DRIP FERTIGATION: EFFECTS ON WATER MOVEMENT, SOIL CHARACTERISTICS AND ROOT DISTRIBUTION.

BY

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DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and has not previously, in its entirety or in part, been submitted at any university for a degree.

SUMMARY

The application of water and nutrients via a drip irrigation system influences the water distribution in the soil, soil characteristics and root distribution beneath the dripper. To determine the water distribution pattern beneath a dripper in sandy soil, EnviroSCAN (Sentek) capacitance probes were installed directly below the dripper and at distances of 20, 40 and 60 cm from the dripper. The continuous monitoring of the soil water content (SWC) beneath the dripper provided a good indication of how the water applied through the dripper is distributed in the soil. In this study a semi-impermeable layer in the soil was detected through observing water accumulation patterns in the SWC. Water accumulated above the layer and SWC values increased to far above the upper level of easily available soil water (EAW_{upper}), while the lower soil layers remained drier. The measurements also show that the horizontal water movement is restricted to 20 cm from the dripper. Specific parameters, such as the lower level of easily available soil water (EAW_{lower}), can be used to determine optimal irrigation management. Together with the water distribution study, the root distribution beneath a dripper was also investigated. A high concentration of roots in the area beneath the dripper was found, which corresponds with the area wetted by irrigation.

In another study, three irrigation/fertigation methods where investigated to ascertain the influence on soil characteristics and root distribution. These were: micro irrigation (MI) (micro-spinner irrigation with broadcast granular fertilization), conventional drip fertigation (CDF) (daily drip irrigation with daily or weekly fertigation with a unbalanced nutrient solution, containing macronutrients only) and daily drip fertigation

(DDF) (daily fertigation of a balanced nutrient solution, containing macro- and micronutrients). The study was conducted in two locations, viz. in the Western Cape Province, on sandy soil, and in the Eastern Cape Province, on silt loam soil.

Micro Irrigation: A wide and even root distribution in the entire wetted volume was found on the sandy and silt loam soil. On the sandy soil, the soil $pH_{(KCl)}$ directly beneath the spinner was significantly lower than the $pH_{(KCl)}$ at positions further away from the spinner.

Conventional Drip Fertigation: Root studies on sandy soil indicate a poor root development beneath the dripper, with a high concentration of roots in the area between the drippers. The poor root development directly beneath the dipper may be due to oxygen deficiency and/or acidification beneath the dripper. The soil $pH_{(KCl)}$ values show a significant lower $pH_{(KCl)}$ value directly beneath the dripper than further away. In comparison to the sandy soil, the roots developed well beneath a dripper in a silt loam soil. It appears as if soil acidity and/or oxygen deficiency was not a problem on this soil type. The rest of the root system was also well developed. This may be due to this soil's higher water holding capacity which creates a bigger wetted zone.

Daily Drip Fertigation: In the sandy soil it seems that the roots developed in a continuous column beneath the dripper line, with little root development further than 20 cm from the dripper line. Where over-irrigation occurred, it caused a poor root development directly beneath the dripper. The root density in this treatment was much higher than in the other two treatments. The use of a balanced nutrient solution and pulse irrigation may be reasons for the better root development. In a silt loam soil a

very high concentration of roots was found beneath the dripper and the rest of the root system was also well developed. As with the CDF treatment, it appears as if oxygen deficiency was not a problem on this soil type.

OPSOMMING

Die toediening van water en voedingstowwe deur 'n drip-besproeiings stelsel beïnvloed die waterverspreiding in die grond sowel as die grondeienskappe en wortelverspreiding onder die dripper. Die waterverspreiding onder 'n dripper in 'n sandgrond is bepaal deur EnviroSCAN kapasitansie meetpenne direk onder die dripper en 20, 40 en 60 cm van 'n dripper af te installeer. Die aaneenlopende monitering van die grondwaterinhoud het 'n goeie indikasie van waterverspreiding in die grond gegee. Die horisontale waterbeweging is grootliks beperk tot 'n 20 cm radius vanaf die dripper en die waterbeweging was hoofsaaklik in 'n vertikale rigting. Die teenwoordigheid van 'n semi-deurlaatbare grondlaag in die grondprofiel is opgemerk deur water-akkumulasie in die profiel waar te neem. Wortelverspreiding onder die dripper is ook ondersoek en 'n hoë konsentrasie wortels is in die benatte sone gevind.

In 'n verdere studie is drie besproeiings/sproeibemestings behandelings gebruik om die invloed van besproeiing/sproeibemesting op grondeienskappe en wortelverspreiding te ondersoek. Die drie behandelings was: mikro-besproeiing (mikro-besproeiing met korrelbemesting), konvensionele-drip-sproeibemesting (daaglikse drip-besproeiing met daaglikse of weeklikse sproeibemesting van 'n ongebalanseerde, voedingsoplossing wat alleenlik uit makro-elemente bestaan) en daaglikse-drip-sproeibemesting (daaglikse drip-besproeiing met daaglikse sproeibemesting van 'n gebalanseerde voedingsoplossing wat mikro- en makro-elemente bevat). Die studie is in twee areas gedoen, een in die Wes-Kaap, op 'n sandgrond, en die ander in die Oos-Kaap, op 'n slik-leemgrond.

Mikro-besproeiing: Die wortelverspreidings studies op die sand- en slik-leemgrond wys op 'n wye en eweredige wortelontwikkeling in die totale benatte volume. Op die sand grond is gevind dat die grond pH$_{(KCl)}$ direk onder die sproeiertjie betekenisvol laer was as die pH$_{(KCl)}$waardes verder weg van die sproeiertjie.

Konvensionele-drip-sproeibemesting: Die wortelverspreiding in die sandgrond wys op geringe wortelontwikkeling direk onder die dripper met die hoogste konsentrasie wortels tussen die drippers. Grondversuring en/of suurstoftekorte onder die dripper kan die oorsaak wees van die swak wortelontwikkeling direk onder die dripper. Die grond pH$_{(KCl)}$ direk onder die dripper was betekenisvol laer as die pH$_{(KCl)}$ verder weg van die dripper. In vergelyking met die sandgrond, het die wortels in die slik-leemgrond goed ontwikkel onder die dripper. Dit wil voorkom of versuring en suurstoftekorte onder die dripper nie 'n probleem was in die slik-leemgrond nie. Die res van die wortelstelsel was ook goed ontwikkel. Dit mag wees weens die grond se hoë waterhoudingsvermoë wat 'n groot benatte area tot gevolg het.

