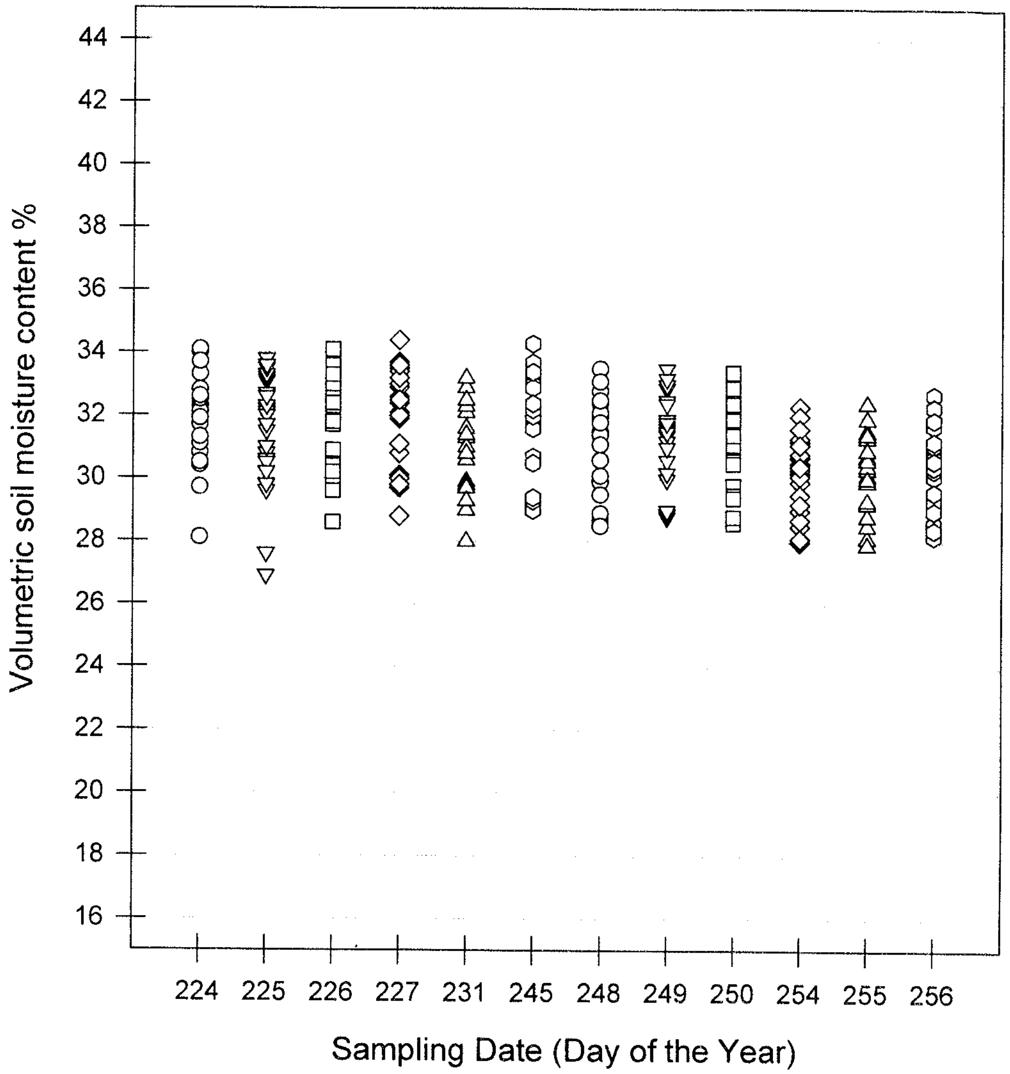

Figure 3.6 Soil moisture data distribution as measured with TDR Trase 30cm waveguides at 1.00H, 1.25H and, 1.50H in the test field in 1998. H represents windbreak height.

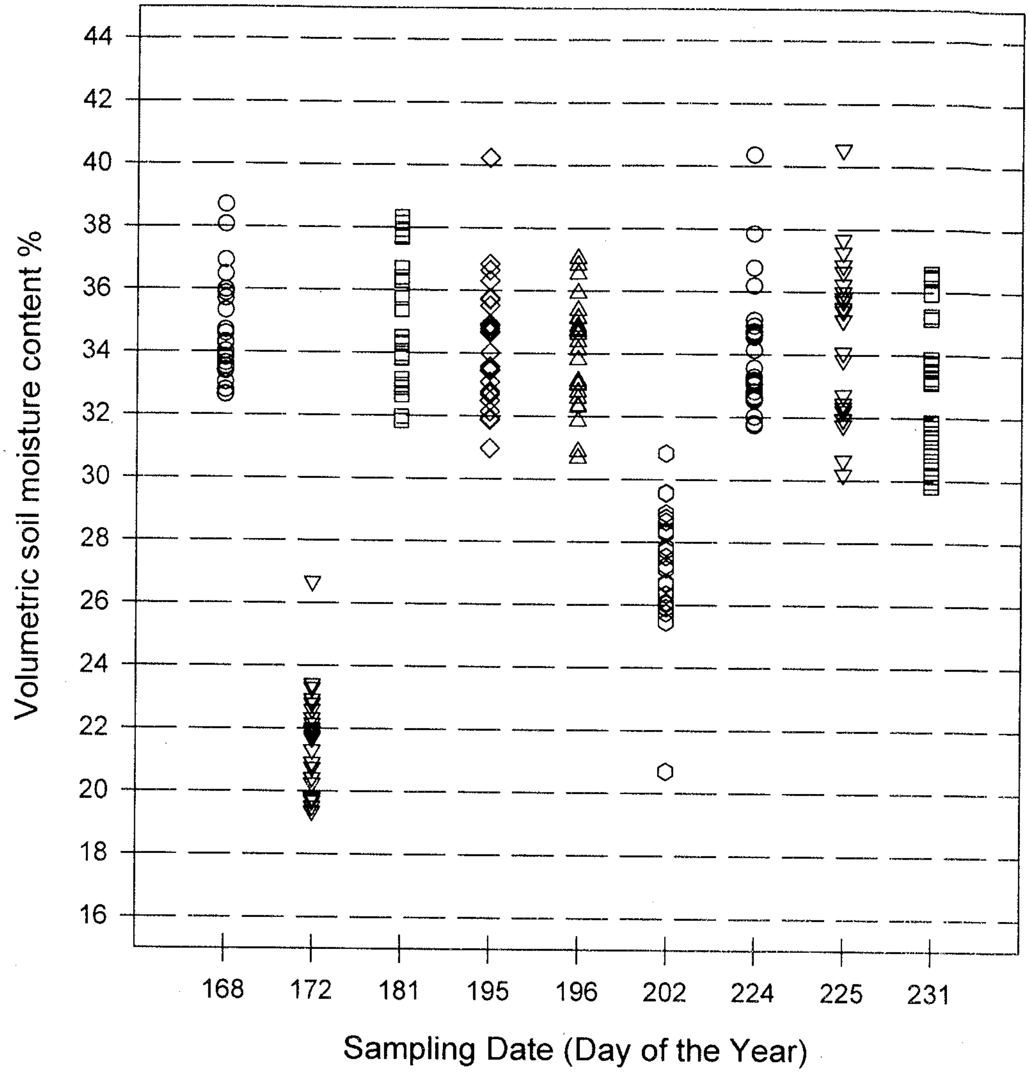

Figure 3.7 Soil moisture data distributions as measured by gravimetric sampling method in the top 30cm profile at 1.00H, 1.25H, and 1.50H in the test field in 1998. H= windbreak height.

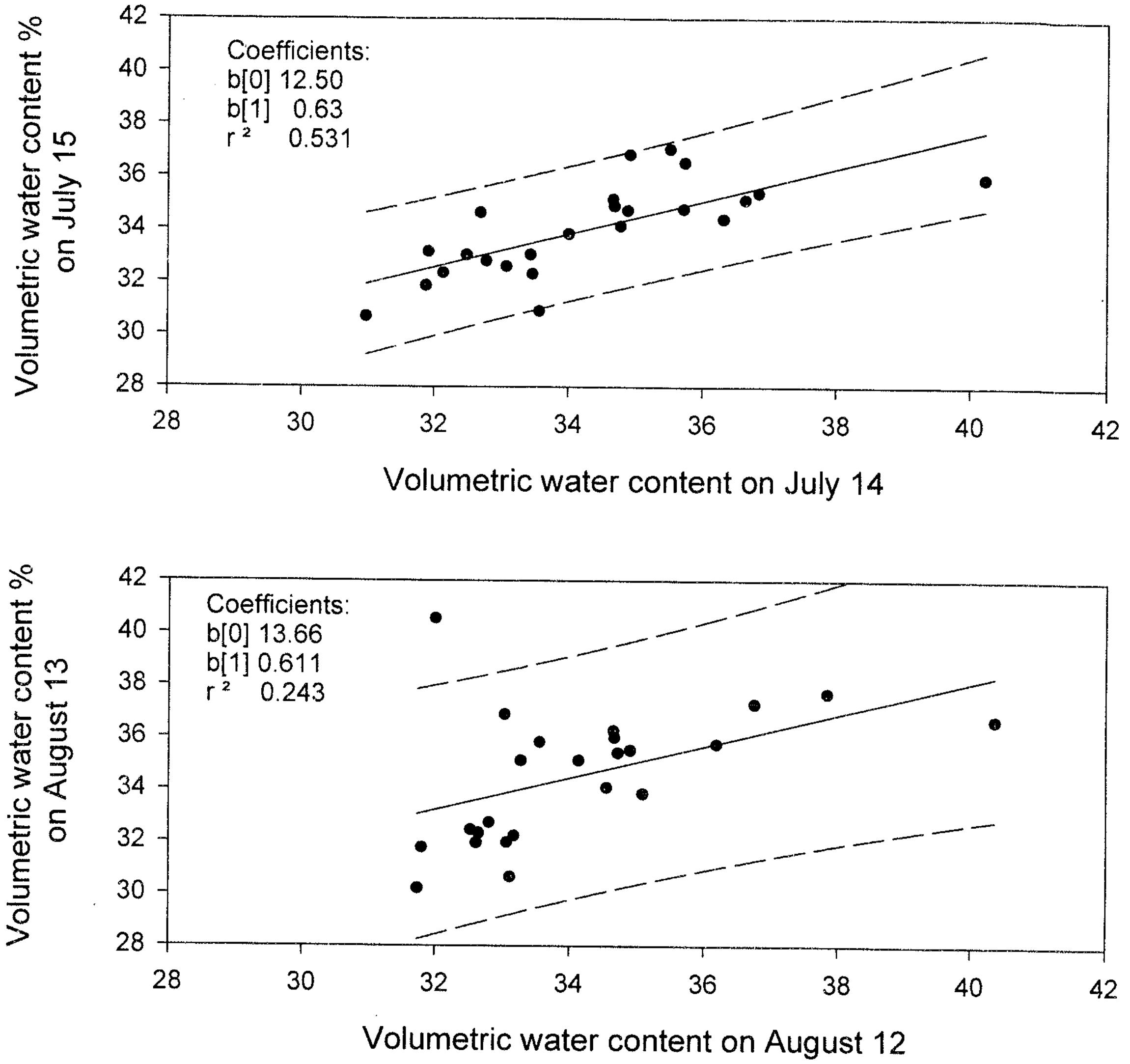

Figure 3.8 Correlation of soil moisture data measured at the same set of relative loctions on consecutive days by the gravimetric method. Dashed lines represent 95% confidence intervals.

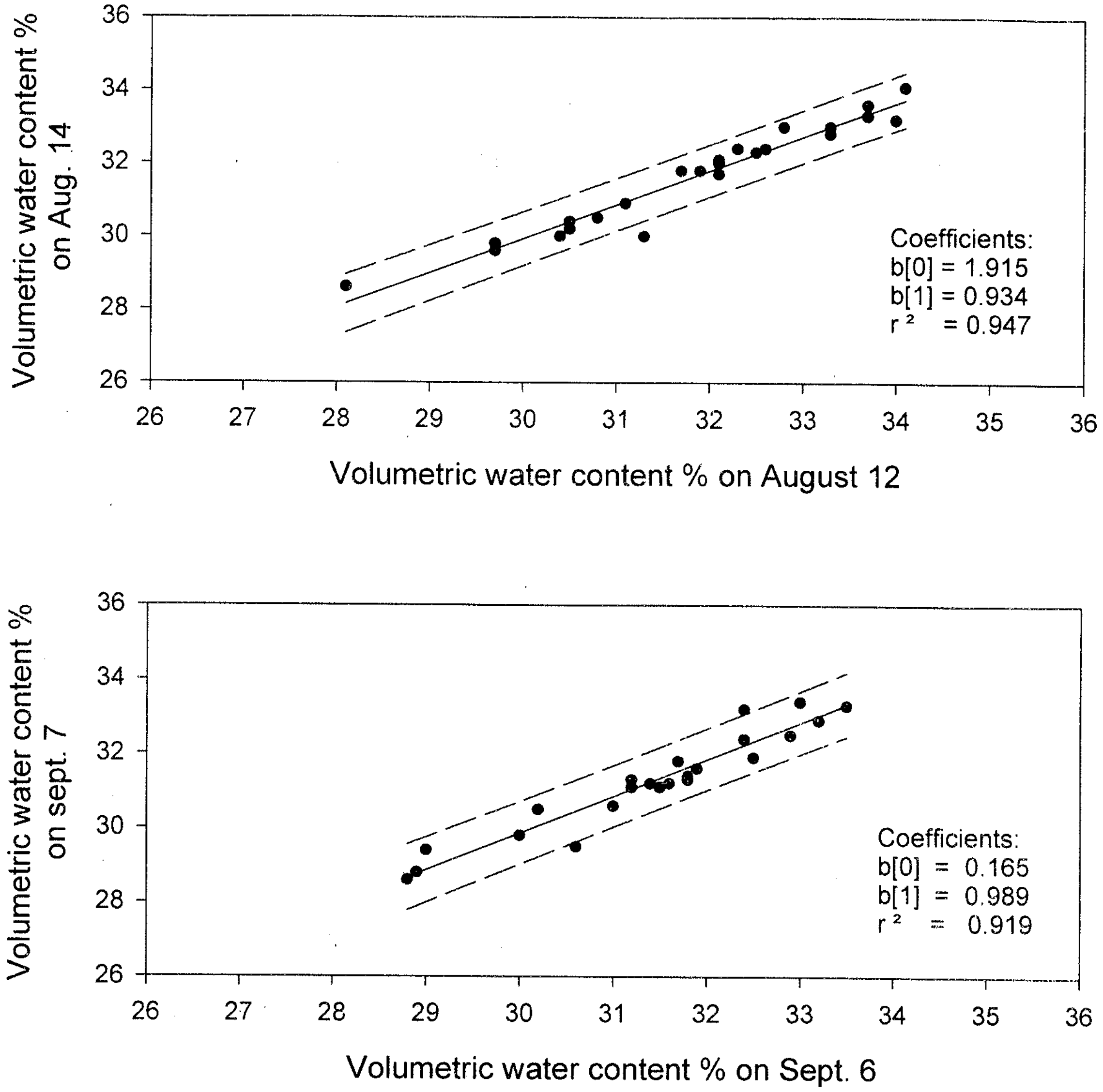

Figure 3.9 Correlation of soil moisture data measured on the same set of wave-guides on consecutive days by the TDR method. Dashed lines represent 95% confidence intervals.

Chapter 4

A COMPARISON OF THRE BRANDS OF SENSORS FOR MEASURING SOIL MOISTURE

Abstract

Some of the newer indirect methods for measuring soil moisture are promising and have advantages over the more traditional gravimetric determination, such as greater volume per sample, limited site disturbance, and capacity for repeated measures. Time Domain Reflectometry (TDR) represents one of the more promising techniques and several sensors are now on the market. We evaluated the ease of use and performance of three different sensors: CS615 Time Domain Reflectometer (Campbell Scientific, Inc., Logan, UT), TDR Trase System with 30 cm waveguides (Model 6050X1, Soilmoisture Equipment Corp., Santa Barbara, CA), and Hydra Soil Moisture Probe (Vitel, Inc., Chantilly, VA), under both greenhouse and field conditions. For the greenhouse study, two sets of two Hydra probes, two CS615s, and a TDR Trase processor with 30 cm waveguides were compared against gravimetrically determined measures inside two soil-filled buckets. Although the trends for each type of sensor compared well with the moisture change for the buckets, significant differences occurred among types in regards to accuracy, inter- and intra-sensor variability, and intra-sensor interchangeability. With the objective of measuring soil moisture in a 30 cm soil profile, those sensors with the larger effective sensing volume, i.e. the CS615 and Trase System, were less influenced by spatial variation and small-scale heterogeneity than the Hydra probe. Over one dry-down cycle inside the bucket, the Trase System with 30 cm waveguides correlated the closest with the gravimetric measures and gave the best performance in terms of

calibration, accuracy, and interchangeability. When vertically inserted in the top 30 cm soil profile under field conditions the Trase with 30 cm waveguides and CS615 sensors correlated better than they did with the Hydra probes inserted horizontally at 15 cm from the surface. When inserted side by side either horizontally at the same depth or vertically from the soil surface, the CS615 sensors showed a smaller variation than the Hydra probes. It seems the smaller sampling volume of the Hydra probe limits the sensor's ability to estimate a soil profile compared to the other two types of sensors. Given the high cost for Hydra probes ($295/unit) is more than compared to the CS615 ($205/unit) or Trase 30 cm waveguides ($10/each pair), it is less efficient to use multiple Hydra probes for estimating a soil profile if budget constraint is of concern.

4.1. Introduction

Competition among neighboring plants is inevitable whenever soil moisture becomes limited. Therefore, our ability to observe, measure, and interpret soil moisture is crucial to understanding the principles governing the competitive relationship in a plant community. Unfortunately, no method for determining soil moisture is perfect. The traditional gravimetric determination of soil moisture content is still believed to be the most reliable although there are limitations to the method, such as small effective sample volume, dependence on soil bulk density measurement for conversion into the more useful parameter of volumetric water content, site disturbance, plus time and labor intensiveness. Indirect methods, which employ access tubes or probes that enable measurement on a more continuous basis with only minimal soil disturbances at the time of installation, may be more desirable when repeated measurements, large sampling numbers, and quick results are a priority.