Daaglikse-drip-sproeibemesting: In die sand grond wil dit voorkom asof die wortels in 'n aaneenlopende kolom onder die dripperlyn ontwikkel met weinig wortelontwikkeling verder as 20 cm van die dripperlyn. Waar oorbesproeiing 'n probleem was, was daar weinig wortelontwikkeling in 'n klein area direk onder die dripper. Die wortel-digtheid in die behandeling was baie hoër as in die ander behandelings. Die gebruik van 'n gebalanseerde voedingsoplossing en puls-besproeiing mag dalk redes wees vir die beter wortelontwikkeling. In die slik-leemgrond is 'n hoë konsentrasie wortels onder die dripper gevind en die res van die wortelstelsel was ook goed ontwikkel. Soos in die konvensionele-drip-sproeibemesting behandeling wil dit voorkom of suurstoftekort en versuring onder die dripper nie 'n probleem was in die grond nie.

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CONTENTS

1. INTRODUCTION

Irrigation and fertilization are two of the most important methods through which farmers can manage productivity. The combination of drip irrigation and fertilization (fertigation) expands the possibilities of controlling water and nutrient supplies to crops and maintaining the desired concentration and distribution of ions and water in the soil (Bar-Yosef, 1999).

Drip irrigation differs from conventional irrigation methods in that water is applied to plants at more frequent intervals and to only a portion of the plant's potential root zone (Elfving, 1982). This localized water application creates a restricted root zone in which moisture stress can be prevented by frequent water application (Haynes, 1985). The application of fertilizers through the drip system increases fertigation efficiency by applying the nutrients only to the restricted root zone (Bar-Yosef, 1999).

The aim of efficient drip irrigation scheduling is to replenish the water deficit within the active root zone, while minimizing leaching below this depth. To maintain this, it is necessary to know how water distributes within the soil after application through a dripper. Knowledge of the shape of the wetted volume is important in the design, operation and management of an irrigation system.

The root distribution pattern of trees irrigated by drippers depends mainly on the wetted soil volume under the drippers. In general, the wetted soil volume in an orchard irrigated by drippers is about 30-50 per cent (Levin *et al.*, 1980) of that irrigated by surface irrigation. Thus, the area for the development of the root system decreases approximately by that proportion. This raises the following questions: How does the root system adapt to this smaller percentage of wetted soil volume? In previous studies it was found that the root system adapts to wetting of only a portion of the soil volume by the proliferation of roots in the wetted zone (Bar-Yosef, 1977; Levin *et al*., 1980 and Goode *et al*., 1978) and that plants adapted physiologically by increasing the water uptake per unit length of roots (Lunin and Gallatin, 1965).

Fertigation influences soil acidity, salinity and oxygen availability beneath the dripper. These factors have an influence on root growth and distribution as well. It is known that a low pH may cause Al toxicity (Magistad, 1925) which results in root growth reduction (Islam *et al*., 1980). A saline environment imposes osmotic (Itoh *et al*., 1987) and ionic (Kafkafi, 1991) stress on roots, which may cause a reduction in root elongation (Roundy, 1985). The root system also responds immediately to a reduction in oxygen supply, by cessation of new root initiation and retardation of root extension (Lemon and Erickson, 1955).

Root distribution studies can determine the concentration of fine roots in and around the wetted volume. The distribution of fine roots will provide an indication of how effective the water and nutrients can be absorbed by these roots. It also shows whether soil acidity, salinity and oxygen supply is a problem. Understanding the root distribution under different irrigation systems can aid in determining appropriate management of irrigation systems.

The objectives of this study were to investigate: water distribution beneath a dripper in sandy soils, by means of EnviroSCAN capacitance probes; the influence of different irrigation and fertigation systems on soil acidity and salinity and the influence of the above mentioned factors on root distribution in the soil profile.

Literature cited

Bar-Yosef, B., 1977. Trickle irrigation and fertilization of tomatoes in sand dunes: Water, N, and P distribution in the soil and uptake by plants. *Agron. J.* **69:** 486-491.

Bar-Yosef, B., 1999. Advances in fertigation. *Adv. Agron.* **65:** 1-77.

Elfving, D.C., 1982. Crop response to trickle irrigation. *Hort. Rev.* **4:** 1-48.

Goode, J.E., Higges, K.H. & Hyrycz, K.J., 1978. Trickle irrigation of apple trees and the effect of liquid feeding with NO_3^- and K^+ compared with normal manuring. *J. of Hort. Sci.***53:** 307-316.

Haynes, R.J., 1985. Principles of fertilizer use for trickle irrigated crops. *Fert Res.* **6:** 235-255.

Islam, A.K.M.S., Edwards, D.G. & Asher, C.J., 1980. pH optima for crop growth: Results of a flowing nutrient culture experiment with six species. *Plant and Soil* **54:** 339-357.

Itoh, K., Nakamura, Y., Kawata, H., Yamada, T., Ohta, E., & Sakata, M., 1987. Effect of osmotic stress on turgor pressure in mung bean root cells. *Plant Cell Physiol.* **28:** 987-994.

Kafkafi. U., 1991. Root growth under stress - Salinity. pp. 375-391. **In**: Waisel,Y., Eshet, A. & Kafkafi, U. (eds.). *Plant roots: The hidden half.* Marcel Dekker, New York.

Lemon, E.R. & Erickson, A.E., 1955. Principle of the platinum microelectrode as a method of characterizing soil aeration. *Soil Sci.* **79:** 383-392.

Levin, I., Assaf, R. & Bravdo, B., 1980. Irrigation, water status and nutrient uptake in an apple orchard. *Acta Hort.* **92** 255-264.

Lunin, J. & Gallatin, M.H., 1965. Zonal salinization of the root system in relation to plant growth. *Soil Sci. Soc. Amer. Proc.* **29:** 608-612.

Magistad, O.C., 1925. The aluminium content of the soil solution and its relation to soil reaction and plant growth. *Soil Sci.* **20:** 181-225.

Roundy, B.A., 1985. Root penetration and shoot elongation of tall wheatgrass and basin wildrye in relation to salinity. *Can. J. of Plant Sci* .**65:** 335-343.

2. CHANGES IN SOIL WATER CONTENT, AERATION, ACIDITY AND SALINITY UNDER DRIP FERTIGATION AND INFLUENCE ON ROOT DISTRIBUTION.

Introduction

The use of dripping as a method of irrigation has become quite a common practice in agricultural production all over the world (Bresler, 1977). Drip irrigation differs from conventional irrigation methods in that water is applied to plants at more frequent intervals and to only a portion of the plant's potential root zone (Elfving, 1982). This localized water application creates a restricted root zone in which moisture stress can be prevented by frequent water application (Haynes, 1985). The application of fertilizers through the drip system increases fertigation efficiency by applying the nutrients only to the restricted root zone (Bar-Yosef, 1999).