The latest developments in the field of environmental instrumentation offer a wide range of soil moisture sensor selection, many of which are based on Time Domain Reflectometry (TDR) and Frequency Domain Reflectometry (FDR)(Rundel & Jarrel, 1989). While these new technologies are promising, further evaluations are necessary before they will be widely accepted. Major concerns with these indirect methods are sensor accuracy and precision when they are used under the more variable and, in some cases, demanding conditions encountered in field studies.

Accuracy, the closeness of a measured value to the true value of the parameter being measured, depends on the sensor's physical characteristics, calibration, and proper installation. The sensor and site selections are therefore crucial to the accuracy of measurement (Hubbard, 1994). Precision is a measure of the scatter about the overall calibration line, while stability and repeatability represent the sensor's ability to hold to its calibration and to reproduce a measurement when exposed to the same environment. Other characteristics pertaining to a sensor's performance include sensitivity, linearity, endurance, as well as interchangeability. Sensor interchangeability refers to the goodness that one sensor's measure can be repeated by another when they are exposed to the same conditions: the higher the interchangeability the less the sensor's systematic error. Higher sensor interchangeability is crucial when the experiment demands multiple sensor replications. In addition, cost and installation requirement are also important aspects for sensor selection.

Techniques for the indirect determination of soil water content have improved rapidly since the discovery that the relative dielectric constant of soil material varies directly with soil water content (Topp et al., 1980, 1982). Both the working principles and field application of TDR are well-documented (Dasberg and Dalton, 1985, Dasberg and Nadler, 1987; Topp, 1981,1984, 1985; Dalton, 1984,1987; Richardson, 1992). In a typical TDR measurement, an electromagnetic pulse is transmitted into the soil where the parallel pair transmission line serves as a waveguide. The velocity of the pulse travelling in the soil is proportional to the dielectric constant of the soil, which is mainly determined by soil water content. Topp et al.(1980, 1982) have shown that calibration for alternative soil types was unnecessary and that soil and environmental factors such as texture, density, salt content, and temperature do not affect the TDR measurement of the liquid water content of soil.

The TDR method offers the advantages of measuring a relatively large soil volume and the potential for repeated sampling throughout periods of time (i.e. the growing season) (Pearcy, 1989). By comparing the TDR measured values with values obtained gravimetrically on a variety of soil types and soil water contents using both parallel transmission lines and waveguides, Topp et al.(1982, 1984) concluded that TDR measured values were as accurate and precise as those from gravimetric samples. Using a portable TDR cable tester, they found that the standard deviations of differences between TDR and gravimetric values were ± 0.02 $m^3 m^{-3}$ when measured locations were the same but increased to ± 0.06 $m^3 m^{-3}$ when measured locations were different.

Under greenhouse conditions, Richardson et al.(1992) studied the ability of TDR to estimate soil water content in closed containers. They concluded that estimation by TDR was highly correlated to gravimetric measure of soil cores with R^2 (correlation) values of 0.84, 0.96, and 0.98 depending on the types of soil and container. They suggested that comparative analysis of TDR with gravimetric samples is not needed to present accurate soil water measurements in closed-container studies.

Another technique used for measuring soil moisture is Frequency Domain Reflectometry (FDR), also known as the radio frequency capacitance technique. As high-frequency radio waves are pulsed through the soil via a pair of electrodes, a natural resonant frequency is established which is dependent on the soil capacitance. The soil capacitance is related to the dielectric constant by the geometry of the electric field established around the electrodes (Ley, 1994). Like Time Domain Reflectometry, the soil dielectric constant depends largely on soil water content and can be used to develop a calibration for FDR sensor readings to soil water content.

4.2. Working Principles of Direct Sampling and Three Types of Sensors for Measuring Soil Moisture

4.2.1 Gravimetric determination:

Gravimetric measurement is the only direct method for measuring soil water content. The fresh weight (W_{fresh}) of a sample is taken, preferably as soon as possible. Its dry weight (W_{dry}) is taken after drying the sample to a constant weight. The standard procedure requires keeping the sample in an oven at 105 °C for about 24-36 hours or until the sample attains a steady weight. The percent moisture on a mass basis is then calculated by:

$$\text{Moisture by mass } \% = (W_{fresh} - W_{dry}) / W_{dry} \times 100\%.$$

To convert weight-based values into volumetric water content, moisture by mass is multiplied by the soil bulk density, which is expressed as the dry weight per unit volume of the soil (kg/liter) and is determined by:

BK= Dry weight of soil / Volume of the soil.

Volumetric moisture content % = Moisture by mass % × BK.

Direct sampling is a standard method for determining soil moisture. It is effective over the full range of soil water contents, easy to employ, and requires minimal equipment. When done carefully and with enough samples, direct sampling yields reliable results and is often used for the calibration of other techniques. Unfortunately, the method is time-consuming, labor-intensive, destructive to the sampling location, and, depending on the sampling probe, measures only a small volume that may or may not be representative of the targeted site depending on the spatial variability. Generally soils are sampled with a 2 cm push probe necessitating a large number of subsample in order to obtain a reasonably good estimate of the real moisture status. Frequent sampling disturbs the soil leading to a distortion in results over time. Gravimetric sampling is therefore not ideal for studies requiring repeated measurements. In addition, setting the drying temperature at 105 °C is arbitrary in itself. The remaining soil moisture content after drying may or may not be the same depending on the texture of the soil because clay is capable of retaining much higher water contents than do sandy soils (Hillel, 1980). Precise measurement of soil water content by gravimetric sampling therefore requires knowledge of soil texture.

4.2.2 Time Domain Reflectometry (TDR) Trase System I (Model 6050X1, Soilmoisture Equipment Corp., Santa Barbara, CA)

Soil constituents—mineral particle, organic material, air, and water, are dramatically different in their dielectric constants. The dielectric constant (Ka) for water is about 40 times that of mineral and 80 times that of air. Consequentlyy, the soil bulk dielectric constant is essentially determined by soil water content. The relationship of Ka to the volumetric water percentage has been established by careful measurements of Ka in test cells prepared with accurately known volumes of water in soil. This relationship is then used to automatically convert field measurements of Ka to the volumetric water content of the soil.

Besides being able to measure the soil moisture on a continuing basis with a buriable waveguide, a single portable TDR processor can be used with a number of paired rods over a large field. A selection of different rod lengths offers the flexibility to measure a soil profile at various depth levels via vertical installation. Depending on one's specific interest, the Trase waveguides can be used either at a specific depth level (horizontal installation) or for estimating a whole soil profile (vertical installation).

The TDR Trase System has some advantages over gravimetric determination. It is relatively independent of soil physical properties and effective over a wide range of soil water contents. A pair of paralleled waveguides senses a large volume of the soil profile with minimal disturbance to the site if used in vertical installation. Once inserted into the soil profile the waveguides can be left on site for repeated measurements. The TDR Trase System requires a significant initial investment, however the waveguides are relatively inexpensive enabling a large number of points to be sampled. Rod lengths are currently constrained to around 15 cm, below which the signal length is too short for accurate detection, and 60 cm, above which the signal length is too long. Special care is needed for probe insertion to ensure good contact with the soil. Soil shrinkage during drought and excessive movement of the waveguides during measurement result in poor soil contact and will lead to substantial error in readings.

4.2.3 CS615 Water Content Reflectometer (Campbell Scientific, Inc., Logan, UT)

Like the TDR Trase System I, the CS615 Water Content Reflectometer uses the soil dielectric constant as an indirect measurement of soil moisture (CS615 Water Content Reflectometer Instruction Manual, 1996). Designed for automated operation with a data acquisition system, a CS615 sensor consists of two stainless steel rods connected to a printed circuit board. A shielded four-conductor cable is connected to the circuit board to supply power, enable the probe, and monitor the pulse output. High speed electronic components on the circuit board are configured as a bistable mutilvibrator. The multivibrator is connected to the rods that act as waveguides. The oscillation frequency of the multivibrator is dependent on the dielectric constant of the media being measured. The period of the square wave output, which ranges from 0.7 to 1.6 milliseconds, is used as the independent parameter for calibration and subsequent conversion into volumetric water content.

CS615 sensors are compatible with the common data acquisition system for measuring moisture dynamics on a continuing basis. They are easy to calibrate and fairly accurate over a wide range of soil water contents. The long rods of the sensor and convenience for vertical installation causes little disturbance to the soil when inserted from the soil surface and senses a cylinder of soil with a volume approximately 4.8 cm in diameter and 30 cm long. Different insertion angles from the surface can be used to measure the average volumetric water content in a vertical soil profile of different depths up to 30 cm.

CS615 Time Domain Reflectometers are relatively temperature dependent. Temperature coefficients can be applied to correct this thermal effect. Depending on the soil electrical conductivity, site specific calibration will help improve the accuracy of moisture measurements.

4.2.4 Hydra Soil Moisture Probe (Vitel, Inc., Chantilly, VA)

Based on Frequency Domain Reflectometry (FDR), the Hydra Soil Moisture probes determine soil moisture and salinity by making a high frequency (50 MHz) complex dielectric constant measurement. Because of the large differences in dielectric constants among soil particle, organic material, air, and soil solution, the dielectric constant measurement can be directly related to soil moisture through the use of appropriate calibration curves. The dielectric constant of moist soil has a small, but significant dependence on soil temperature. By the use of a built-in thermistor, soil temperature can be determined and therefore its effect reduced via a temperature coefficient.

The Hydra probe has three main components, a multiconductor cable, a probe head, and probe sensing tines. The probe head contains the necessary electronics to generate the 50 MHz stimulus and generate DC data channel voltages that reflect the soil's electrical properties. Using special software provided by the manufacture, the sensor's voltage outputs can be converted into parameters of soil physical property, i.e. water content, salinity, conductivity, and temperature.

Like CS615s, Hydra probes can be automated through the use of a common data acquisition system. They are rugged and suitable for use in frozen soils, less dependent on soil temperature compared to CS615s, and versatile in providing soil specific information such as salinity, conductivity, and temperature. The tines of a Hydra probe extend from a tiny cylinder that is 2.5 cm in diameter and 6 cm high. The effective sensing volume is confined within the tine-bounded cylinder thus makes it suitable for monitoring a wetting front or site specific moisture dynamics on a long time basis. Given the short tine length, Hydra probes need to be installed or embedded within the profile via access pits.

Characteristics of the three types of sensors and gravimetric sampling are listed in Table 4.1.

4.3. Objectives of the Study

Measuring and monitoring the soil moisture contents in the rooting zone are crucial tasks to understanding the competitive relationship in a plant community. Under a competitive scenario, it is the total available soil water that most heavily influences the plant's performance. The objectives of this study were to evaluate the ability of three brands of sensors to estimate the mean volumetric soil water content of a 30 cm soil profile and to contrast the sensor's intra- and inter-type variability under both greenhouse and field conditions. We selected the top 30 cm soil profile because this zone hosts the majority of crop fine roots (Casper and Jackson, 1997) and is subject to the most fluctuations due to frequent recharge through precipitation and fast moisture release caused by evapotranspiration. The instruments (sensors) were:

1. TDR Trase System (Model 6050X1) with two pairs of 30 cm waveguides.
2. Four Hydra Soil Moisture Probes.
3. Four CS615 Water Content Reflectometers.

4.4. Materials and Methods

4.4.1 Greenhouse Experimental Design

The experiment was conducted inside a greenhouse of the National Agroforestry Center (USDA Forest Service). Two sets of two Hydra Soil Moisture Probes and two CS615 Time Domain Reflectometers were used. Data for each set of Hydra probes and CS615s were recorded on a datalogger (CR10, Campbell Scientific Inc., Logan, UT). Before inserting each set of sensors into the soil medium, each sensor was programmed, connected to the designated input and output channels, and test run for any possible malfunction. Along with each set of Hydra probes and CS615s, a pair of 30 cm waveguides for the TDR Trase System, which correspond to the length of CS615 probe rods, were installed and systematically measured in accordance with each set of automated recordings.

Each set of sensors was set up in a plastic bucket, which was 30 cm and 25 cm in diameter at the upper and bottom, respectively, and 35 cm high. In order to create a thoroughly saturated and relatively proportionally desiccated soil profile and to accelerate the dry down cycle, the sides and bottom of the buckets were perforated with 3 mm holes on 2 cm by 2 cm spacing using an electric drill. Each bucket was filled with a well-mixed silty clay soil medium. While filling, the soil was packed uniformly in order to keep the bulk density throughout the whole profile as homogeneous as possible. When the buckets were filled to 19 cm high, two Hydra Soil Moisture Probes were vertically inserted on opposite sides halfway between the bucket's edge and the geometric center. This arrangement allowed the tines of Hydra probes to be positioned at the middle of the buckets in the vertical and halfway between the edge and center in the horizontal directions. The bucket was then filled to the 32 cm line. After the buckets were filled, a pair of CS615 sensors was fully inserted into the buckets at the midpoint between the edge and the center equally spaced from the Hydra probe locations. Similarly, a pair of 30 cm waveguides was inserted for the TDR Trase System. This arrangement allowed the five sensors to be evenly distributed within the pots but all within the same soil zone (cycle) halfway between the bucket edge and the center (Fig. 4.11 and Fig. 4.12). After sensor installation, the soil in both buckets were fully saturated with water by applying amounts equal to twice the volume of the bucket over a 48 hour period.

Data collection began two days after the last water application. The CS615s and Hydra probes were programmed to take readings every minute with their 30 minute averages logged into datalogger memory. For each pair of the Trase waveguides, two measurements were taken on a daily basis (8:00 ~9:00AM and 4:00~5:00PM) by connecting the waveguides to the TDR Trase processor via a waveguide connector. Both buckets were weighed each day (4:00~5:00PM) with readings taken to the nearest one gram. The soil net weight was obtained by drying the whole bucket without sensors at 105 °C to a constant weight. Daily volumetric soil water content for each bucket was calculated using the weight recordings, the net dry weight, and the bulk density of each bucket as a whole unit. Soil bulk density for each bucket was obtained by dividing the net dry weight of the soil with the bucket volume.

For the CS615 sensors, both the raw outputs (period of the square wave in milliseconds) and the converted soil moisture readings were recorded. Daily averages were calculated using 48 readings obtained at 30 minute intervals. For the Hydra probes, 30 minute averages were used for calculating daily mean output which was then converted into soil water content using the Hydra File.Exe software provided by the company. Data collection lasted from the middle of October 1998 to the middle of January 1999. Each of the five sensors measuring volumetric soil water content were compared to and calibrated against the corresponding volumetric water contents calculated from daily weight changes and the bucket averaged soil bulk density using the SAS linear regression procedure (SAS Institute, 1994).

4.4.2 Field Measurement and Sensor Comparison

Sensors were tested and calibrated on site before installation in the field. For calibrating the TDR Trase processor a series of measurements were taken on the waveguides, which were fully inserted into soil profiles of different moisture levels. At each measuring location gravimetric samples were taken to the corresponding depth between the paired rods. Soil bulk density at each location was determined at a location close to the measuring point. SAS regression procedure was used for calculating the linear regression between TDR Trase and the volumetric water content by gravimetric determination. The four CS615s and Hydra probes were similarly calibrated against site conditions.

After calibration the CS615s and Hydra probes were installed in the south exposure of a field windbreak during the 1998 growing season (Chapter 2). A datalogger (CR10, Campbell Scientific, Inc., Logan, UT) was used to collect data from each set of sensors using a 60 second sampling interval and storage of the 30 minute average. In order to estimate the mean soil moisture in the top 30 cm profile, each Hydra probe was horizontally installed into the side wall of an access pit at 15 cm from the soil surface while CS615s were vertically inserted from the top into the 30 cm soil profile. Each of the paired sensors was located separately at the same distance (7.5 m) from the windbreak at sites with no noticeable difference in site conditions. In addition, eight pairs of TDR waveguides (30 cm), spaced at 20 m interval, were vertically installed at the same distance from the shelterbelt as CS615s and Hydra probes and systematically measured. Since the Trase waveguides corresponded to each set of automatic sensors but covered a wider range of the experiment field, their means were used as an approximation to the actual soil moisture at the automatic sensor locations on a daily basis.

To compare sensor variability, one week of data was collected from the two sets of sensors maintained side by side. All of the eight sensors were installed in parallel either vertically from the soil surface (within a uniform 1×1 meter square) or horizontally at the 15cm and 20cm depth levels on the side wall of an access pit dimensioned 1.5×1.0×1.0 m^3.

4.5. Statistical Analysis

For the greenhouse study, separate statistical analyses for sensors by brands and by individual sensor were conducted using SAS Mixed and General Linear Model (GLM) procedures. The absolute differences between a sensor's bucket-calibrated readings and the corresponding water content determined by gravimetric procedures were designated as the dependent variables. For comparisons among sensor brands, SAS mixed procedure was appropriate with bucket and its interaction with brand as having random effects. On an individual sensor basis, SAS GLM procedure was used for testing the treatment effects and mean separations, where dates of observation, buckets, and sensors in each bucket were treated as having fixed effects. No interaction between bucket and sensor was included in the model statement since each individual sensor was treated as a single treatment. Mean separation between individual sensors was made using pairwise t-test (SLD option with the SAS means statement) at the 5% level.

For the field evaluation, each sensor's daily mean output was compared with the corresponding TDR determinations. Data collected during one week side-by-side installation were used for evaluating sensor's (CS615 and Hydra probe) intra- and inter-units variability.

4.6. Results and Discussion

During data collection from inside the buckets, soil weight decreased from 35.39 kg to 31.07 kg in bucket 1 and from 34.31 kg to 30.01 kg in bucket 2, which corresponded to a change in volumetric soil moistures from 41.4% to 16.2% and from 40.9% to 17.1%, respectively. Soil temperature during the same period fluctuated between 4 °C and 25 °C.

For sensor comparison inside the buckets, the following assumptions were made:

1. The whole bucket had a relatively uniform soil bulk density.

2. The whole soil profile inside the bucket was saturated uniformly at the start of data collection.

3. The vertical soil profile through any point on the circle that has a radius half that of the bucket are relatively homogeneous in terms of average volumetric soil water content during the whole drying process.

4. Despite the existence of a moisture gradient from the edge to the center and from the top to the bottom as the soil drying down, the volumetric soil water content of a vertical soil profile through the circle maintains a proportional relationship with the whole bucket average moisture percentage.

5. To estimate the mean soil moisture of the 30 cm profile using a Hydra probe a reasonable sensor location would be on a circle with half the radius of the bucket right at the middle in the vertical direction.

Using manufacture provided calibration parameters, both CS615s and the Trase System demonstrated good linear relations with the corresponding gravimetric determination during the drying process (Fig. 4.1). These indicated that both types of sensors proportionally integrated into their outputs the moisture gradients surrounding their sensing components in both the horizontal and vertical directions. Moisture gradients were possible since the outskirts of the soil core along the bucket edge and upper layer near the surface could lose soil moisture at a higher speed than the interior and lower portions. While Hydra probes also showed an overall clear response to the moisture change the linear relationship with the gravimetric determination was not quite as good as those by the Trase and CS615s. At the start for data collection, moisture outputs by Hydra probes remained nearly constant when the overall soil moisture was higher than 38%. Although the Hydra probe data indicated an overall decline in response to the buckets thereafter, the generated regressions had much smaller slopes compared to those regressions generated by Trase and CS615s. This indicates the Hydra probes were less sensitive to the moisture dynamics of the targeted soil volume. The larger sensing volumes due to the long rods of the TDR Trase System and CS615 sensors were better able to integrate moisture gradients along the whole profile while the much shorter Hydra probes were not.

Proper interpretation of the physical behavior of the responding material is the key to determining a sensor's performance. In order to improve measurement accuracy and to compare each sensor on an equal basis, all of the five indirect measurements in each bucket were calibrated against the corresponding mean volumetric soil water content determined by the daily weight change and the whole bucket averaged bulk density. According to the manufacture, CS615s can be calibrated with their period outputs in milliseconds against gravimetric determination using a linear model (Fig.4.2). Hydra probes need the special software for converting their outputs in voltages into volumetric water contents. As with the millisecond output by the CS615, the linear relationships between gravimetric determination and those by Trase waveguides and Hydra probes were used for their respective bucket-specific calibrations (Table 4.2).

After calibration, Trase outputs in both buckets showed a close relationship with the corresponding gravimetric determination over the whole moisture range, followed by CS615 sensors, which exhibited some fluctuation when soil moisture was low. Compared to the gravimetric determinations, the calibrated outputs for Hydra probes exhibited three distinct stages during the entire drying process (Fig. 4.3). At first when the overall moisture level was high, the Hydra sensor measured water contents were lower than that of the bucket average. This was followed by an overestimation of moisture content as the gravimetrically determined levels in the buckets dropped to about 25%. This tendency continued until moisture levels reached about 15%, after which larger variations by both CS615s and Hydra probes were observed with their mean readings lower than that of the gravimetric and TDR Trase determinations. This again indicates the limited sensing volume of the Hydra probe could not incorporate moisture changes outside the cylinder bounded by its tines (e.g. approximately ($2.5^2 \times 3.14 \times 6$) 120 cm^3 in volume). The limited effective volume constrained the sensor's ability to reflect the average soil moisture, a potentially serious problem in field studies where spatial heterogeneity is more the norm and the number of sensors than can be deployed is limited.

On individual sensor basis, the distributions of the dependent variables, which are the absolute differences between sensor's calibrated outputs and the corresponding mean volumetric water content of the buckets, showed clear inter-brand differences and intra-brand similarity (Fig. 4.4). These differences and similarities are substantiated by the respective statistics for the absolute and arithmetic differences between each sensor's calibrated outputs and the corresponding gravimetric determinations (Table 4.3 and Table 4.4).

Among the three brands, the difference of least square means of the dependent variable between Trase and Hydra probes was significant at the 5% level (P=0.02) while those between TDR and CS615 as well as between Hydra probe and CS615 were not

(P=0.09 and 0.08, respectively). Hydra probes produced the greatest departure from that of gravimetric determination with a mean of 1.67% (P= 0.02), followed by CS615 with the mean of 1.07%(P= 0.05). TDR Trase had the smallest mean at 0.49% with the associated probability level of 0.2 (Table 4.5).

On an individual sensor basis, Hydra probes had the greatest departures from gravimetric determination with means ranging from 1.87% to 2.18%, followed by CS615 probes with means from 1.13% to 1.54%. The Trase 30 cm waveguides approximated the best to the gravimetric line with the corresponding means of 0.35% and 0.58%. Using SAS mean separation (LSD), the four sensors (both Hydra probes and CS615s) fall into two groupings. This indicates both brands had at least one sensor yielding significantly different recordings from the other (Table 4.6). It also suggests that the inter-sensor variations were significant for both CS615s and Hydra probes. On the contrary, the means for Trase waveguides belong to one grouping suggesting no existence of significant inter-waveguides variation (Fig. 4.5). Specifically, significant differences were observed between sensor A and C for Hydra probes. For CS615, sensor C produced significantly different recordings with both sensor A and D but not with sensor B. Consequently, the interchangeability for both CS615s and Hydra probes were lower than for Trase waverguides.

Despite the differences among brands, the overall performance by every sensor after calibration showed a good linear response to the actual soil moisture during the entire drying process (Fig. 4.3). Looking at the Pearson correlation coefficients of sensor calibrated outputs with the gravimertic determination and with soil temperature on a daily basis, the Trase had the closest correlation with gravimetric determination, followed by

CS615s and Hydra probes (Table 4.7). The inter-brand correlation for both CS615s and Hydra probes were higher than that of the intra-brands, indicating the consistency and interchangeability within a brand is higher than between brands (Table 4.8).

Data generated by CS615s correlated higher with soil temperature than did Trase waveguides and Hydra probes (Table 4.7), suggesting a greater influence of soil temperature on the soil moisture readings as mentioned by the manufacture.

4.6.1 TDR Trase vs. Gravimetric Determination

According to the manufacture, Trase does not need site specific calibration for general use, and this proved to be true with the greenhouse study (Fig. 4.1 and 4.2). Nevertheless, if very accurate determinations are expected, site specific calibration will help. For both pairs of waveguides, the TDR Trase readings followed the bucket-averaged soil moisture dynamics determined by daily weight changes without large variations as evidenced by their higher correlation coefficients (0.995 for bucket 1 and 0.997 for bucket 2). The Trase waveguides were highly interchangeable because measurements in both buckets showed the same pattern and very small differences with respect to the gravimetrically determined water loss. Their sensitivities were as good as that of the gravimetric determination as indicated by the similar slopes for both lines (Fig. 4.1 and 4.2). With regard to accuracy, TDR Trase underestimated the mean soil moisture for the whole buckets at first when soil moisture was high, then overestimated it. This discrepancy may be related to the geometry of the buckets and the soil water evaporation characteristics, which may have induced a higher evaporation outer portion of the soil compared to that in the interior of the bucket. The sensing volume may not have been adequate enough to reliably measure this continuum from the edge to interior of the bucket. If this is the case, you would expect the TDR Trase to give higher moisture readings compared to the whole bucket at a later stage, which is what our data indicated.

After calibration, the mean differences between TDR Trase and that of gravimetric determination ranged from −1.1% to 1.3% in bucket 1 and from −1.1% to 0.9% in bucket 2 with the associated standard deviations of 0.7% and 0.5%, respectively. The corresponding means of absolute differences between Trase and gravimetric recordings were 0.6% and 0.4% with the same associated standard deviation of 0.3% for both buckets. As a result, the 95% confidence intervals for individual measurement are $\pm(0.6+0.32\times t_{0.05})$ %, or ±1.2 % for Bucket 1, and ± 0.9% for Bucket 2.

4.6.2 CS615 vs. Gravimetric Determination

During the drying process CS615 Water Content Reflectometers produced a dry-down pattern with similar sensitivity as determined by the slope of the moisture curves to the gravimetric determination (Fig. 4.1 and 4.2). However, there existed some fluctuations in the sensor's daily mean recordings during the drying process, especially near the end of the sampling period when the soil moisture was low. Because no water was applied after the beginning of data collection, these fluctuations may be related to the sensor's sensitivity to soil temperature and/or condensation from the air. We did not record air humidity during the test, but if condensation was responsible for such fluctuations its influence should be comparable regardless the sensor brand.

According to the producer, the magnitude of the temperature coefficient for CS615s varies with water content with a maximum of 1.6% difference between temperature-corrected and uncorrected water contents. Our data indicated that the temperature effect was higher when soil water content was low. When soil moisture dropped to around 20% the maximum fluctuation is about 2% compared to about 0.5% at soil moisture contents near 30%. Looking at inter-sensor variations on calibrated data, the maximum difference in moisture percentage between CS615s and gravimetric determination ranged from –3.5% to 3.4% for sensor A (the largest) and from –2.6% to 3.0% for sensor D (the smallest), with standard deviations of 1.8% and 1.5% respectively. For all four sensors, the means of absolute differences with gravimetric determination ranged from 1.1% to 1.5% with the corresponding standard deviations of 0.7% and 1.0%. Such variations could translate into a maximum error of 2.5% to 3.5% for individual measurements at the 95% confidence level.

Since the CS615 output is sensitive to temperature, compensation should be applied to enhance accuracy (Instruction manual, Campbell Scientific, Inc.). Using laboratory measurements at various water contents over the temperature range from 10 °C to 30 °C, the manufacture suggested the use of following equation for interpolating the temperature coefficient for a range of volumetric water content (θ_v) values:

$$\text{Coef}_{\text{temperature}} = -3.46\times10^{-4} + 0.019\,\theta_v - 0.045\theta_v^2$$

along with,

$$\theta_{\text{vcorrected}} = \theta_{\text{vuncorrected}} - (T-20)\times\text{Coef}_{\text{temperature}}$$

T is temperature in Celsius.

Among the four sensors, the maximum difference in water content caused by their dependence on temperature ranged from 2.4% to –0.2% when the average temperature changed from 25 to 4 degrees Celsius (Table 4.4). The 95% confidence interval for individual measurements could range from ± (0.5+1.4)% at the largest for sensor C to ± (0.3+0.8)% at the lowest for sensor B (Table 4.9). After the temperature correction was applied, the CS615s correlation coefficients with gravimetric determination approached those of TDR Trase and Hydra probe.

The application of temperature coefficient improved the sensor's measuring accuracy compared to the uncorrected readings in respect to the concurrent gravimetric determinations (Fig. 4.6).

4.6.3 Hydra Soil Moisture Probe vs. Gravimetric Determination

Hydra probes showed minimal inter-sensor variation and thus are essentially interchangeable. However, Hydra probes gave consistently higher moisture readings than the whole bucket average, most probably because of the Hydra probe's short sensing component which reflects moisture changes only within a small area confined by its four tines (Hydra probe User's Manual, 1994). A small effective volume might be able to reflect the actual soil moisture corresponding to the precise insertion point but it also limits the ability of the sensor to estimate a whole soil profile and tends to result in large variations between probes whenever the moisture gradient is high. In the greenhouse study, when the overall soil moisture was high, most of the soil water loss occurred in the outer and upper portions of the bucket causing large spatial gradients within the buckets. At this stage, the small area the probes were sensing did not match the larger targeted volume for estimation.

The Hydra probes also showed some fluctuation at the later stage of the drying down process (about 1%). Since temperature compensation was provided by an internal temperature sensor such fluctuations could have been related to some other unknown factors.

After calibration the maximum differences in moisture percentage between Hydra probes and that of gravimetric determination ranged from –6.7% to 3.7% for sensor C and –5.4% to 2.9% for sensor A with the respective standard deviations of 2.7% and 2.3%. The means of absolute differences between sensor recordings and the corresponding gravimetric determination were 1.9% for sensor A and 2.2% for sensor D. With the associated standard deviations of 1.3% and 1.5%, sensor A and D could produce a maximum error of 4.4% and 5.3% for individual readings at the 95% level.

4.6.4 Sensor Comparison under Field Conditions

The larger effective sensing volume of the TDR Trase and the CS615s make them more accurate in measuring a soil profile. Further, they are easier to use to estimate soil water levels than gravimetric sampling, which, besides being labor intensive, also requires bulk density sampling for conversion of the weight measure to a volumetric basis. Because soil water contents and bulk densities can be more precisely determined for a larger volume than a smaller one during field calibration, both Trase 30 cm waveguides and CS615s had smaller standard errors and higher correlation coefficiency (R^2) than Hydra Soil Moisture Probes by following similar calibration procedures (Table 4.10).

With site specific calibration, paired sensors produced quite similar soil moisture recordings by both CS615s and Hydra probes (Fig. 4.7). Installed at 15 cm below the surface (from Day of the Year 244 to 268), paired Hydra probes generated similar outputs but with larger variations between sites of installation, again most likely due to their localized small effective sensing volumes. Although soil moisture in the top 30 cm profile fluctuated during this period, Hydra probes could not pick up these changes outside of the effective sensing range and thus were limited for estimating the moisture dynamics of the larger, targeted volume.

CS615 sensors showed some fluctuation with date of sampling and a larger variation within paired sensors compared to Hydra probe but had less variation between sites. This reduced variation, or better representation of moisture conditions was due to the vertical integration of soil moisture in the profile and the larger sensing volume. Since vertically installed CS615s cause minimum site disturbance, paired sensors can be switched. After switching sensors, the same soil moisture trend was obtained as evidenced in the lower plot of Figure 4.7. This constitutes a major advantage for the CS615 because any systematic error pertaining to a particular sensor can be avoided by balanced measurements that switch sensors. Obviously, this advantage is not possible with sensors that necessitate horizontal insertion.

Compared to the concurrent means from the eight pairs of TDR Trase waveguides on a number of dates, both CS615s and Hydra probes yielded higher moisture values ranging from -0.3% to 7% and from 4.8% to 10.6%, respectively (Fig. 4.8). The big difference could have come from site variation since each set of automatic sensors were confined within a limited area surrounding the pre-selected datalogger stations while TDR Trase waveguides were not. Differences between individual sensors within each brand ranged from 0.4% to 1.5% for CS615s compared to 0.1% to 2.0% for Hydra probes (Fig. 4.9). The differences between sensor brands were significant (P=0.06). Further, within each brand at least one sensor was different from the others for both CS615s and Hydra probes with the magnitude being greater for the Hydra probes (Table 4.11). Again, this performance can be attributed to the sensing volume with the sensors. It seems that even for estimation of a specific layer via horizontal installation the CS615 can do a better job than does the Hydra probe.

3.7. Conclusions

Side by side comparisons against the gravimetrically determined soil water content during a dry down cycle inside soil-filled buckets demonstrated differing performances by three brands of soil moisture sensors. Without calibration, the rank of correlation coefficients between sensor outputs and the bucket-averaged soil moisture contents by brand is TDR Trase 30 cm waveguides > CS615 > Hydra Probe. After calibration, all sensors correlated well with the actual soil moisture dynamics on a daily basis but had varying abilities to estimate the actual values. When the intended objective was to measure the average water content in the top 30 cm profile, TDR Trase System using 30 cm waveguides gave the best results followed by CS615s and Hydra probes throughout a range from saturation to near permanent wilting point (Fig. 4. 3).

Field results demonstrated that all sensors followed the soil moisture fluctuation with time but with a larger difference from site to site, suggesting the spatial variation in soil moisture need to be addressed by increasing sensor replications. The largest difference between an individual sensor reading and that of the TDR Trase were 7% for CS615 and 11% for Hydra probe. These large differences could have resulted from the spatial variation, different sensing volumes, calibration, sensor installation, or a mixture of all four. Data from the greenhouse and field studies indicate that both the sensing volume of a sensor and the level of spatial variability will have to be taken into account in order to design a system that will accurately estimate the soil moisture condition. Sensor selection will be a matter of balancing the trade-off of expense and the ability to capture spatial and temporal variability.

The greenhouse study indicated that the variations for the absolute differences between the gravimetrically determined soil water content and that of sensor-calibrated readings ranged from 0.4 ± 0.3% ~0.6 ± 0.3% for the Trase 30 cm waveguides, 1.2 ± 0.7% ~ 1.5 ± 1.0% for the CS615s, and 1.9 ± 1.3% ~2.2 ± 1.5% for Hydra probes. Consequently, at the 95% confidence level, a maximum error of 1.2%, 3.5%, and 5.2% could occur during a single measurement for the Trase (30 cm waveguides), CS615s, and Hydra probes, respectively, if the intended soil profile is 30 cm deep.

Obviously, when equipment is limited and the intended measurement is average water content in a vertical soil profile (i.e. soybean rooting volume), TDR Trase and CS615 sensors are preferable to the Hydra Soil Moisture Probes. The reality of the moisture gradient that exists from the surface down to a deeper horizon makes detecting devices with vertical installation and long sensing probes desirable for integrating moisture variation along this profile.

While a point estimation can be argued to be representative of the average for the whole profile, such a point is hard to locate and tends to change with time and space. A logical way to yield meaningful readings with sensors having short detecting devices is to use a number of sensors at different layers and integrate the readings. But often times, budget constraint does not permit unrestricted replications, especially if the sensors concerned are expensive.

Soil types as well as environmental factors also have some effects on sensor outputs. Under some circumstance such effects could be significant, thus making site-specific calibration of instruments necessary if higher accuracy in determination is required.

Table 4.1 Characteristics of four methods for measuring soil moisture.

Criteria	TDR Trase System (Model 6050X1)	CS615 Time Domain Reflectometer	Hydra Soil Moisture Probe	Gravimetric Determination
1. Principle of Measurement	Time Domain Reflectometry	Time Domain Reflectometry	Frequency Domain Reflectometry	Water physical property
2. Unit of Measurement	Volume of water/volume of soil	Volume of water/volume of soil	Volume of water/volume of soil	Weight of water/ weight of soil
3. Accuracy*	± 2 % Without calibration	± 2 % After calibration	± 1.5 ~ 2 % Without calibration	High
4. Calibration	No calibration required for general use.	Need site specific calibration	Can be calibrated	Used as standard to calibrate other methods
5. Repeated measures/Site disturbance	Yes / Minimal	Yes / Minimal	Yes / Strong in the access pit	No / Severe at every sampling point
6. Time to get a measuring result	Instantaneous	Instantaneous	Need special software for data conversion	At least 24 hours
7. Sensing/ Measuring volume	A cylinder 1.5 times the space between rods in diameter and 30 cm long	Similar to Trase System	A cylinder 2.5 cm in diameter and 6 cm in length	A cylinder about 2 cm in diameter with the standard auger
8. Effective range	0 ~100 %	0 ~100 %	0 ~100 %	0 ~100 %
9. Field range of operation	Unlimited	One location per unit	One location per unit	Unlimited
10. Installation	No need for access pit for vertical installation	No need for access pit within the top 30 cm for vertical installation	Need an access pit	Leave an open hole after core removal
11. Expenses /Cost	$ 9.20 /one pair of waveguides	$ 205 /unit	$ 295/unit	Minimal cost, but labor intensive

*Accuracy and sensing volume as reported in the operation manuals provided by the respective manufacturer.