Understanding how water distributes within the soil after application through a dripper is necessary for efficient water management. The root distribution pattern of trees, in turn, is influenced by the wetted soil volume under the drippers. It is also necessary to know how drip fertigation influences soil characteristics, e.g. pH and resistance, and the effect thereof on root distribution.

2.1 Soil water content

The drip irrigation system consists of a labyrinth fitted into an outer case. Water enters through an orifice, travels the length of the labyrinth which reduces the pressure, and discharges out as a trickle at a controlled rate. The dripper line is placed directly on the soil surface so that the area of infiltration is very small compared with the total soil surface. Water spreads from a dripper in a three-dimensional flow pattern, according to potential gradients, and creates an onion-shaped volume of wetted soil (Brandt *et al.*, 1971). Therefore, the soil is saturated only in the vicinity of the dripper, while most of its volume is wetted by an unsaturated flow. This differs from the conventional modes of irrigation (furrow, flood and sprinkler systems), where there is a one-dimensional downward water flux from the entire wetted soil surface (Zur, 1996).

The dimensions of the wetted volume under a point source, its width and depth, depend on the hydraulic properties of the soil, the discharge rate of the emitter and the quantity of water applied (Brandt *et al.*, 1971; Bresler *et al.*, 1971). Other conditions being constant, a shallower and wider cone is found in the "heavier" soils, in which the major acting force is capillary, whereas in the "lighter" soils the movement of water is essentially caused by gravity and a smaller, deeper cone results (Benami and Ofen, 1984).

Brandt *et al.* (1971) developed a model to define infiltration of water into the soil from the dripper. The implication seems to be that at low application rate the wetting pattern will be narrower and deeper than at high application rates. Bresler *et al.* (1971) have tested these models and found that, while the application of water at higher rates increased the width of wetting pattern relative to depth, the Brandt models tended to overestimate the depth of wetting at low rates and underestimate it at high rates.

Rawlins (1973) has shown that the moisture content at which water moves through the soil is not necessarily restricted to the level appropriate to movement under conditions at saturated hydraulic conductivity. At low application rates the soil water content is less than the saturated level to such an extent that the hydraulic conductivity is equated to the application rate. Under such unsaturated conditions gravitational forces are likely to be minimal and the form of the wetting pattern will mainly reflect matric suction potential gradients away from the dripper. As the application rate is increased the soil water content increases towards the saturated hydraulic conductivity level. Under these conditions the gravitational component will become progressively more important, particularly in soils with a high proportion of large pores (sandy soils). The effect would be a progressive distortion of the wetting pattern by increasing depth of wetting relative to width. Further, since the soil is wetter with the high application rate, the deep percolation effect will be greater after the application ceases. The mathematical models have not taken all of this into account, and it may explain the discrepancy between the Brandt model and field tests.

The traditional irrigation cycle consists of a relatively short period of infiltration followed by a long period of simultaneous redistribution, evaporation, and extraction of water by the growing plant. There is a fixed cost associated with each water application, therefore it is possible to cut costs by decreasing the number of irrigations by increasing the time interval between two successive irrigations. Here it is necessary to maximize the quantity of available water stored in the soil for water use by the crop before the next irrigation (Rawlins, 1973). This method causes extremely large time fluctuation in the soil-water potential (Bresler and Yaron, 1972). Economic constraint has been lifted by the development of irrigation systems capable of delivering water to the soil in small quantities as often as desired with no additional cost (Rawlins, 1973). As the frequency of irrigation increases, a continuously high water potential can be maintained, thus minimizing the fluctuations in the soil-water content during the irrigation cycle. The increased soil-water potential results in both high (less negative) average matric potential and osmotic potential (Bresler, 1977). The low osmotic potential in the soil is due to the low salt concentration of the incoming irrigation water. There is some evidence to support the view that crop yield is increased by maintaining a high average soil-water potential (Goldberg *et al*. 1976). In comparing a three-day sprinkling schedule with daily drip irrigation for tomatoes grown on sand dunes, Goldberg *et al*. (1976) observed a relatively stable soil water potential for drip irrigation, while by the second day of the sprinkler cycle soil water potential was decreasing in the sprinkle plots. By the third day, soil water depletion was sufficient to produce a reduced xylem pressure potential over the entire day, although recovery was almost complete at night. Yields differed markedly, 79 ton/ha for drip as opposed to 30 ton/ha for sprinkled plants, probably reflecting both effects of improved plant water relations on growth as well as adverse effects of sprinkling with saline water.

2.1.1 The effect of soil water content on root distribution

The root distribution pattern of trees irrigated by drippers depends mainly on the wetted soil volume under the dripper. As mentioned previously, the shape and size of the wetted soil volume are a function of the hydraulic conductivity of the soil, the discharge rate of the emitter, and the duration of irrigation (Bresler *et al.*, 1971; Levin *et al.*, 1979). In general, the wetted soil volume in an orchard irrigated by drippers is about 30-50 per cent (Levin *et al.*, 1980) of that irrigated by surface irrigation. Thus the area for the development of the root system decreases approximately by that proportion. This raises the following questions: How does the root system adapt to this smaller percentage of wetted soil volume and what is the relationship between the size of the root system, the rooting density and the performance of the tree?

Soil water potential directly influences root growth by its effect on the water potential gradient for water entry into the root. Significant reductions in cotton root growth have been measured at about –0.1 MPa soil water potential in rhizotron experiments (Taylor and Klepper, 1974). Under field conditions Rogers (1939) reported, as quoted by Atkinson (1980), that root growth of apples was reduced at a soil water potential of –0.04 to –0.05 MPa and citrus root growth was limited at soil water potentials less than about –0.05 MPa (Bevington and Castle, 1985).

Experiments showed (Lunin and Gallatin, 1965) that local application of water to less than the total root volume did not affect the ability of the tree to take up sufficient water. The plants adapted physiologically to irrigation of only a portion of their root system since the uptake of water per unit length of roots in the wetted portion was increased. Dasberg *et al.*

(1981) reported that partial wetting of the root zone resulted in higher water use efficiency. West *et al*. (1970) found that water would distribute laterally across the vascular tissue to all parts of apple trees with quartered root systems grown in four separate pots, when only one quarter was supplied with water. The total tree water use dropped to only 60% of that of control trees when only 25% of the root system received water.

The root systems also adapt structurally to wetting of only a portion of the soil volume by the proliferation of roots in the wetted zone. Under conditions where there is little water available to the tree during the summer season, the roots adapt to the relatively small soil volume wetted by the drippers (Bar-Yosef, 1977; Levin *et al*, 1979; Levin *et al.*, 1980). Bar-Yosef (1977) found tomato roots restricted to a wetted zone of inverted conic shape approximately 30 cm in diameter and depth. In a drip irrigation experiment conducted in an apple orchard on a clay soil with 830 trees per hectare, several wetted soil volumes were created, using drippers with different discharge rates. The root system developed in this orchard was limited to a relatively small volume of soil. Almost all the roots were concentrated along the lateral line at distances and depths that did not exceed 60 cm from the dripper. No differences in growth or yields were observed (Levin *et al.*, 1980). Levin *et al.* (1979) observed that shortening the intervals between irrigation cycles and thus reducing the time of water stress further away from the dripper, could extend the root distribution.

In temperate regions where significant spring and summer rainfall occurs, there will always be some new root growth outside the wetted volume. Nonetheless, the bulk of the root growth still occurs within the wetted volume. Goode *et al*. (1978) found that the main difference in root distribution between drip-irrigated and non-irrigated trees were that the proliferation of fine roots under the dripper amounted to four or five times as many roots than were present in similar regions of non-irrigated soil. Away from the wet zone there was little difference between irrigated and non-irrigated trees.

Araujo *et al.* (1995) determined the soil water content and root distribution under drip and furrow irrigation methods. Their data indicated that soil water content and root distribution of young (3-year-old) vines differed significantly under drip and furrow irrigation. The initial vertical distribution of soil water became a predominantly lateral distribution under drip irrigation, whereas the distribution remained primarily vertical under furrow. However, during each furrow irrigation cycle temporal and dynamic availability of soil water was observed. In contrast, a relatively static and localized region of wet soil was established under drip irrigation. The differences in soil water distribution resulted in the development of a localized region of high root density near the soil surface and the emitter under drip, compared with the greater lateral and deep development of roots under furrow irrigation. Roots of furrow-irrigated vines were much more evenly distributed through the soil volume.

Plants with restricted root systems develop smaller canopies than plants with unrestricted root development. Plaut *et al.* (1988) restricted the root system of cotton by applying small quantities of water at high frequencies through drip irrigation. In a restricted root zone it was possible to control soil water status and consequently manipulate vegetative and reproductive growth. This made it possible to grow smaller plants at high densities and maintain yield per unit land area. Proebsting *et al.* (1977) noted more and shorter shoots, but the same total shoot length along with more rapid onset of fruiting in drip-irrigated apple trees, where the root system volume was limited to about 0.69 m^3, as compared to a maximum potential root volume of 13.5 m^3 for trees irrigated by sprinklers. The same results were achieved with peach trees grown in restricted container volumes. The available root volume was directly correlated with total dry matter production by the tree (Erez *et al.*, 1992).

Bar-Yosef *et al.* (1988) found that restricting container volume decreased yield, total dry matter production and N and water uptake rates, but increased root permeability to NO_3^- and water, and total soluble solids in fruits. Since the decline in yield coincided with a decrease in tree growth, the fruit yield per unit land area can be enhanced by increasing planting density in the field. Further, the higher total soluble solids may compensate economically for the reduced fruit yield per tree.

Water content and soil strength are closely interrelated. If soils are wet above field capacity soil strength will be quite favourable for root growth. As the soil water content decreases, soil strength becomes less favourable. Thus, the lowest soil water content suitable for root elongation may be determined by increases in strength as the soil dries. Taylor and Ratliff (1969) showed that with a constant low bulk density, soil strength declines and root elongation rates increase as soil water content increases. When roots penetrate the soil, the soil is compressed (Dexter, 1987). Thus, the compressibility of the soil is an important controlling factor relative to root growth extent (Rickman *et al.*, 1992). When soil strength exceeds 2.0 MPa, root growth is severely restricted (Taylor *et al.* 1966).

2.2 Aeration

Excess water fills the large soil pores that normally remain drained and usually filled by air. Such air-filled pores provide a low-resistance pathway for the aeration of soils and minimize the path length for the slower diffusive transfer of oxygen dissolved in the soil solution. High water content also results in poor continuity of the remaining air-filled pore spaces. The rate of gaseous diffusion to and from roots is thus seriously limited by excess water content, and may not be adequate to support metabolic processes in roots or shoots. Portions of the root zone may thus become limiting to oxygen diffusion due to inappropriate water management, even when physical properties are otherwise favourable for adequate aeration (Grable, 1966).

Water distributes from a dripper in a three-dimensional flow, according to the potential gradients, and creates an onion-shaped volume of wetted soil. Therefore, the soil is only saturated in the vicinity of the dripper, while most of its volume is wetted by an unsaturated flow (Brandt *et al*, 1971). Thus, drip irrigation may cause an insufficient oxygen supply for root growth in the vicinity of the drippers.

2.2.1 The effect of aeration on root distribution

In order to achieve proper growth, the root zone of a plant must be well supplied with both water and oxygen. If a low water tension is maintained in the soil, plants will suffer from a sub-optimal level of oxygen supply in the root zone (Wiegand and Lemon, 1958). Oxygen is essential for good root development. Oxygen controls respiration in roots of intact plants as well as in individual cells or tissues. Harris and Van Bavel (1957) concluded that root respiration was "the most sensitive aspect of plant activity in regard to soil aeration. Since growth of roots, and uptake of water and nutrients are dependent upon energy which is supplied by respiration, it may be assumed that reduction in respiratory activity is the first step in growth-limiting effects of insufficient aeration." Fulton and Erickson (1964) showed that flooding of tomato roots quickly inhibited respiration and metabolism in all plant parts and inhibited the Krebs citric acid cycle in roots. The root system responds immediately to a reduction in oxygen supply by a cessation of new root initiation and retardation of root extension. The further reduction in oxygen will cause extension to cease altogether and ultimately there will be no recovery of normal root growth when roots are well-supplied again with oxygen (Lemon and Erickson, 1955).

Work by Boynton *et al.* (1938) on critical oxygen concentration for root activity in orchard soils gave positive correlations between results from field studies and those conducted under controlled conditions. They recognized four levels of root activity: (1) the subsistence level was 0.1% to 3.0% O_2, and below 1% the root weight loss occurs; (2) O_2 content between 5% and 10% was necessary for maintaining growth of existing root rips; (3) 12% O_2 was required for new root initiation; (4) below 15% O_2 there was a progressive decrease in absorption of minerals. Gardner and Danielson (1964) also found a high correlation (r=0.998) between soil penetration by cotton roots and percentage of aeration porosity.