Table 4.2 Sensor calibration coefficients based on the greenhouse data.

	Sensors in Bucket 1		
Sensor	Calibration coefficients	R square	MSE
TDR Trase	$Y = 1.689*\chi - 19.87$	0.9874	0.0068
Hydra probe A	$Y = 1.821*\chi - 37.86$	0.9166	0.0228
Hydra probe B	$Y = 1,891*\chi - 42.04$	0.8898	0.0261
CS615 A	$Y = 72.82*\chi - 51.96$	0.9588	0.0181
CS615 B	$Y = 61.20*\chi - 56.13$	0.9357	0.0155
	Sensors in Bucket 2		
TDR Trase	$Y = 1.518*\chi - 17.55$	0.9958	0.0045
Hydra probe C	$Y = 2.169*\chi - 53.39$	0.8483	0.0271
Hydra probe D	$Y = 1.9828*\chi - 45.5$	0.8600	0.0267
CS615 C	$Y = 75.485*\chi - 73.1$	0.9521	0.0153
CS615 D	$Y = 76.095*\chi - 74.29$	0.9386	0.0173

Independent variable for the linear regressions are: sensor readings in volumetric water content for TDR Trase, converted volumetric soil water contents for Hydra probes, and sensor's outputs in milliseconds for the CS615.
MSE = root mean square of the error.

Table 4.3 Statistics for the absolute differences between gravimetrically determined volumetric soil water content and the calibrated recordings by individual sensor.

Treatment	Mean	Number	Std	SE	Maximum	Minimum
CS615A	1.54	57	0.968	0.128	3.53	0.08
CS615B	1.36	57	0.794	0.105	2.80	0.01
CS615C	1.13	57	0.667	0.088	2.78	0.04
CS615D	1.47	57	1.012	0.134	3.58	0.01
TDR A	0.59	57	0.318	0.042	1.29	0.03
TDR B	0.35	57	0.264	0.035	1.12	0.00
VITEL A	1.87	57	1.253	0.166	5.55	0.00
VITEL B	2.12	57	1.456	0.192	6.52	0.01
VITEL C	2.18	57	1.542	0.204	6.67	0.01
VITEL D	2.10	57	1.484	0.196	6.44	0.02

Std = Standard Deviation; SE = Standard Error.

Table 4.4 Statistics for the daily arithmetic mean differences between gravimetric determinations and individual sensor's readings after calibration.

Sensor	Number	Mean	Std	SE	Minimum %	Maximum %
			Bucket 1			
TDR Trase	57	-0.007	0.6728	0.089	-1.10	1.29
VITELA	57	0.017	2.2639	0.300	-5.55	2.92
VITELB	57	-0.011	2.5822	0.342	-6.52	3.14
CS615A	57	0.004	1.7996	0.238	-3.53	3.34
CS615B	57	0.001	1.5420	0.204	-2.80	2.60
			Bucket 2			
TDR Trase	57	-0.016	0.4450	0.058	-1.12	0.89
VITELC	57	-0.222	2.6891	0.356	-6.67	3.74
VITELD	57	0.0001	2.5838	0.342	-6.44	3.54
CS615C	57	0.0052	1.7104	0.226	-3.09	3.09
CS615D	57	-0.003	1.5117	0.200	-2.60	3.03

TDR Trase: Time Domain Reflectometry Trase System (Model 6050X1, SoilMoisture Equipment Corp., Santa Barbara, CA).
Vitel: Hydra Soil Moisture Probe (Vitel, Inc. Chantilly, VA).
CS615: CS615 Time Domain Reflectomer (Campbell Scientific, Inc., Logan, UT).

Table 4.5 Analysis of variances for sensor comparison by brand in the greenhouse. Dependent variables equal the absolute differences between a sensor's calibrated output in volumetric water contents and that of the corresponding gravimetric determination.

A: Test of fixed effects by SAS Mixed procedure.

Source	NDF	DDF	F Value	Pr >F
Date	63	375	3.40	0.0001
Brand	2	2	19.5	0.0488
Date*Brand	126	375	2.94	0.0001

NDF = Degrees of freedom of numerator. DDF= Degree of freedom of denominator.

B: Least square means of the independent variable. Probability level represents significance of the differences from zero of the dependent variable.

Brand	Lsmean	Std error	DF	T value	Pr > t
Trase	0.488	0.264	2	1.85	0.2052
Hydra	1.672	0.259	2	6.47	0.0231*
CS615	1.066	0.258	2	4.12	0.0541

DF = Degree of freedom.

C: Differences of least square means by brand.

Brand	Brand	Difference	Std error	DF	T value	Pr > t
Trase	Hydra	-1.184	0.1898	2	-6.24	0.0248*
Trase	CS615	-0.577	0.1899	2	-3.04	0.0933
Hydra	CS615	0.607	0.1830	2	3.32	0.0802

DF = Degree of freedom.

Trase: Time Domain Reflectometry Trase System (Model 6050X1, SoilMoisture Equipment Corp., Santa Barbara, CA).
Vitel: Hydra Soil Moisture Probe (Vitel, Inc. Chantilly, VA).
CS615: CS615 Time Domain Reflectomer (Campbell Scientific, Inc., Logan, UT).

Table 4.6 Analysis of variances for the absolute differences between sensor's calibrated output in volumetric water content and that of gravimetric determination. Sensors with the same letter in T grouping are not significantly different at the 5% level by T test with the SAS GLM procedure.
Sensor A and B were in Bucket 1, C and D in Bucket 2.
Least significant difference (LSD) = 0.3117.

Sensor	**Absolute Mean**	**Standard deviation**	**N**	**T Grouping**	
Vitel C	2.183	1.25	57	A	
Vitel B	2.115	1.46	57	A	B
Vitel D	2.096	1.48	57	A	B
Vitel A	1.870	1.25	57		B
CS615 A	1.543	0.96	57	C	
CS615 D	1.466	1.01	57	C	
CS615 B	1.365	0.79	57	C	D
CS615 C	1.128	0.67	57		D
TDR A	0.587	0.32	57	E	
TDR C	0.355	0.26	57	E	

N = number of observation.

TDR: Time Domain Reflectometry Trase System (Model 6050X1, SoilMoisture Equipment Corp., Santa Barbara, CA).
Vitel: Hydra Soil Moisture Probe (Vitel, Inc. Chantilly, VA).
CS615: CS615 Time Domain Reflectomer (Campbell Scientific, Inc., Logan, UT).

Table 4.7 Pearson correlation coefficients of sensor measured soil water contents with that of gravimetric determination and with soil temperature.

BUCKET 1							
	TDR A	Vitel A	Vitel B	CS615 A		CS615 B	
				Uncorr	Corr	Uncorr	Corr
GRM	0.994	0.937	0.918	0.967	0.971	0.979	0.98
Temp	0.596	0.541	0.522	0.648	0.594	0.611	0.568
BUCKET 2							
	TDR C	Vitel C	Vitel D	CS615 C		CS615 D	
				Uncorr	Corr	Uncorr	Corr
GRM	0.998	0.921	0.927	0.975	0.984	0.969	0.979
Temp	0.65	0.731	0.73	0.786	0.748	0.805	0.768

GRM = Gravimetric, Temp = Temperature, Uncorr = Not temperature corrected, Corr = Temperature corrected.

TDR: Time Domain Reflectometry Trase System (Model 6050X1, Soilmoisture Equipment Corp., Santa Barbara, CA).

Vitel: Hydra Soil Moisture Probe (Vitel, Inc. Chantilly, VA).

CS615: CS615 Time Domain Reflectomer (Campbell Scientific, Inc., Logan, UT).

A, B, C, D are individual sensors.

Table 4.8 Pearson correlation coefficients between and within sensors by brand.

Sensors in bucket 1.

	TDR A	Hydra A	Hydra B	CS615 A	CS615 B
TDR A	1.000	0.943	0.923	0.978	0.979
Hydra A	0.943	1.000	0.998	0.962	0.986
Hydra B	0.923	0.998	1.000	0.945	0.974
CS615 A	0.978	0.962	0.945	1.000	0.991
CS615 B	0.979	0.986	0.974	0.991	1.000

Sensors in bucket 2.

	TDR C	Hydra C	Hydra D	CS615 C	CS615 D
TDR C	1.000	0.925	0.931	0.987	0.984
Hydra C	0.925	1.000	0.999	0.943	0.941
Hydra D	0.931	0.999	1.000	0.948	0.946
CS615 C	0.987	0.943	0.948	1.000	0.998
CS615 D	0.984	0.941	0.946	0.998	1.000

TDR: Time Domain Reflectometry Trase System (Model 6050X1, Soilmoisture Equipment Corp., Santa Barbara, CA).
Vitel: Hydra Soil Moisture Probe (Vitel, Inc. Chantilly, VA).
CS615: CS615 Time Domain Reflectomer (Campbell Scientific, Inc., Logan, UT).
Sensor A and B were in Bucket 1, C and D were in Bucket 2.

Table 4.9 Statistics for the effects of temperature coefficients on CS615 soil moisture sensors. Means equal differences between readings with and without temperature correction.

Sensor	Mean %	N	Std	SE	Minimum %	Maximum %	T range °C
CS615 A	0.351	57	0.384	0.05	-0.361	1.37	24 to 4
CS615 B	0.339	57	0.381	0.05	-0.308	1.34	24 to 4
CS615 C	0.537	57	0.621	0.08	-0.242	2.42	25 to 11
CS615 D	0.541	61	0.621	0.08	-0.233	2.38	25 to 11

Std : standard deviation. SE: standard error. T: soil temperature.

CS615: CS615 Time Domain Reflectomer (Campbell Scientific, Inc., Logan, UT).

Sensor A and B were in Bucket 1, C and D in Bucket 2.

Table 4.10 On site calibration parameters for TDR Trase waveguides, Hydra Soil Moisture Probes, and CS615 Time Domain Reflectometers.

Sensors	Slope(b)	Intercept (a)	SE for (b)	SE for (a)	Root MSE	Adjusted R^2
Vitel A	0.8967	-0.0202	0.069	0.022	0.0137	0.9536
Vitel B	0.8283	-0.0080	0.105	0.034	0.0216	0.8844
Vitel C	1.1419	-0.1040	0.131	0.048	0.0270	0.9052
Vitel D	1.1074	-0.0810	0.116	0.042	0.0249	0.9191
TDR 30	1.0130	-2.1741	0.049	1.366	0.0086	0.9760
TDR 45	0.8838	0.4689	0.0697	2.4659	0.0196	0.9410
TDR 60	1.0873	-5.5582	0.0667	2.2432	0.0088	0.9397
CS615C	0.3138	-0.1967	0.0097	0.0137	0.0064	0.9936
CS615D	0.2729	-0.1360	0.0109	0.0152	0.0077	0.9905
CS615A	0.2533	-0.1021	0.0189	0.0266	0.0099	0.9728
CS615B	0.2603	-0.1354	0.0297	0.0439	0.0143	0.9380

SE =Standard Error.
TDR Trase: Time Domain Reflectometry Trase System (Model 6050X1, SoilMoisture Equipment Corp., Santa Barbara, CA).
Vitel: Hydra Soil Moisture Probe (Vitel, Inc. Chantilly, VA).
CS615: CS615 Time Domain Reflectomer (Campbell Scientific, Inc., Logan, UT).
Sensor A and B were in Bucket 1, C and D were in Bucket 2.

Table 4.11 Analysis of variances for sensor comparison in the field. Data came from side by side installation in either horizontal or vertical directions.

A: Tests for fixed effects by SAS Mixed procedure.

Source	NDF	DDF	F value	Pr >F
Brand	1	6	5.31	0.0606
Sensor (Brand)	6	36	7.65	0.0001

NDF= Degree of freedom of numerator. DDF= Degree of freedom of denominator.

B: Means separation between sensors within a brand.

Sensors		Difference	Std error	DF	T value	Pr > t
CS615A	CS615B	-0.17	0.39	36	-0.46	0.6511
CS615A	CS615C	-1.06	0.39	36	-2.73	0.0097**
CS615A	CS615D	0.43	0.39	36	1.11	0.2728
CS615B	CS615C	-0.88	0.39	36	-2.28	0.0288*
CS615B	CS615D	0.61	0.39	36	1.57	0.1252
CS615C	CS615D	1.50	0.39	36	3.85	0.0005**

Sensors		Difference	Std error	DF	T value	Pr > t
VitelA	VitelB	0.51	0.39	36	1.31	0.1974
VitelA	VitelC	-0.04	0.39	36	-0.12	0.9056
VitelA	VitelD	-1.52	0.39	36	-3.90	0.0004**
VitelB	VitelC	-0.55	0.39	36	-1.43	0.1606
VitelB	VitelD	-2.03	0.39	36	-5.21	0.0001**
VitelC	VitelD	-1.47	0.39	36	-3.78	0.0006**

** Significant at 1% level; * significant at 5% level.
Vitel: Hydra Soil Moisture Probe (Vitel, Inc. Chantilly, VA).
CS615: CS615 Time Domain Reflectomer (Campbell Scientific, Inc., Logan, UT).
Sensor A and B were in Bucket 1, C and D were in Bucket 2.

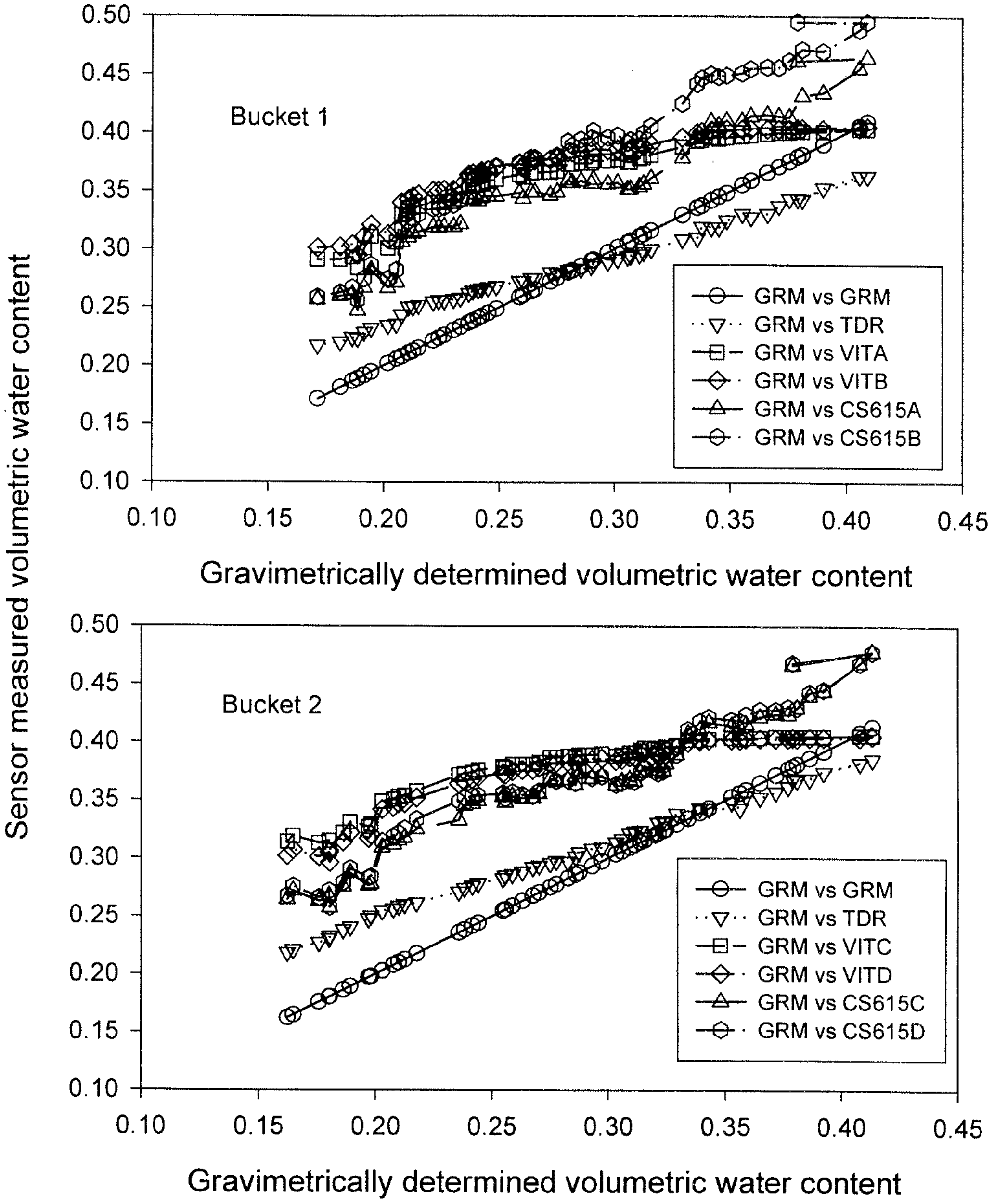

Figure 4.1 Linear relationships between sensor measured volumetric soil water contents and gravimetrically determined volumetric soil water contents.