The influence of the oxygen diffusion rate (O.D.R.) on the development of the root system beneath a dripper was determined by Silberbush *et al.* (1979). The root system was markedly concentrated in the periphery of the drip irrigated soil volume, while in the center there were few roots. An exponential correlation was found between root distribution and O.D.R. in which 20 x $10^{-8}cm^{-2}min^{-1}$ was the critical value for root growth. Above this value there is an exponential rise in root density, while at lower levels, root density is very low. Ellis and Barnes (1980) reported that low O.D.R. decrease rates of root elongation.

It was also found that a sufficient supply of oxygen was necessary for maximum water uptake (Kelly, 1947) and that low O.D.R. decrease root conductance of water (Holder and Brown, 1980). Letey *et al.* (1961) reported that plants grown under lower oxygen concentration were less turgid and showed signs of wilting during midday, which was not due to the lack of water. They suggested that the increased wilting indicated that water uptake is influenced by oxygen level. Thus, insufficient O.D.R. to the root system may interfere with water and mineral uptake and also result in hormonal imbalance within the plant (Drew and Stolzy, 1996).

2.3 Soil acidity

Application of ammonium-containing or ammonium-forming fertilizers has been reported to cause soil acidification (Bouman *et al.*, 1995; Neilsen *et al.*, 1994; Parchomchuk *et al.*, 1993). In general, soil acidity is increased with increasing application of N fertilizer (Bouman *et al.*, 1995). Fertigation with 100 or 200 kg $N.ha^{-1}$ using either urea or ammonium sulphate reduced soil pH by more than one $pH_{(KCl)}$ unit within 3 months (Haynes and Swift, 1987). Edwards *et al.* (1982) reported that fertigation of peach trees with eight equal doses (33 kg $N.ha^{-1}$) of ammonium nitrate caused $pH_{(H_2O)}$ of a sandy soil to decline from 6.2 to 3.7 in two seasons. Likewise, He *et al.* (1999) found that the application of 112 kg $N.ha^{-1}yr^{-1}$ (NH_4^+ -based fertilizers) for four years decreased the soil pH by 0.7 to 1.7 unit.

Parchomchuk *et al.* (1993) found that soil acidification extended to approximately 60 cm vertically and horizontally from the dripper and was most severe directly beneath the emitter where the soil $pH_{(CaCl_2)}$ decreased from 5 to 4.5 after one year and to 3.7 after three seasons of fertigation, using ammonium nitrate as N source.

2.3.1 Acidification process

Nitrogen fertilizers can acidify the soil in two ways: (1) nitrification of ammonium-containing fertilizers; (2) and the uptake of N in a cation (NH_4^+) form. These mechanisms will be discussed in the following sections.

2.3.1.1 Nitrification

The process whereby NH_4^+ (from NH_4^+ -based fertilizers) is oxidized to yield N is referred to as nitrification. The process broadly involves two steps: oxidation of NH_4^+ to NO_2^- and subsequent oxidation of NO_2^- to NO_3^-. The overall reaction can be expressed as follows:

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+$$

Thus, the oxidation of ammonium fertilizers can generate 2 moles of protons for every mole of N (Bolan *et al.*, 1991). These H^+ can only be neutralized if the NO_3^- can be completely transformed by the N cycle back into the original input forms. If NO_3^- is lost from the system by leaching, the H^+ remains as permanent soil acidity (Van Breemen *et al*, 1983).

The denitrification reactions, which consume protons, are essentially the reverse of those for nitrification in which protons are produced. Thus the amount of acidity entering and remaining in the soil from ammonium N sources depends largely on the relative magnitudes of these two processes (Pierre *et al*., 1971).

2.3.1.2 The uptake of Nitrogen in a cation form

Plants take up N in three main forms, niz. as an anion (nitrate, NO_3^-), as a cation (ammonium, NH_4^+) or as a neutral N_2 molecule (N_2 fixation). Depending upon the form of N taken up and the mechanism of assimilation in the plant, excesses of cation or anion uptake may occur (Kerby and Knight, 1977). To maintain the charge balance during the uptake process, H or OH ions must be excreted from the root into the surrounding soil. It has been shown that while the uptake of NO_3^- can result in a net release of OH ions, the uptake of $NH_4^+$and N_2 fixation results in a net release of H ions. The imbalance of cation over anion uptake in the rhizosphere by plants taking up NH_4^+ ions as the major source of N (from NH_4^+-containing fertilizers) cause soil acidification (Bolan *et al*., 1991).

Acidification of the soil can disadvantage root and plant growth mainly through: (1) direct effects of high H^+ concentrations, (2) aluminium toxicity and (3) the changes in the concentration of exchangeable Ca^{2+}, Mg^{2+} and K^+. This will be discussed in the next section.

2.3.2 Disadvantages of soil acidity

2.3.2.1 H ion toxicity

Direct effects of the H ion on plant growth are difficult to assess. At soil pH values where it is potentially harmful, Al, Mn and other mineral elements may also be present in toxic concentrations, and the availability of essential elements, particularly Ca, Mg, P, Mo and Si, may be suboptimal. In most acidic soils (pH above 4.0), Al and Mn toxicity are probably more important than H ion toxicity in limiting the growth of the plant. However, H ion toxicity may restrict the survival and activity of rhizobia and other soil microorganisms (Moore, 1974).

Since the effects of H ions are entangled with those of other factors in acidic soil, investigators have resorted to nutrient solutions or sand culture to study the effects of low pH. In general, nutrient solutions having pH values below 4.0 reduce root growth (Islam *et al.*, 1980).

The pH of the soil solution affects both cation and anion absorption by roots. In short-term experiments with excised roots, the maximum adsorption rate from a nutrient solution occurs at pH values from 5 to 7. Below pH 5, cation absorption is sharply reduced by H ions. Pre-treatment of barley roots with HCl at a solution pH below 5.0 caused a pronounced loss of K and also markedly reduced the capacities of roots for subsequent uptake of K (Hussain *et al.*, 1954). The H ion, within the solution pH range of 3.0 to 5.0, markedly reduced Ca uptake by excised maize roots (Maas, 1969). This behaviour has also occured with Mg (Moore *et al.*, 1961), Mn (Maas *et al.*, 1968), Zn (Rashid *et al.*, 1976) and Cu (Bowen, 1969).

In addition to its competitive effects on ion absorption, H^+ can be damaging to roots. At a solution pH value below 4, H^+ causes a loss of previously absorbed ions from root tissue. Sizeable losses of K from roots exposed to low pH in short-term experiments have been reported (Jacobson *et al.*, 1950; Nielsen and Overstreet, 1955). Similar results were reported for Mg (Moore *et al.*, 1961), and Ca (Jacobson *et al.*, 1950). The H ion generally increased the permeability of the cell membranes and allowed cell constituents to leak out. Thus, roots can lose previously-absorbed cations as well as organic substances, and prolonged exposure to low pH may reduce their capacities for subsequent absorption of nutrients (Christiansen *et al.*, 1970).

2.3.2.2 Aluminium toxicity

Low pH (below 5.0 in water) frequently causes toxicity of aluminium. Aluminium toxicity is an important root growth-limiting factor in acid soils. Symptoms of Al rhizotoxicity include: stunted roots; poor root hair development; swollen root apices; stubby and brittle roots; less branching; fewer primary and secondary roots; and coralloid, dense and compacted root systems (Foy, 1992).

The critical soil pH at which Al becomes soluble or exchangeable in toxic concentrations depends on many other factors, including the predominant clay minerals, organic matter levels, anions and total salts, concentrations of other cations and, particularly, the plant species or cultivar (Foy, 1974). In general, Al toxicity does not occur in soils above $pH_{(H_2O)}$ 5.5 (McCart and Kamprath, 1965), but it is common at lower pH values, and particularly severe below $pH_{(H_2O)}$ 5.0, where the solubility of Al increases sharply

(Magistad, 1925) and more than half the cation exchange sites may be occupied by Al (Evans and Kamprath, 1970).

Aluminium toxicity is a complex disorder which may be manifested as a deficiency of P, Ca, Mg, or Fe or as drought stress (Foy, 1974). In some plants, the foliar symptoms resemble those of P deficiency (Foy and Brown, 1963, Chiasson, 1964) (overall stunting; small, dark green leaves; late maturity; purpling of stems, leaves, and leaf veins; and yellowing and death of leaf tips). In others, Al toxicity appears as an induced Ca deficiency or reduced Ca transport within the plant (Lance and Pearson, 1969) (curling or rolling of young leaves, inhibited growth of lateral branches, or a collapse of growing points or petioles). Excess Al has even induced Fe deficiency symptoms in rice, sorghum and wheat (Clark *et al.*, 1981; Furlani and Clark, 1981; Foy and Fleming, 1982).

2.3.2.3 Influence of low pH on exchangeable Ca^{2+}, Mg^{2+} and K^+

Some of the more striking results of acidification of the soil are the changes in the exchange properties and in the concentration of exchangeable Ca^{2+}, Mg^{2+} and K^+. Abruna *et al.* (1958) fertilized a well-drained, clay-loam soil from Puerto Rico with $(NH_4)_2SO_4$ for three years with a total of 880 and 4030 kg N/ha, respectively. The soil $pH_{(H2O)}$ in the upper 15cm decreased from 7 to 4.1 with the low rate of fertilization and to 3.6 in the plots receiving 4030 kg N/ha. The sum of extractable bases decreased from 22 $cmol_c$/kg in the untreated plots to 11.5 and 4.0 $cmol_c$/kg for the 880 and 4030 kg N/ha treatments, respectively. Although a significant portion of this decrease was due to greater yield and increased uptake by the crop, the majority of the reduction was due to displacement by the acidity generated by nitrification of the applied NH_4.

Blevins *et al.* (1977) applied up to 336 kg N/ha as NH_4NO_3 for 5 years to a Paleudalf soil from Kentucky with a silt loam texture with an initial $pH_{(H_2O)}$ of 5.3 and cation exchange capacity of 11 $cmol_c/kg$. With increasing quantities of N applied, the pH was lowered, exchangeable Ca^{2+} and Mg^{2+} decreased and Al and Mn increased to a depth of 15 cm.

Long-term fertility plots were established at the Kansas State University Agronomy Farm in 1946, in which N rates, up to 220 kg/ha as NH_4NO_3 were applied annually (Schwab *et al.*, 1989). In 1965, the fertilization was permanently discontinued in one-half of each plot. In the continuously fertilized plots, pH and exchangeable Ca^{2+}, Mg^{2+} and K^+ decreased in the upper 20cm of the soil. The discontinuation of fertilization for 20 years in the other half, resulted in a significant, but incomplete, trend of the exchange properties toward values of unfertilized soil. Thus, the acidification resulting form NH_4 application, was reversed somewhat after fertilization ceased.

The effects of soil acidification $pH_{(CaCl_2)}$ values from 6.5 to 3.8, and subsequent leaching, on levels of extractable nutrients in a soil were studied in a laboratory experiment (Haynes and Swift, 1986). Below $pH_{(CaCl_2)}$ 5.5, acidification resulted in large increases in the amounts of exchangeable Al in the soil. Simultaneously, exchangeable cations were displaced from exchange sites and Ca, Mg, K and Na in soil solution increased markedly. With increasing soil acidification, increasing amounts of cations were leached; the magnitude of leaching loss was in the same order as the cations were present in the soil: $Ca^{2+} > Mg^{2+} > K^+ > Na^+$.

2.3.3 Amelioration of soil acidity

Liming materials are used widely to raise soil pH levels to that desirable for plant growth. Minerals which are commonly used to raise soil pH are $CaCO_3$ (limestone) and $CaMg(CO_3)_2$ (dolomite) (Cregan *et al.*, 1989). The mechanisms through which $CaCO_3$ reacts with acid soils are complex. In water, $CaCO_3$ react as follows:

$$CaCO_3 + H_2O \rightarrow Ca^{2+} + HCO_3^- + OH^- .$$

The OH ions reacts with H ions to form water, thus neutralizing the H ions and increasing the pH. The rate of this reaction, and thus of $CaCO_3$ in solution, is directly related to the rate at which the OH ions are removed from solution. As long as sufficient H ions are in solution, Ca and HCO_3^- ions will increase in number. When the H ion concentration is lowered, the solubility of Ca and HCO_3^- is reduced (Coleman and Thomas, 1967).

Lime applied to acid soils may be beneficial to plant growth for several reasons: it reduces the H ion concentration, it may remove the toxic Al from the sphere of action by precipitation and it supplies Ca and Mg. The precipitation of Al is caused by a decrease in acidity (Magistad, 1925).

Lime is usually broadcast on the soil surface and then mixed with the soil during the course of tillage operations. Undoubtedly, the mixing is not uniform throughout the soil profile and thorough mixing is very expensive (Barber, 1967). This may cause problems in drip irrigation, since there is a chance that the dripper may be positioned outside the limed area. The distribution of maintenance liming in the restricted root zone of the drip irrigation system may also be a problem. More research is needed on the topic of acidification under drip irrigation, for liming does not seem to be the answer to this problem.