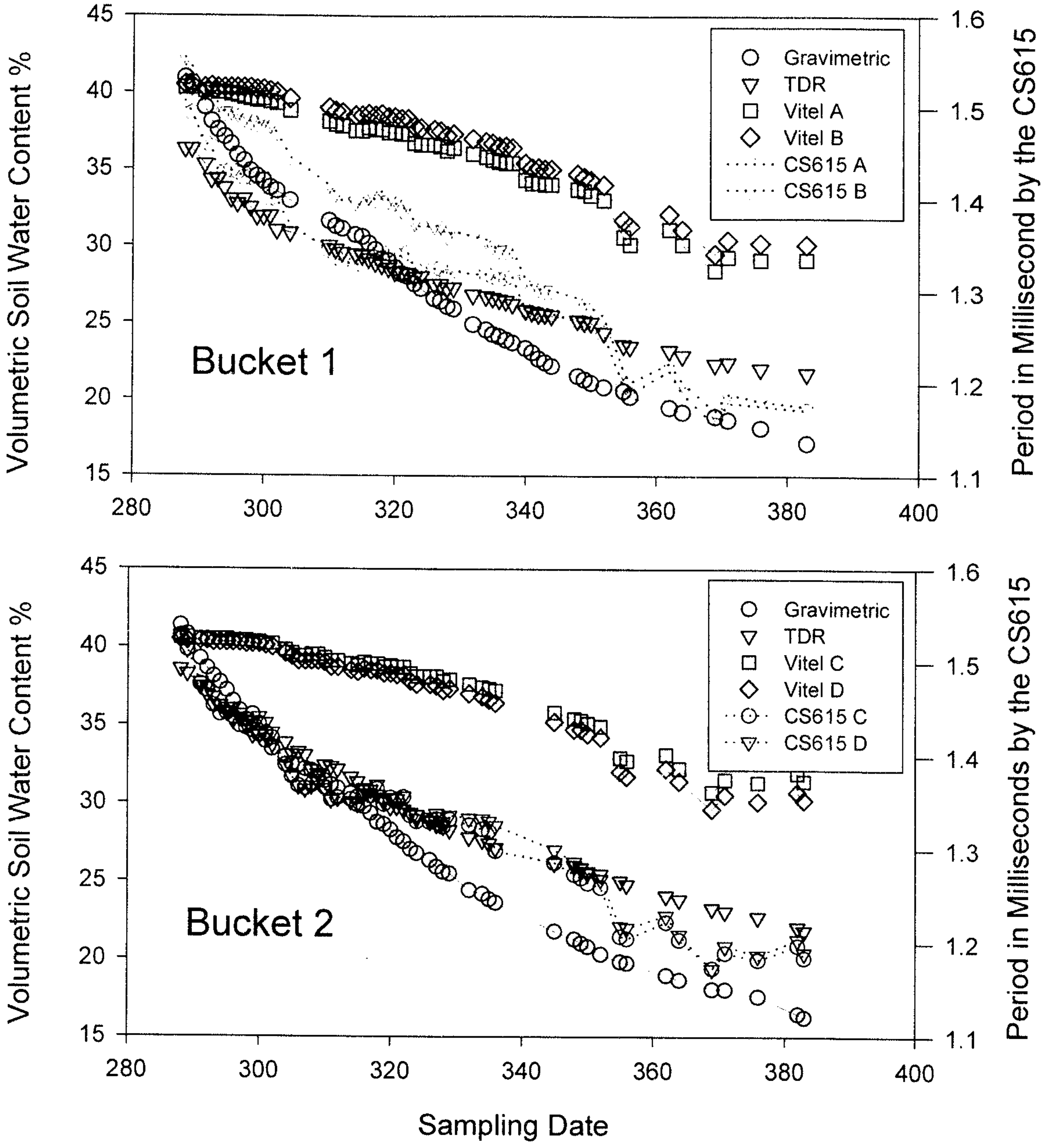

Figure 4. 2 Soil moisture as measured by four methods, gravimetric determination, TDR Trase, Hydra probe, and CS615. Readings for the CS615s are sensors output in milisecond.

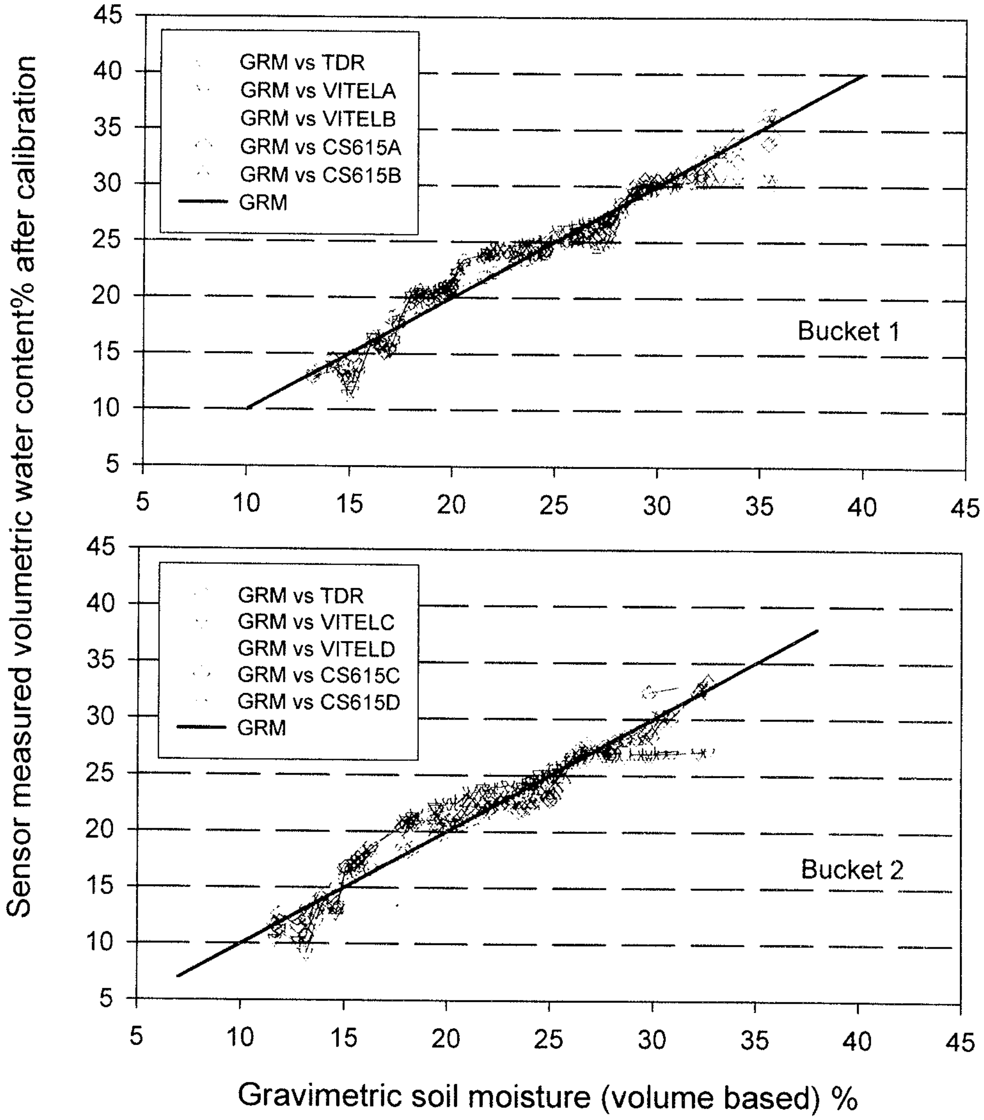

Figure 4.3 Linear relations between sensor measured volumetric water contents after calibration and the gravimetrically determined volumetric water contents in both buckets.

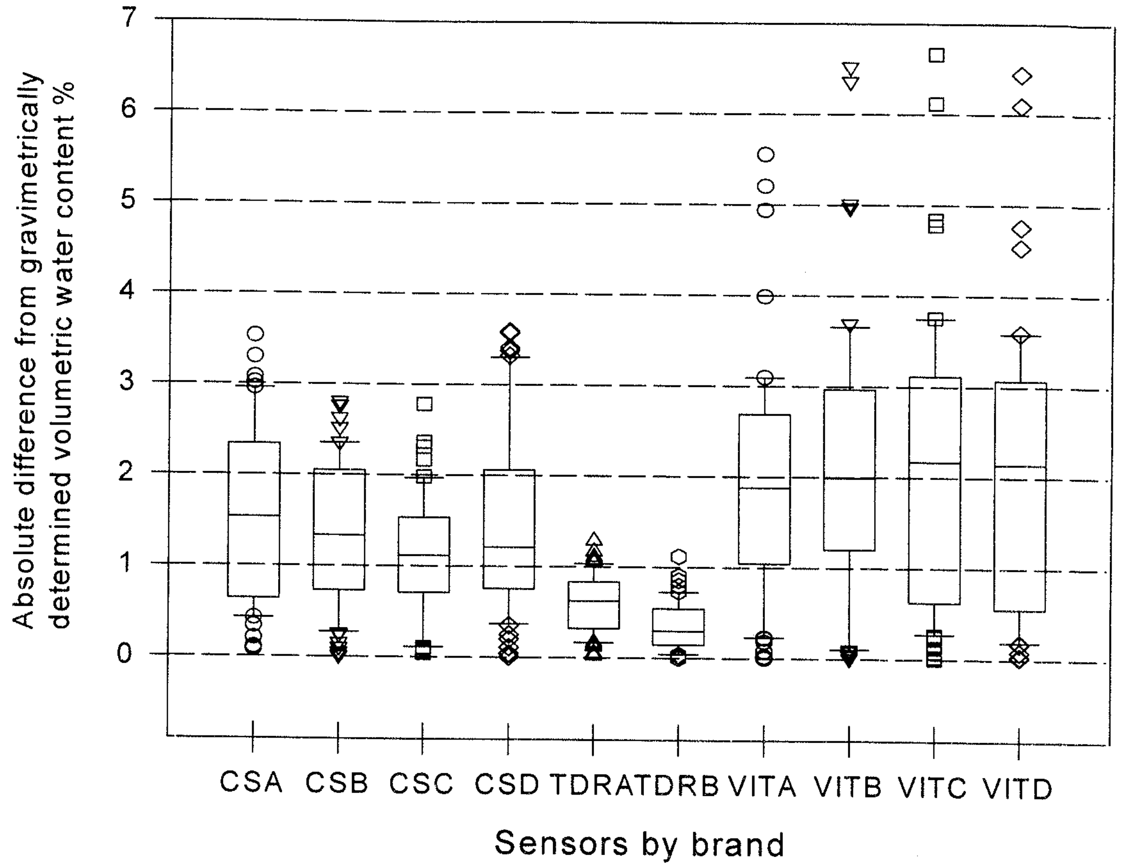

Figure 4.4 Data distribution for the absolute differences between sensors' calibrated recordings and the corresponding gravimetric soil water content. Each box includes the mean, the upper and lower 50% & 95% limits, and every individual outlyer.

CS ----- CS615 Water Content Reflectometer.
TDR --- TDR Trase System.
VIT ----- Hydra Soil Moisture Probe.

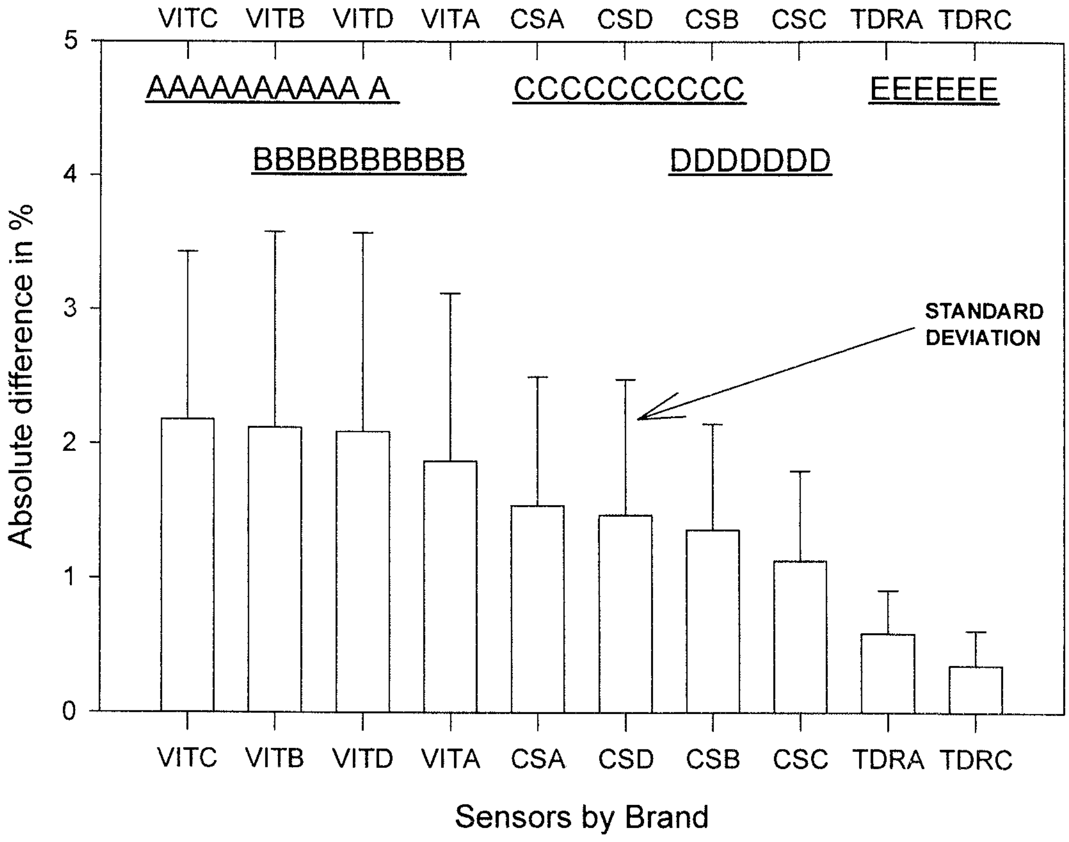

Figure 4.5 Means of the absolute differences in water content between sensor's outputs and that of gravimetric determination. Error bars stand for standard deviations. Sensors with the same letter are not significantly different.
Sensors A and B were in Bucket 1, sensor C and D were in Bucket 2. LSD=0.31%.

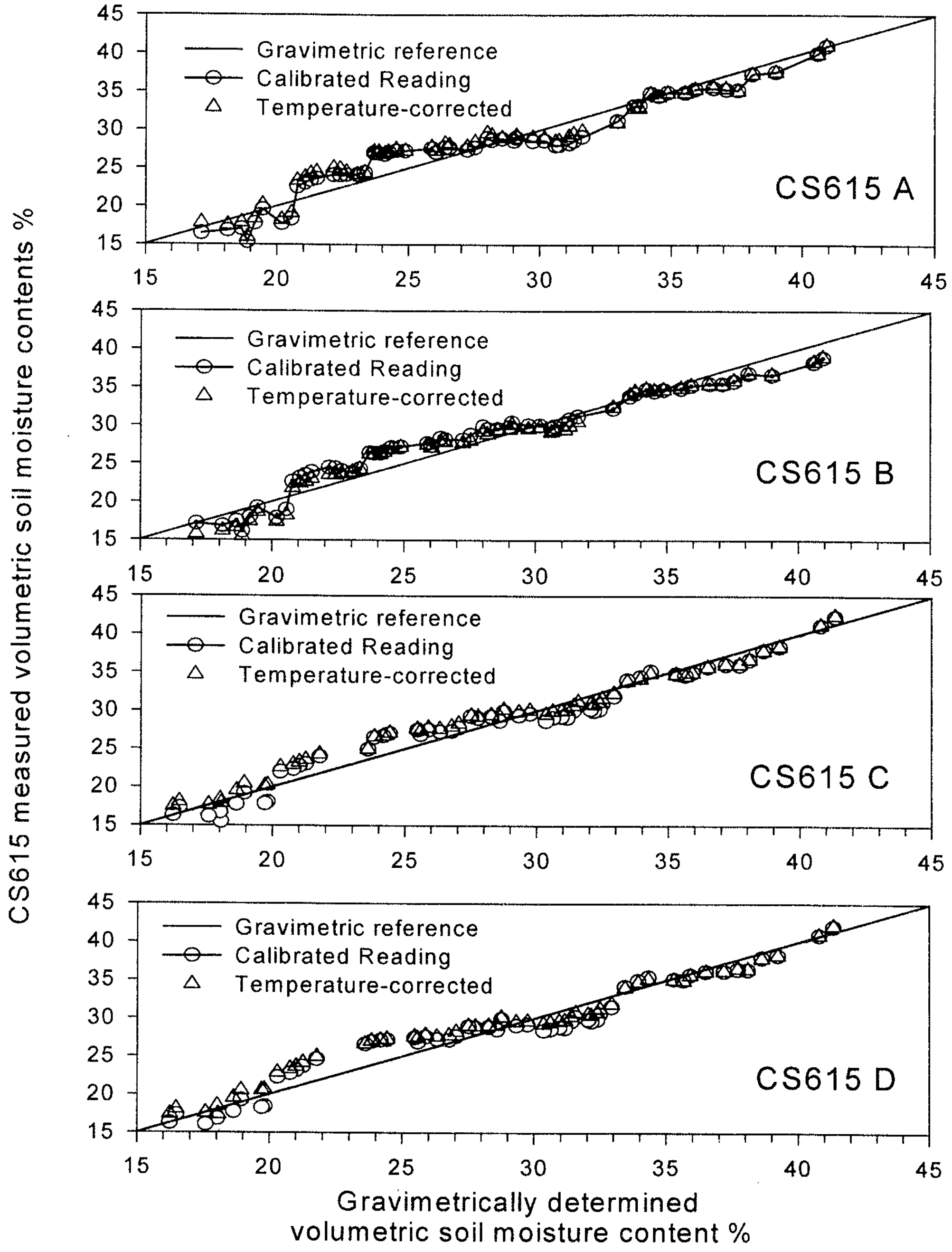

Figure 4.6 Effects of temperature coefficients on the CS615 measured soil moistures.

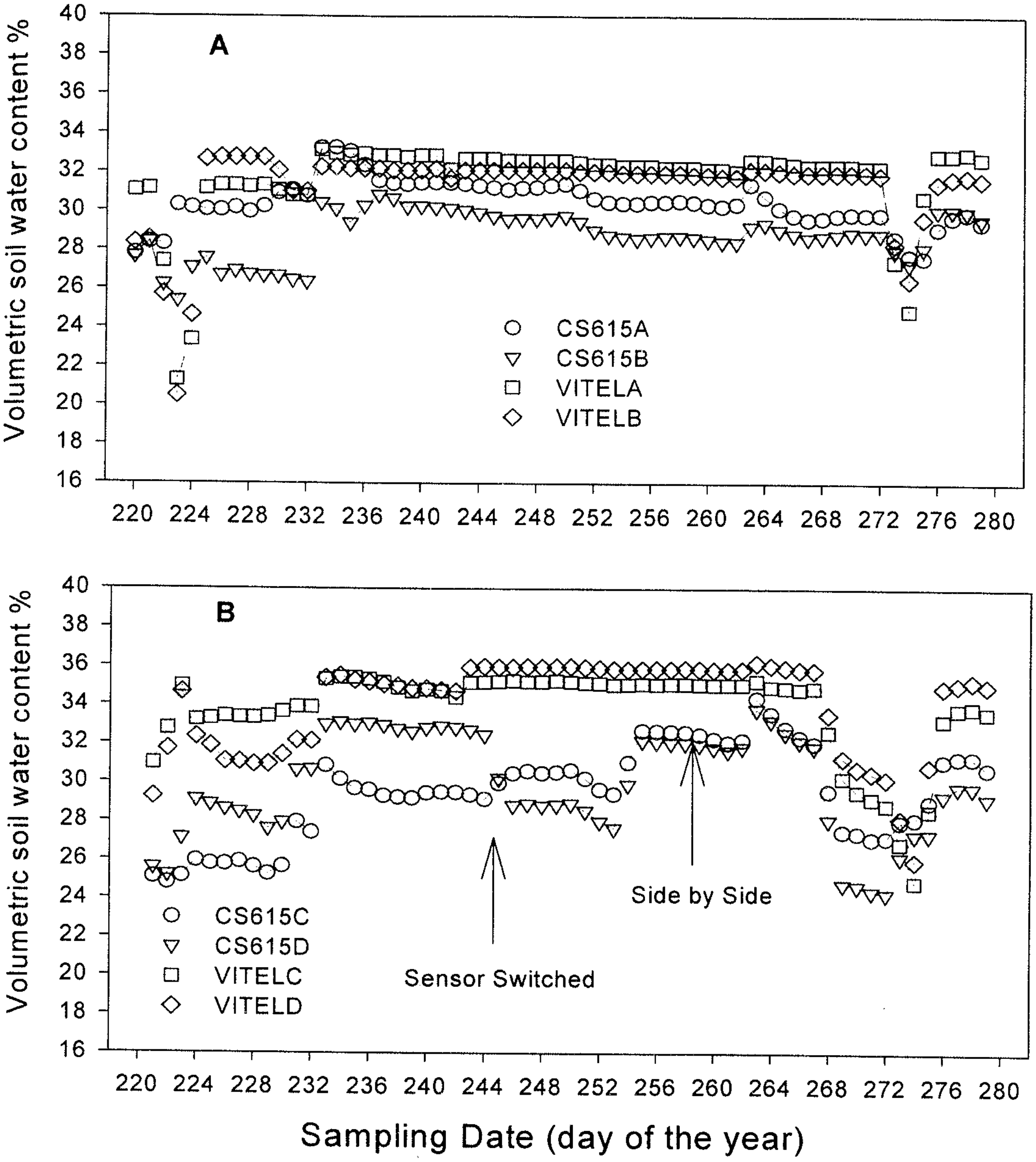

Figure 4.7 Paired automatic sensors for measuring soil moisture dynamics in the top 30 cm profile at two locations.
A: sensors at datalogger station 1.
B: sensors at datalogger station 2.

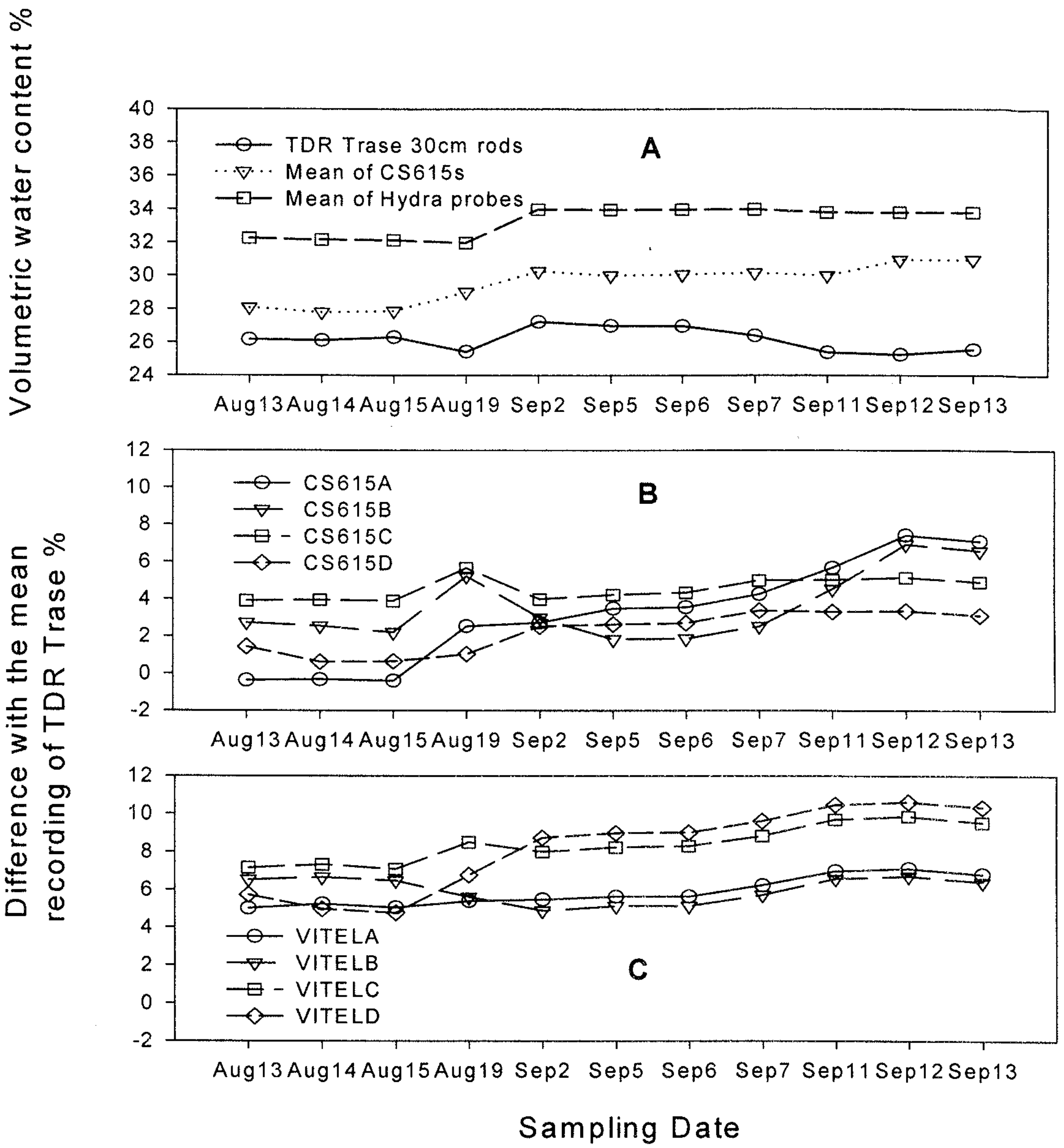

Figure 4.8
A: Daily mean soil moistures in the field measured with TDR Trase, CS615, and Hydra probe.
B: Daily mean differences between TDR Trase and CS615s.
C: Daily mean differences between TDR Trase and Hydra probes.

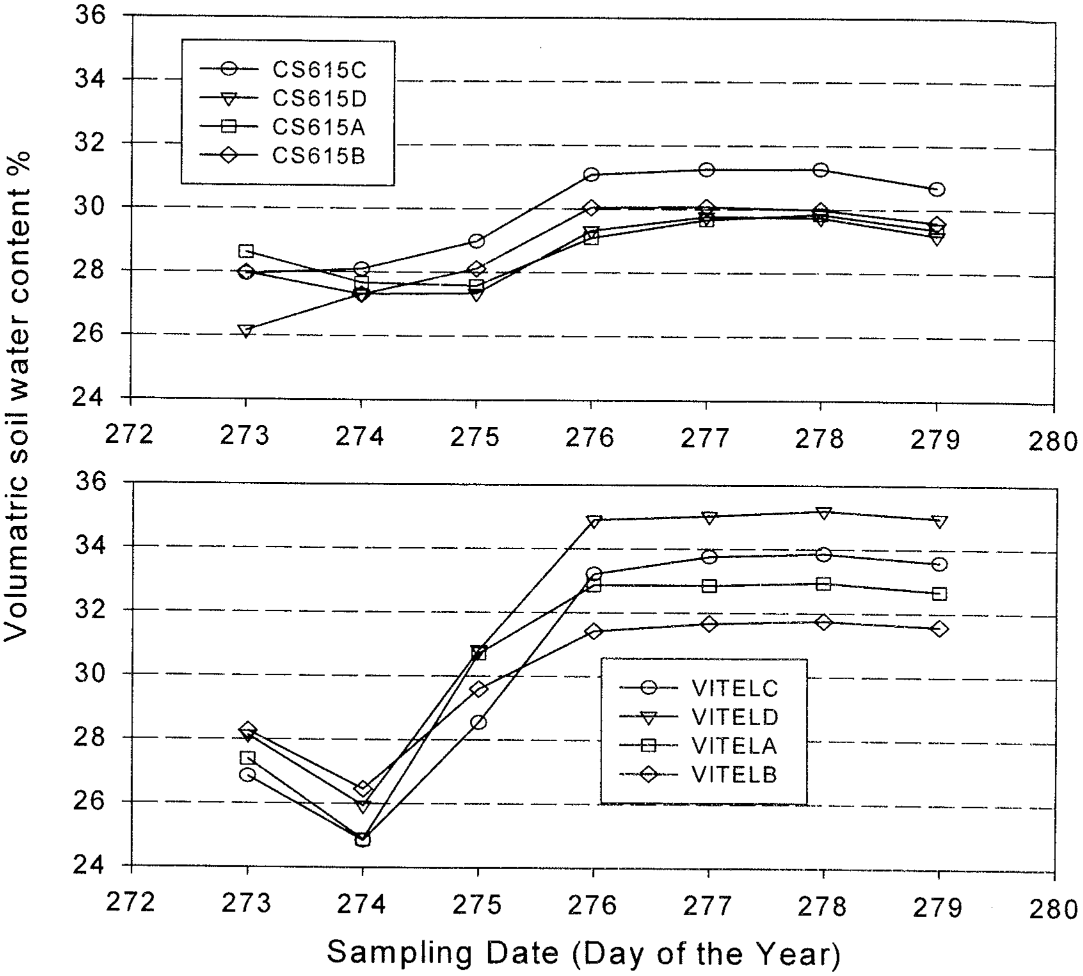

Figure 4.9 In the field side by side comparisons of Hydra Soil Moisture probes and CS615 Time Domain Reflectometers. Day of the year 273, 274, and 275 for vertical installation from the surface. Day of the year 276, 277, 278, and 279 for hrizontal installation at the same depth.

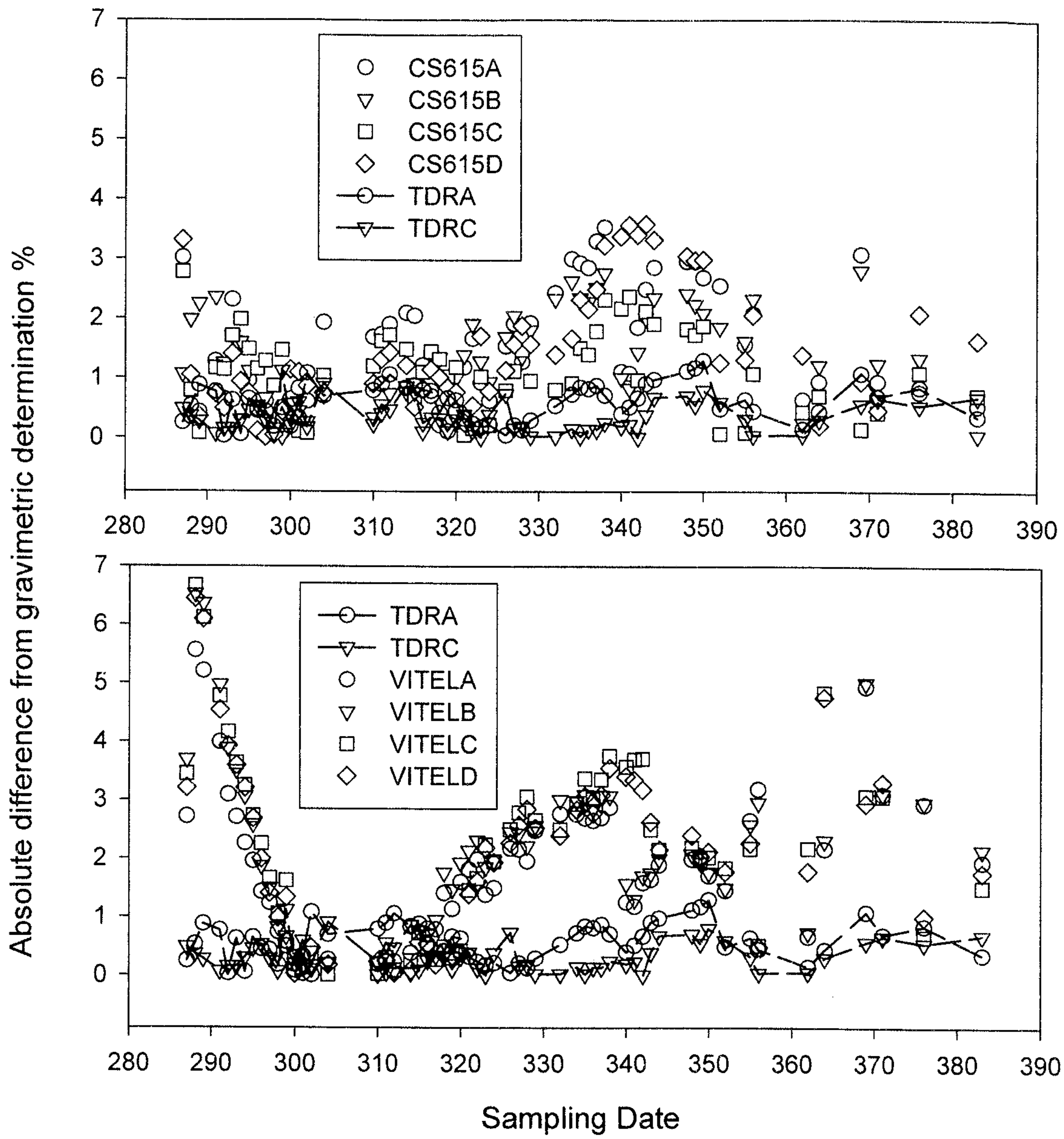

Figure 4.10 Sensor comparison between brands. Upper plot TDR Trase vs. CS615. Lower plot TDR Trase vs. Vitel Hydra Probes.
Sensor A and B from bucket 1; C and D from bucket 2.

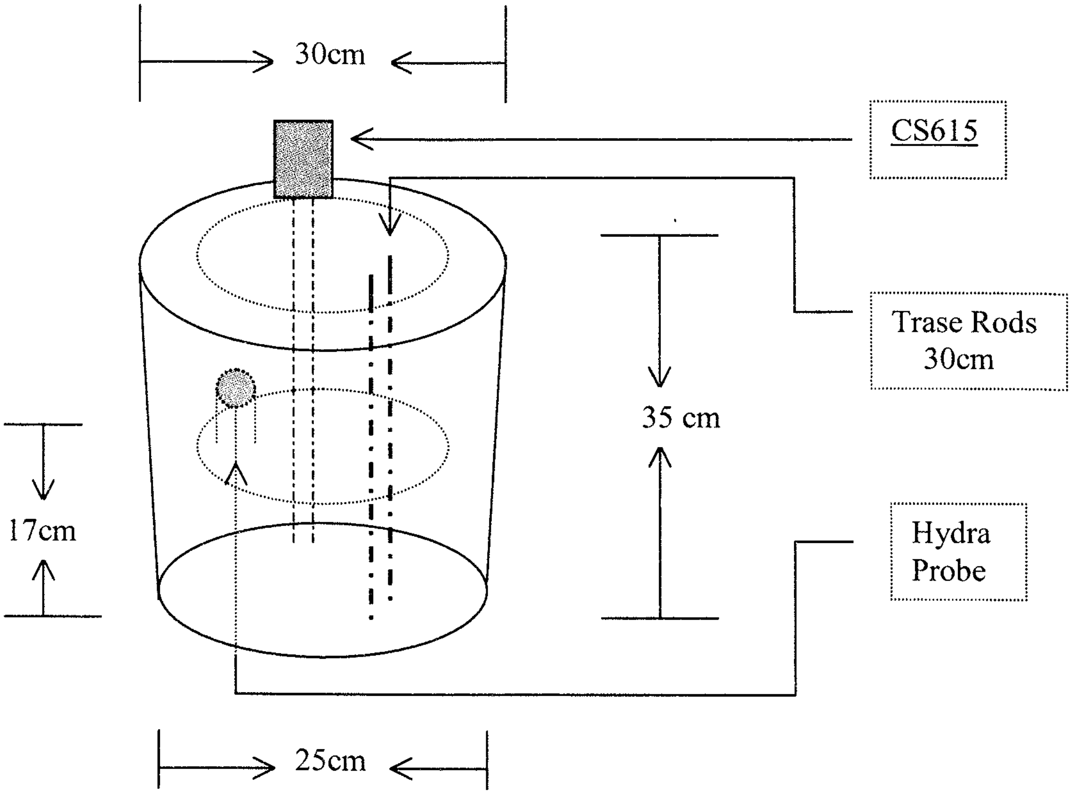

Figure 4.11. Sensor installation diagram for the greenhouse study. Inside the bucket there were two CS615 sensors, two Hydra probes, and one pair of 30 cm TDR Trase waveguides.