2.4 Salinity

The salt distribution under drip irrigation was presented and discussed by Bresler (1977). Salt movement in soil is directly related to water movement. As water moves within the soil by mass flow or diffusion in response to water potential gradients, it carries along soluble salts. Plant roots take up only a small fraction of the soil water salt load, and no salt is lost to the atmosphere along with water evaporated from the soil surface. As a result, salts tend to accumulate at the wetted front, between emitters where flux reaches zero, and at the surface, where evaporation occurs. Continued water extraction results in increasing salt concentrations in the soil solution, which will eventually lead to precipitation of salts (Bernstein and Francois, 1973; Singh *et al.*, 1978).

The actual distribution achieved under drip irrigation depends upon the salinity of the irrigation water, the leaching fraction, the frequency of irrigation, the spacing of the drippers and the pattern of root water uptake (Bowman and Nakayama, 1986).

2.4.1 The effect of salinity on root distribution

A saline (accumulated salts) environment imposes osmotic and ionic stress on roots. In osmotic stress, high salt concentrations lead to lower water potentials in the soil and eventually cause water stress. Roots that are exposed to a sudden event of salt or water stress lose their turgor and respond via an immediate cessation of elongation (Itoh *et al.*, 1987). Ionic stress in saline soil is due to high concentrations of Na^+, Mg^{2+}, Cl^- and SO_4^{2-} and, in some soils, a toxic concentration of boron (Kafkafi, 1991). Ionic imbalance due to high concentrations of salts may cause slow root extension in the soil (Roundy, 1985). The reduction in root elongation due to salinity prevents the amount of ions that move by diffusion toward the root from reaching the plant in the quantities required, and consequently reduces water and nutrient uptake.

Several studies (Bernstein and Francois, 1975; Singh *et al.*, 1978; Meiri and Plaut, 1985) indicate that irrigation water with total salt concentrations of approximately 2 g/liter can be used successfully in drip irrigation to obtain almost the same yield as non-saline, good quality water. Using the same water for furrow and sprinkler irrigation caused yield reductions of 54 and 94%, respectively. The reduced salinity hazard under drip irrigation can be related to the efficient displacement of salts to the periphery of the wetted soil volume and to the reduction in salt concentration because the higher irrigation frequency maintains a high soil water content.

Bernstein and Francois (1973) found that irrigation with saline water results in the lowest concentration of salts immediately below the dripper, and this is also the zone of highest root concentration. Salts accumulate in the surface soil midway between drippers and at the perimeter of the wetted zone. This salt accumulation inhibits root development. The salts that accumulate at the surface midway between drippers may cause injury if rain pushes the salt back into the underlying root zone.

Goldberg *et al.* (1971) studied the effect of drip irrigation on the distribution of carnation roots and minerals in a 3-dimensional soil profile. They found that the concentration of soluble salts is high near the soil surface, and especially at the midpoint between adjacent drippers. This concentration gradually increases if the salt content of the soil or water is high, and if the wetting fronts between the 2 nozzles meet at a greater depth. Root distribution was shallow, mainly to a depth of 10cm and concentrated close to the dripper.

West *et al.* (1979) found that the percentage root distribution was higher immediately below the dripper outlet with increasing salt loading of the root zone. They concluded that an essential factor in the management of drip irrigation under saline conditions is to provide a large enough volume of wet soil with low salt concentration to minimize contact between roots and zones of high salinity. This should prevent growth depression caused by uptake of Na^+ or Cl^- to toxic concentrations, osmotic effects, or restriction of the size of the root system. The work of Tscheschke *et al.* (1974) indicates the importance of avoiding under-irrigation whenever high saline water is used. They found the highest salt concentration occurred in the profile irrigated with volumes of water below the evapotranspiration of tomato plants.

Another factor that may ameliorate salinity stress under drip fertigation is the high and steady nutrient concentrations in the soil root volume. Salinity reduces plant root length and surface area. Under such conditions high and steady nutrient concentrations in the fertigated soil volume may partially compensate for the expected decline in uptake rate by the plant (Bar-Yosef, 1999).

2.5 Conclusion

Research has established basic knowledge on how drip fertigation influences soil water content, soil characteristics and root distribution. However, substantially more research is required to improve upon current practices. Research is needed on the following topics: different ways to rectify acidification beneath a dripper, how to increase oxygen concentration directly beneath the dripper and how different soil types react to fertigation.

Careful management of water and nutrients applied through a drip system is required to prevent excessive leaching losses. A system capable of continuously monitoring changes in the soil water content, at different positions from the dripper, makes it possible to investigate the actual water distribution beneath a dripper. This may help to point the direction to more efficient water and nutrient management techniques.

Literature cited

Abruna, F., Pearson, R.W. & Elkins, C.B., 1958. Quantitative evaluation of soil reaction and base status changes resulting from field application of residually acid-forming nitrogen fertilizers. *Soil Sci. Soc. Amer. Proc.* **22:** 539-542.

Araujo, F., Williams, L.E., Grimes, D.W. & Matthews, M.A., 1995. A comparative study of young 'Thompson Seedless' grapevines under drip and furrow irrigation. I. Root and soil water distributions. *Scientia Hortic.* **60:** 235-249.

Atkinson, D., 1980. The distribution and effectiveness of the roots of tree crops. *Hort. Rev.* **9:** 424-490.

Barber, S.A., 1967. Liming materials and practices. pp. 125-160. **In**: Pearson, R.W. and Adams, F. (eds.). *Soil acidity and liming*. American Society of Agronomy, Madison, Wisconsin.

Bar-Yosef, B., 1977. Trickle irrigation and fertilization of tomatoes in sand dunes: Water, N, and P distribution in the soil and uptake by plants. *Agron. J.* **69:** 486-491.

Bar-Yosef, B., 1999. Advances in fertigation. *Adv. Agron.* **65:** 1-77.

Bar-Yosef, B., Schwartz, S., Markovich, T., Lucas, B. & Assaf, R., 1988. Effect of root volume and nitrate solution concentration on growth, fruit yield, and temporal N and water uptake rates by apple trees. *Plant and Soil* **107:** 49-56.

Benami, A. & Ofen, A., 1984. **In:** Benami, A. & Ofen, A. (eds.) *Irrigation Engineering: Sprinkler, trickle, surface irrigation. Principles, design and agricultural practices*. Irrigation Engineering Scientific Publications, Israel.

Bernstein, L. & Francois, L.E., 1973. Comparisons of drip, furrow, and sprinkler irrigation. *Soil Sci.* **115:** 73-86.