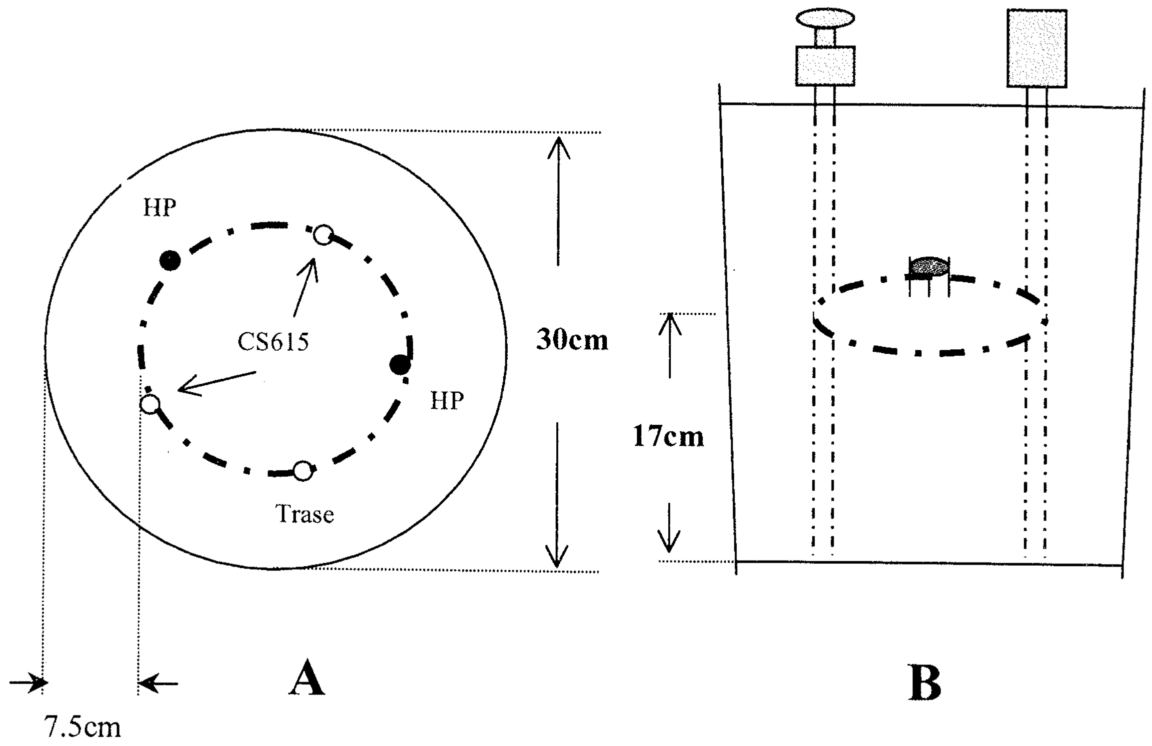

Figure 4.12. A sketch showing sensors positions inside the buckets. Both CS615s and TDR 30 cm waveguides were inserted from the surface while the Hydra probes were buried in the middle of the buckets.

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Appendix 1

DESCRIPTION OF MICROCLIMATE VARIABLES AT THE VICINITY OF THE WINDBREAK/CROP INTERFACE

Abstract

Along with the measurement of soil moisture in the 1998 field test, as described in Chapter 2, microclimate variables, precipitation, air temperature and relative humidity, net radiation, wind speed and direction, and soil temperature, were also measured. Despite the fact that limitations in sensor replications and space might dictate cautiousness in interpreting the observed results, some trends in respect to the distance from the windbreak are obvious. Considering the consistently measurable differences in soil moisture with distance from the windbreak in the root pruned plots (Chapter 2), it seems probable that microclimate variations are a contributing factor.

Results and Discussion

Root-pruning was found to improve soil moisture conditions in the top 45cm profile in the south exposure of the windbreak (Chapter 2). Volumetric soil water contents in the pruned plots were consistently higher than the nonpruned plots for up to 1.25 times tree height into the field. However, root-pruning did not completely eliminate differences in soil moisture with distance from the windbreak (Fig. 2.7), suggesting other factors besides tree competition may also playing a role. Such factors include rainfall distribution, which was discussed in Chapter 2, and aboveground microclimate variables.

In order to detect if any consistent differences in microclimate variables existed at the windbreak/crop interface, field instrumentation was implemented along with the systematic measuring of soil moisture in 1998 (see Chapter 2 for experimental layout). Air temperature, relative humidity, net radiation, wind speed and direction, precipitation, and soil temperature at 0.75H, 1.00H, and 1.25H were measured in two replications throughout much of the 1998 growing season. Data analysis was made after checking out abnormal recordings against some quality control criteria described by Hubbard (1988). Some trends in microclimate variables are described below.

Net radiation

The net radiation in the vicinity of a windbreak/crop interface can be calculated from the following energy conservation equation:

$$R_n = SW\downarrow(1-\alpha) + \varepsilon(LW\downarrow - \sigma T_s^4) = H + LE + G_0 + S + Ps$$

where R_n represents net radiation at the surface; $SW\downarrow$ and $LW\downarrow$ stand for incoming short wave and long wave radiation; α and σ are the surface albedo and emissivity, respectively; and T_s refers to the surface temperature. In regard to distance from the windbreak in the south exposure both $SW\downarrow$ and $LW\downarrow$ tended to be higher at sites closer to the windbreak because of the greater reflected portion by the surface of the trees. If α and σ remain the same, surface temperature is the only term controlling the respective net radiation at each specific location.

During daytime, net radiation at 0.75H was consistently lower than at the control point (assumed at 2H from the windbreak for this study), especially during sunny middays. The differences of half-hourly averaged net radiation from 11:00am to 16:00pm at 0.75H and control points observed during days of the year 176 to 216 is illustrated in Appendix Fig. 1.

Air temperature and relative humidity

Air temperature is one of the most important microclimate factors directly affecting evapotranspiration and net radiation. It also influences relative humidity, which in combination with wind speed and sensible heat advection, comprise the key factors controlling the evaporative loss of soil water.

Appendix Fig. 2 shows the differences of mean air temperatures between 0.75H and 1.50H during 11: 00 AM to 16:00 PM from June 29 to July 25 (Day of the Year (DOY)180 to 206). Mean air temperature at 0.75H was consistently higher than at 1.5H on most of the dates. This is likely due to windbreak suppression of air turbulence which makes the sensible heat exchange near the windbreak less efficient and less active compared with further locations. Difference in air temperature ranged from –0.71 to 1.78 degrees Celsius. Using SAS Mixed procedure, we found that date and distance were a significant interaction ($P< 0.001$). On several dates (DOY 180, 182, 187, 194, 197,198, 203, 205) the differences were significant at the 5% level and on other dates at the 10% level (DOY 181, 188, 195, 199). Differences in relative humidity between corresponding locations were less significant. All together six temperature sensors were used at each measuring location in two replications. The sensor as well as replication numbers may not have been adequate enough to ascertain the observed difference in air temperature and humidity, because of the higher fluctuation in turbulence and temperature which are generally expected within the narrow strip adjacent to the south face of the windbreak.

The air temperature trend with distance from the windbreak we observed in this study needs further investigation.

Soil temperature

During the same period soil temperatures measured at both 10 cm and 15 cm below the soil surface showed similar patterns as air temperature in regards to distance: the closer to the windbreak the higher the soil temperature. Daily average soil temperature at 10 cm on June 21 (DOY 202) are illustrated along with air temperature in Appendix Fig. **3**. Again, the limited numbers of sensors used here require caution in interpreting whether these differences are statistically significant on a large field basis, because soil temperature not only tends to change within short ranges but also is critically related to the exact position in the vertical profile. Small difference in installation could result in dramatically different readings.

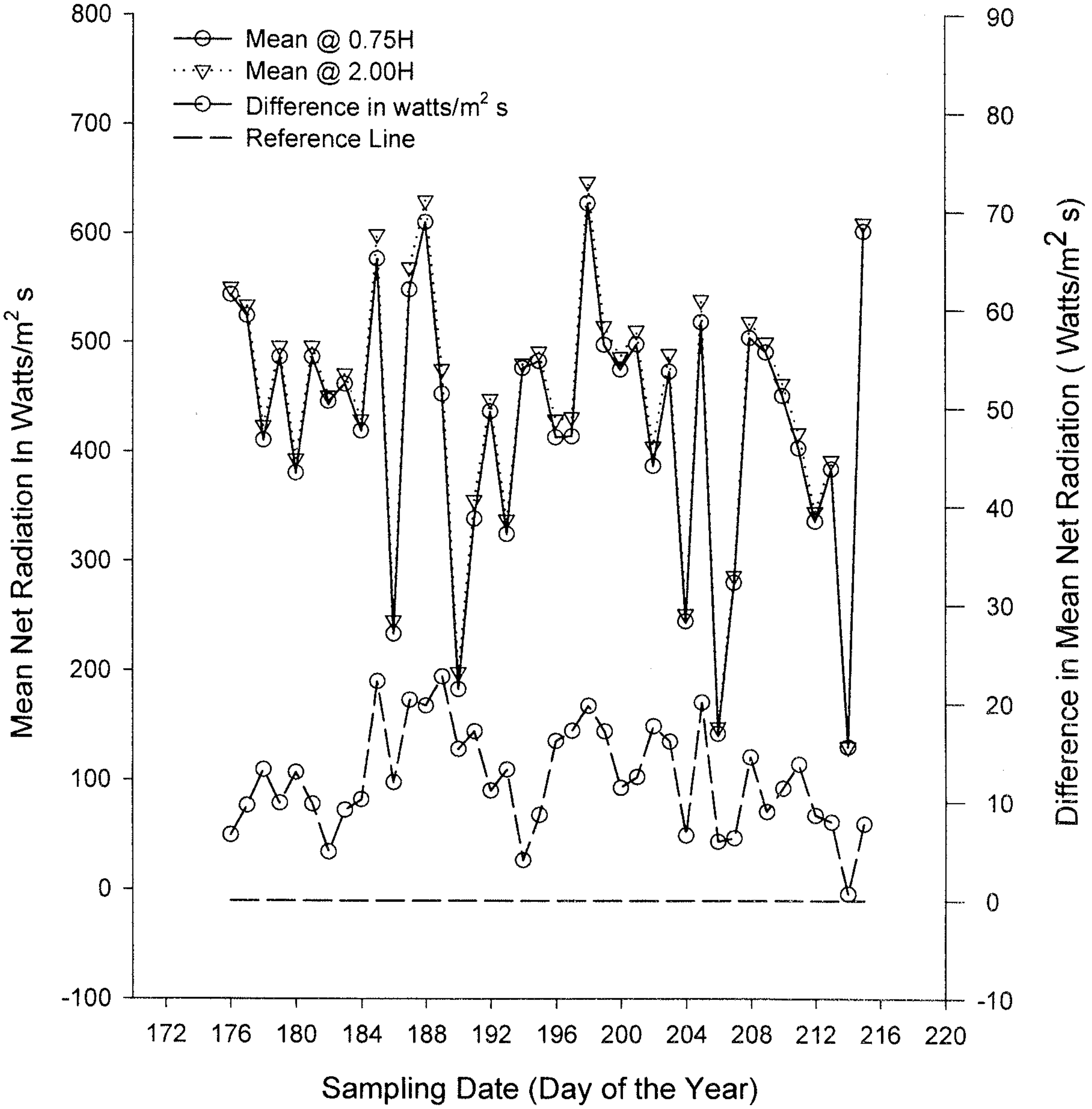
Based on data recorded from June 25 to August 3 at 0.75H, net radiation was 12.4 ± 5.3 Watts/s m^2 higher, air temperature was 1.35 ± 0.47 °C higher, and the soil temperature was 1.58 ± 0.83 °C higher than those at 1.50H (Table 2.7). We did not, however, detect any differences in relative humidity nor in wind speed between these points (Appendix Fig. 4).

Regarding a windbreak's effect on air temperature, general agreement exists that the windbreak increases air temperature during the daytime because of the reduction in heat flux away from the surface in the sheltered areas. Brown and Rosenberg (1972) reported the daytime air temperature averaged 1.8 °C greater in a corn-sheltered sugarbeet field than that in a nonsheltered area. Van Eimern et al. (1964) found soil moisture at 0.05 m in a sheltered area was more than 1 °C higher compared to an open field. Unfortunately, there are few other studies reporting microclimate variables in the near vicinity of a windbreak.

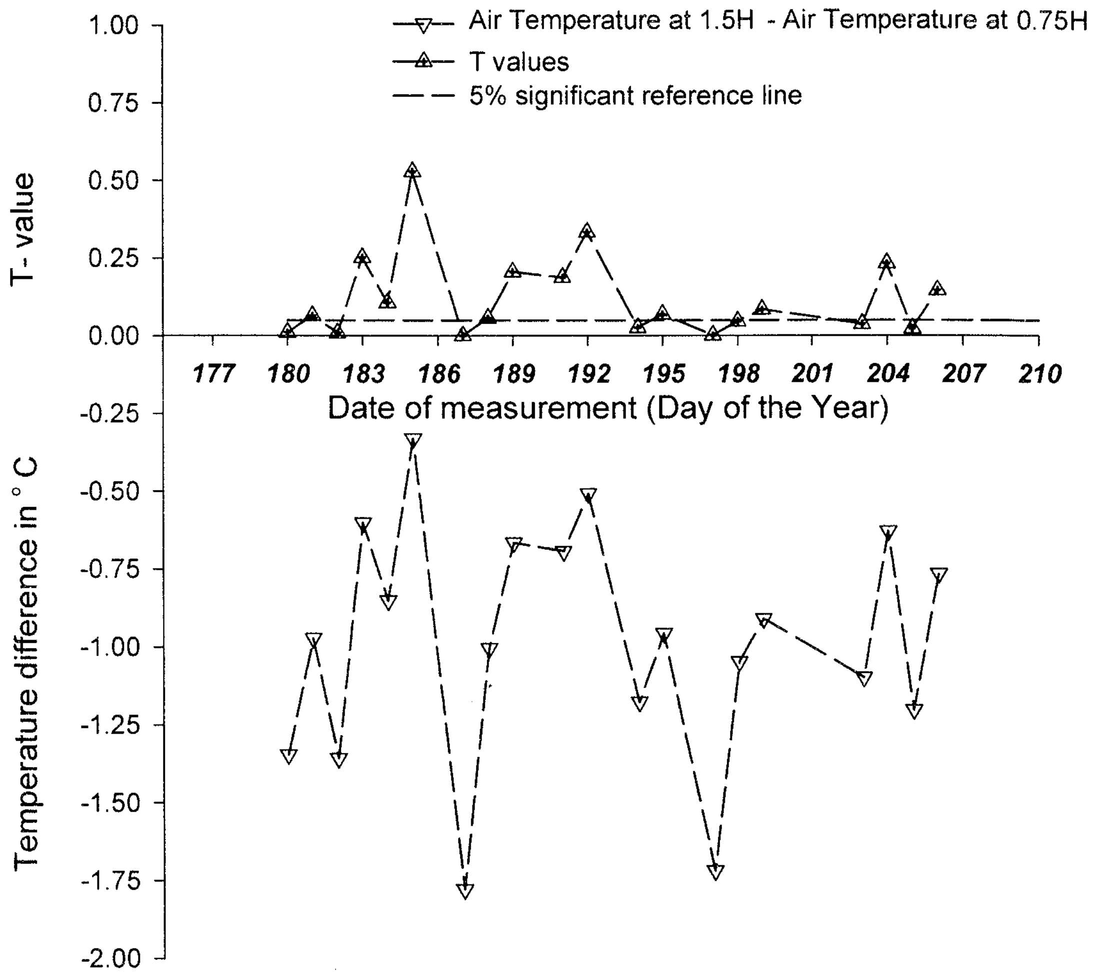
In a study for microclimatic interactions in an agroforestry system in southern India, Monteith (1991) found that the advantages in terms of the interception of radiation, windspeed, VPD and temperature are relatively unimportant compared with the adverse effects on interception of rainfall and belowground competition. In this study, the cumulative rainfalls at 0.5H and 0.75H were 14% and 3% less respectively, than those at 1.00H, 1.25H and 1.50H (Chapter 2). If root-pruning did effectively eliminated or at least reduced the windbreak's extraction of soil water from the top 45 cm layer, the existence of a measurable gradient in soil moisture with distance beyond the pruning line could be a combined effect of windbreak's edge effect on precipitation and aboveground microclimate variables.

Conclusion

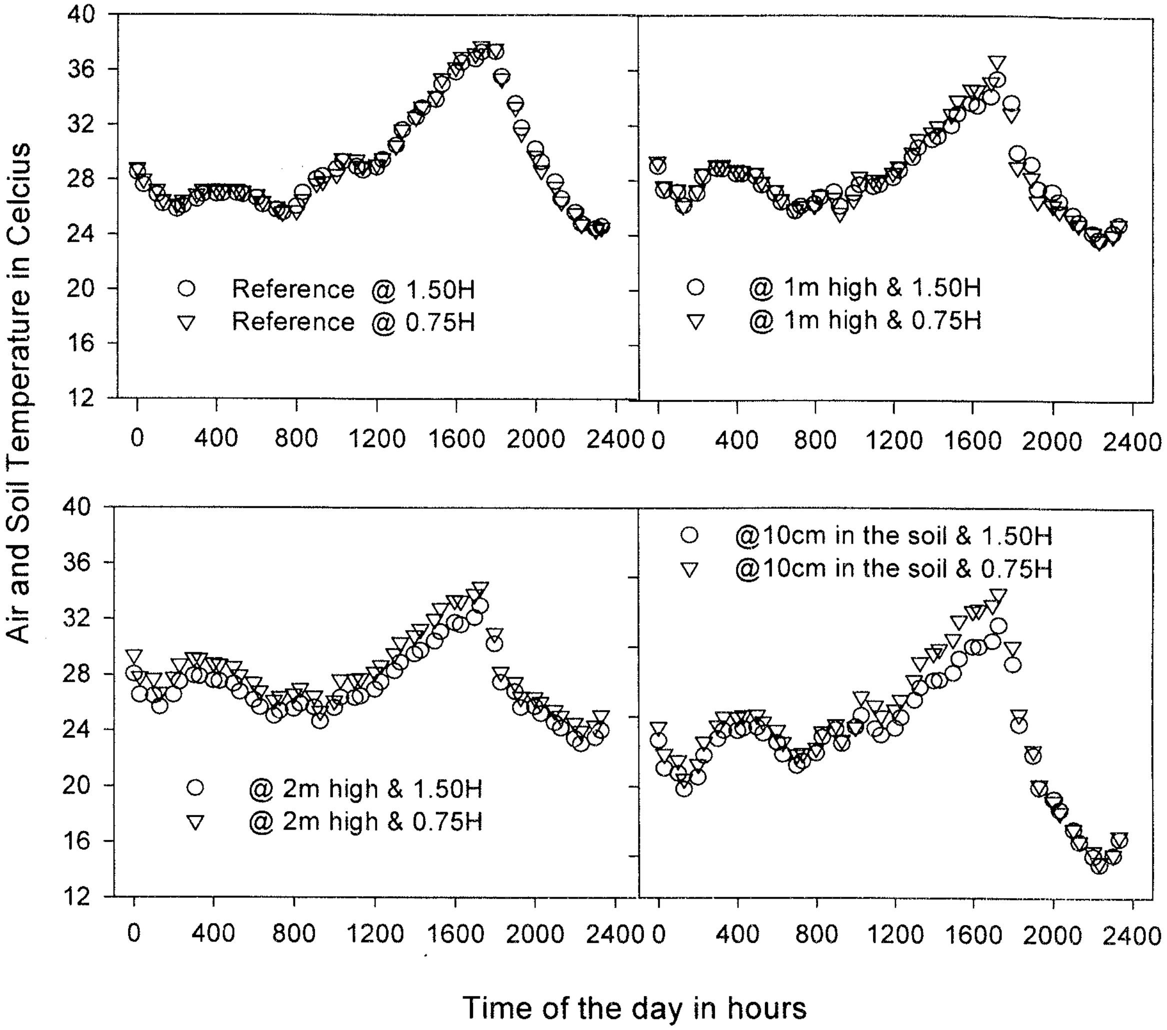
In general, microclimate measurements in the southern exposure of a field windbreak showed some consistent trends with distance from the windbreak. At 0.5H the mean precipitation was 14% less than those at 1.00H, 1.25H, and 1.50H ($P<0.001$). At 0.75H the reduction was 3%, also significantly less than the mean of the three further locations ($P<0.05$). Both air and soil temperatures increased while net radiation and windspeed decreased with proximity to the windbreak. We think these variations may have contributed to the observed consistent decline in soil moisture with proximity to the windbreak in both root-pruned and nonpruned plots. It also suggests that, although highly important, soil moisture extraction by the windbreak vegetation in the interface does not comprise the whole picture of the competitive relationship at the tree/crop interface. Aboveground microclimate factors did vary with distance from the windbreak, even at the south exposure where shading effect is minimal. Variations in microclimate variables were at least partially responsible for the lower soil moisture near the windbreak and consequently may be contributing to the well-documented competitive yield suppression within the windbreak/crop interface.



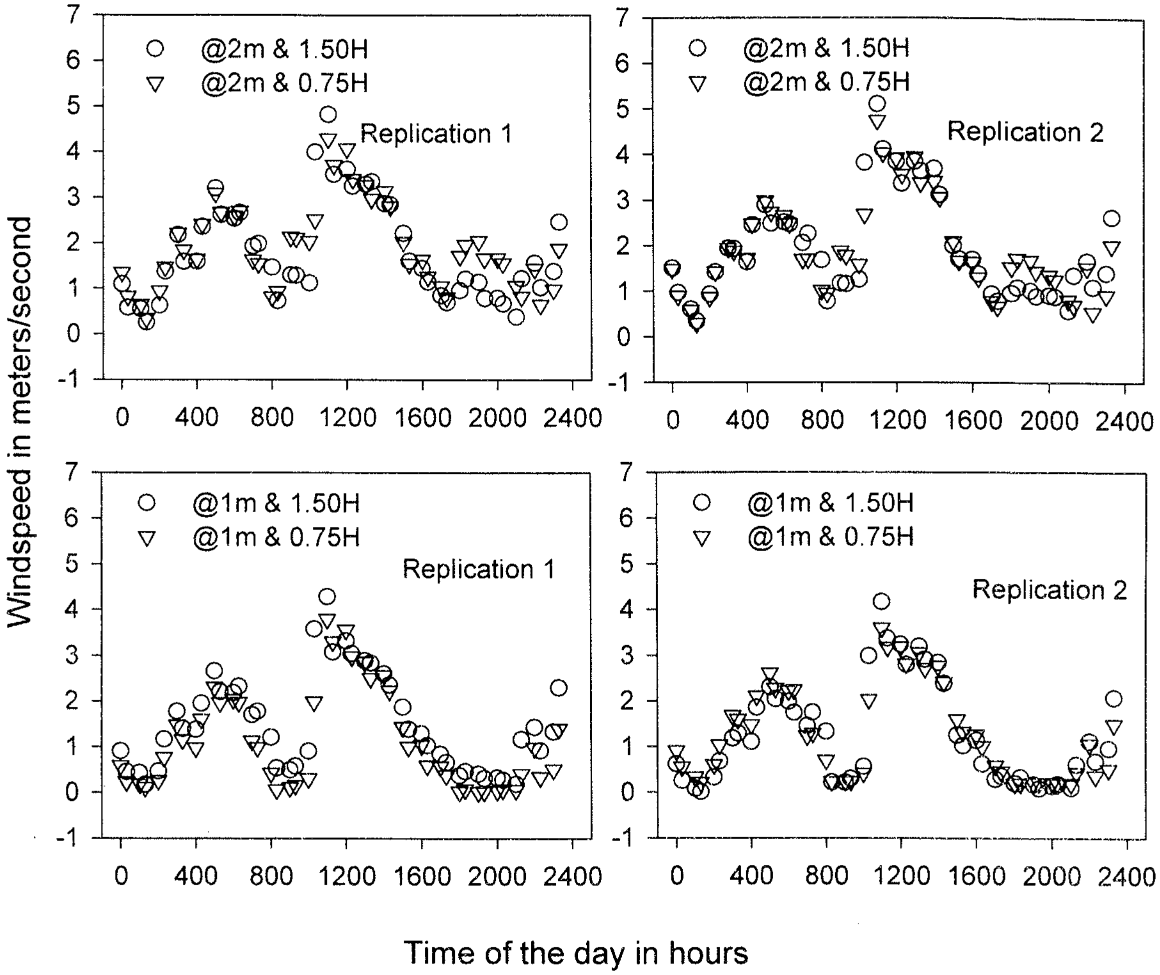
Appendix Figure 1. Mean net radiation at 0.75H vs. at 2.0H and their differences during 11:00am to 16:00pm from Day of the Year 176 to 220. Data taken on the south exposure of a windbreak in 1998. H represnets windbreak height.



Appendix Figure 2. Differences in air temperatures between 1.50H and 0.75H as measured with six pairs of sensors at two height levels and the interior of dataloggers. The associated t values were calculated using SAS Mixed procedure with Diff option for the Lsmeans statement.
From 11:00 am to 16:00 pm mean temperature at 0.75H was always higher than those at 1.50H. H represents windbreak height.



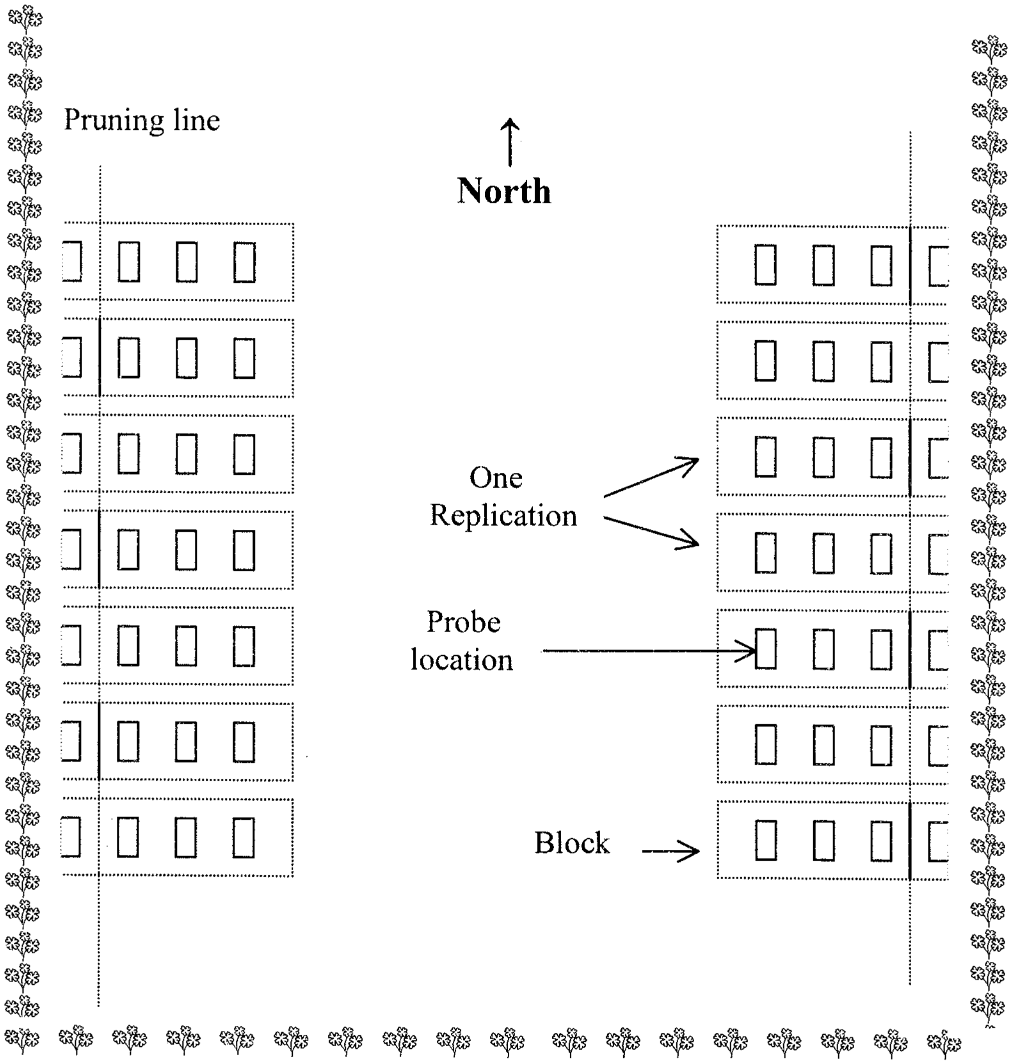
Appendix Figure 3 Air temperatures measured at 0.75H and 1.50H from the windbreak at 1 meter and 2 meter height levels as well as the interior of Data logger. Soil temperature was taken at 10cm depth level at 0.75h and 1.50H locations. Reference refers to the interior air temperature.
H represents windbreak height.



Appendix Figure 4. Windspeeds measured at 0.75H and 1.50H from the windbreak at 1 meter and 2 meter height levels in two replications. H represents windbreak height. Data for Day of the Year 202, 1998.

Appendix Figure 5

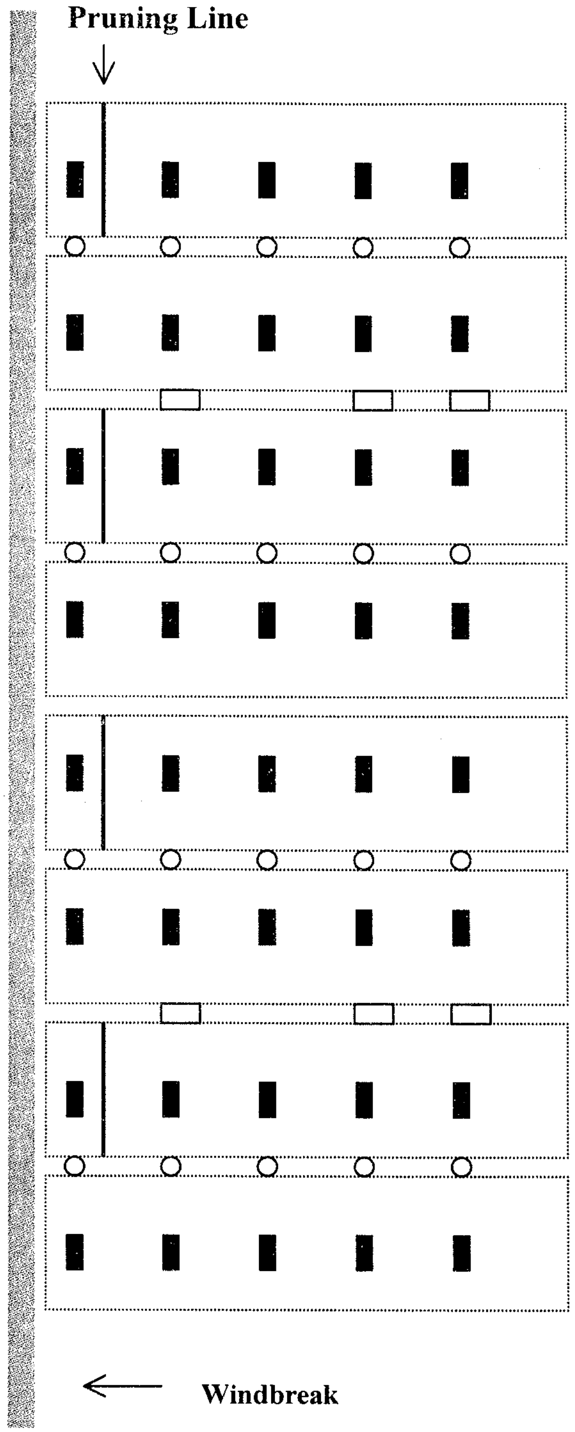
EXPERIMENTAL LAYOUT IN 1997



Windbreak system

Appendix Figure 6

EXPERIMENTAL LAYOUT IN 1998



○ ***Rain Collector***

▮ **Probe Location**

▭ **Data logger**

- **Probe locations were 0.50H, 0.75H, 1.00H, 1.25H, and 1.50H**
- **Pruning line was 0.60H From the windbreak.**
- **Dataloggers located At 0.75H, 1.25H, and 1.50H, respectively.**
- **H represents windbreak height (11meters).**

← North

Appendix Table 1

Windbreak Heights and distances from the tree row for the soil moisture measurement points in 1997 and 1998 .

Windbreak systems	Exposure (Height)	Relative distance from the windbreak				
		0.5H	0.75H	1.0H	1.25 H	1.5 H
Southwest windbreaks	East (11.9)	6.0	8.9	11.9	14.9	17.9
	West (10.9)	5.5	8.2	10.9	13.6	16.4
North windbreaks	East (12.3)	6.2	9.2	12.3	15.4	18.5
	West (11.7)	5.9	8.8	11.7	14.6	17.6
East windbreaks	East (12.3)	6.2	9.2	12.3	15.4	18.5
	West (12.0)	6	9	12	15	18
Windbreak(98)	South(10.5)	5.3	7.9	10.5	13	15.8

Measuring unit is meters.

Appendix 2

HINTS FOR MEASURING SOIL MOISTURE USING THREE KINDS OF INSTRUMENTS

The proper use of ecophysiological equipment is crucial to the success of any kind of indirect measurement, especially if the targeted matrix is heterogeneous in terms of the variable to be measured. For soil moisture, site selection and proper installation are highly critical because soil moisture tends to vary within very short distances in both the horizontal and vertical directions. Based on our field experiences with the TDR Trase System, Hydra Soil Moisture Probes, and CS615 Time Domain Reflectometry, we think the following points need special attention when designing and conducting soil moisture sampling.

Hints for using the TDR Trase System (6050X1 SoilMoisture Equipment Corp., Santa Barbara, CA)

- Use the special driving tool to keep the waveguides parallel while driving them into the soil. This is critical since deformation will change the propagation of the electrical wave, causing serious errors in measurement.
- The exposed portion of the waveguides must only be exposed enough to make good contact with the cable connector since the machine will integrate whatever it senses along the whole waveguide into moisture readings.

- Air pores along the waveguide can result in large differences in moisture readings. Change position whenever a stone or larger obstacles are encountered during installation.
- Frequent measurements will inevitably cause some loss of contact between the waveguides and the soil, especially at the soil surface. Connect cable head gently and fill the surface space by pushing additional soil around the top of the waveguides.
- Avoid inadvertently compacting the soil around the waveguides while conducting measurements.
- Avoid micro-topographical differences while selecting the insertion locations. Rainfall may accumulate in the depression creating aberrant conditions compared to the whole field being sampled.
- The cable is not very durable. During a field season, it helps to keep a spare one handy.
- Try to measure all the waveguides at about the same time of the day especially when doing repeated measurements during an entire season. This will reduce the impact of thermal variation in the soil profile and reduce the temperature effect, if there is any, on the soil dielectric constant.
- Calibrate the machine against site specific conditions.

Hints for using CS615 Time Domain Reflectometers (Campbell Scientific, Inc. Logan, UT)

- Program the data logger according to the manual description. Connect each wire to the specific data logger input and power channel as designated in the program.

- Test run to see if the readings are reasonable. If abnormal readings appear check the wire connections.
- Calibrate the sensor against gravimetrically determined measures taken over a wide range of soil moisture conditions most likely to occur at the intended site. Carefully insert the sensor into the soil to the full length so that the waveguides remain parallel. Take readings for about 10 minutes then pull sensor out. Collect gravimetric soil sample from soil inbetween the two waveguides and determine the moisture content as described earlier. Determine the bulk density near the same location. Repeat the procedure for ten to twelve locations of different moisture contents. Keep in mind to cover the full moisture range expected for the intended field conditions.
- Determine the calibration coefficients using the sensor's raw output in milliseconds against volumetric water contents calculated from direct sampling data and the corresponding soil bulk density.
- Input the specific calibration coefficients for each individual sensor into the data logger program. After on-site calibration the accuracy can reach 2%.
- The CS615 is suitable for both horizontal and vertical installation in the soil profile, but site selection deserves great attention. For treatment comparison sensors should be kept in paired conditions to yield the maximum information.
- As a quality control procedure, paired sensors should be switched on a regular basis to eliminate systematic error caused by either calibration or the data acquisition system.
- Frequent checking of sensor readings from the data logger will ensure a timely correction of malfunctioning.

- The CS615 is temperature sensitive. A temperature correction should be conducted using corresponding soil temperature data.

Hints for using the Hydra Soil Moisture Probe (Vitel, Inc. Chantilly, VA)

- The Hydra probe can be automated with a data logger. Programming is fairly simple, however, it takes four output channels and thus is very power consuming.
- Little information on the vendor's calibration is available from the manual.
- On site calibrations can be conducted as described for the CS615, but calibration accuracy is not as good due to the small sensing volume (hard to determine the corresponding soil water content by direct sampling).
- According to the manufacture's description the effective sensing volume is a cylinder approximately 2.5 cm in diameter and 6 cm in length bounded by the three outer tines. The manufacture argues that a confined effective volume by the sensor can be "an important advantage as the probe can be installed very near the soil surface without a surface induced error".
- The Hydra Soil Moisture Probe is appropriate for determining soil moisture status at specific site or layer such as monitoring the wetting front in a soil profile. It is inappropriate for measuring a vertical soil profile unless multiple sensors are available for installation at different horizons and their individual readings integrated for an average.