Bernstein, L. & Francois, L.E., 1975. Effects of frequency of sprinkling with saline waters compared with daily drip irrigation. *Agron. J.* **67:** 185-190.

Bevington, K.B. & Castle, W.S., 1985. Annual root growth pattern of young citrus trees in relation to shoot growth, soil temperature, and soil water content. *J. Amer. Soc. Hort. Sci.* **110:** 840-845.

Blevins, R.L., Thomas, G.W. & Cornelius, P.L., 1977. Influence of no-tillage and nitrogen fertilization on certain soil properties after 5 years of continuous corn. *Agron. J.* **69:** 383-386.

Bolan, N.S., Hedley, M.J. & White, R.E., 1991. Processes of soil acidification during nitrogen cycling with emphasis on legume based pastures. *Plant and Soil* **134:** 53-63.

Bouman, O.T., Curtin, D., Campbell, C.A., Biederbeck, V.O. & Ukrainetz, H., 1995. Soil Acidification from long-term use of anhydrous ammonia and urea. *Soil Sci. Soc. Amer. J.* **59:** 1488-1494.

Bowen, J.E., 1969. Absorption of copper, zinc and manganese by sugarcane leaf tissue. *Plant Physiol.* **44:** 255-261.

Bowman, R.S. & Nakayama, F.S., 1986. Design principles: Salt distribution. pp. 117-141. **In**: Nakayama, F.S. & Bucks, D.A. (eds.). *Trickle irrigation for crop production: Design, Operation and Management*. Developments in Agricultural Engineering, Elsevier, Amsterdam.

Boynton, D, DeVilliers, J. & Reuther, W., 1938. Are there different critical oxygen concentrations for the different phases of root activity. *Science* **88.** 569-570.

Brandt, A. Bresler, E., Diner, N., Ben-Asher, I., Heller, J. & Goldberg, D., 1971. Infiltration from a trickle source: I. Mathematical models. *Soil Sci. Soc. Amer. Proc.* **35:** 671-674.

Bresler, E., 1977. Trickle-drip irrigation: Principles and application to soil-water management. *Adv. Agron.* **29:** 343-393.

Bresler, E., Heller, J., Diner, N., Ben-Asher, I., Brandt, A. & Goldber, D., 1971. Infiltration from a trickle source: II. Experimental data. *Soil Sci. Soc. Amer. Proc.* **35:** 675-682.

Bresler, E. Yaron, D., 1972. Soil water regime in economic evaluation of salinity in irrigation. *Water Resour. Res*. **8**: 791-800.

Chiasson, T.C., 1964. Effects of N, P, Ca and Mg treatments on yield of barley varieties grown on acid soils. *Can. J. Plant Sci.* **44:** 525-530.

Christiansen, M.N., Carns, H.R. & Slyter, D.J., 1970. Stimulation of solute loss from radicles of *Gossypium hirsutum* L. by chilling, anaerobiosis, and low pH. *Plant Physiol.* **46:** 53-56.

Clark, R.B., Pier, P.A., Knudsen, D. & Maranville, J.W., 1981. Effects of trace element deficiencies and excesses on mineral nutrients in sorghum. *J. Plant Nutr.* **3:** 357-374.

Coleman, N.T. & Thomas, G.W., 1967. The basic chemistry of soil acidity. pp. 1-41. **In**: Pearson, R.W. and Adams, F. (eds.). *Soil acidity* and *liming*. American Society of Agronomy, Madison, Wisconsin.

Cregan, P.D., Hirth, J.R. & Conyers, M.K., 1989. Amelioration of soil acidity by liming and other amendments. pp. 205-264. **In**: Robson, A.D. (ed.). *Soil acidity and plant growth*. Academic press, Australia.

Dasberg, S., Bielorai, H. & Erner, Y., 1981. Partial wetting of the root zone and nitrogen effects on growth, yield and quality of shamouti oranges. *Acta Hort.* **119:** 103-107.

Dexter, A.R., 1987. Compression of soil around roots. *Plant and Soil* **97:** 401-406.

Drew. M.C. & L.H. Stolzy., 1996. Growth under oxygen stress. Pp. 331-350. **In**: Waisel,Y., Eshet, A. & Kfkafi, U. (eds.). *Plant roots: The hidden half*. Marcel Dekker, New York.

Edwards, J.H., Bruce, R.R., Horton, B.D., Chesness, J.L. & Wehunt, E.J., 1982. Soil cation and water distribution as affected by NH_4NO_3 applied through a drip irrigation system. *J. Amer. Soc. Hort. Sci.* **107:** 1142-1148.

Elfving, D.C., 1982. Crop response to trickle irrigation. *Hort. Rev.* **4:** 1-48.

Ellis, F.B. & Barnes, B.T., 1980. Growth and development of root systems of winter cereals grown after different tillage methods including direct drilling. *Plant and Soil* **55:** 283-295.

Erez, A., Ran,Y. & Bar-Yosef, B., 1992. The effect of restricted root volume on the development, yield and dry matter partitioning of young fruiting peach trees. *Acta Hort.* **322:** 199-207.

Evans, C.E. & Kamprath, E.J., 1970. Lime response as related to percent aluminium saturation, solution aluminium and organic matter content. *Soil Sci. Soc. Amer. Proc.* **34:** 386-896.

Foy, C.D., 1974. Effects of Aluminium on plant growth. pp. 601-642. **In**: Carson, E.W. (ed.). *The Plant Root and Its Environment*. University Press of Virginia, Charlottesville.

Foy, C.D., 1992. Soil chemical factors limiting plant root growth. *Adv. Soil Sci.* **19:** 97-149.

Foy, C.D. & Brown, J.C., 1963. Toxic factors in acid soils I. Characterization of aluminium toxicity in cotton. *Soil Sci. Soc. Amer. Proc.* **27:** 403-407.

Foy, C.D. & Fleming, A.L., 1982. Aluminium tolerance of two wheat genotypes related to nitrate reductase activities. *J. Plant Nutr.* **5:** 1313-1333.

Fulton, J.M. & Erickson, A.E., 1964. Relation between soil aeration and ethyl alcohol accumulation in xylem exudate of tomatoes. *Soil Sci. Soc. Amer. Proc.* **28:** 610-614.

Furlani, P.R., & Clark, R.B., 1981. Screening sorghum for aluminium tolerance in nutrient solution. *Agron. J.* **73:** 587-594.

Gardner, H.R. & Danielson, R.E., 1964. Penetration of wax layers by cotton roots as affected by some soil physical conditions. *Soil Sci. Soc. Amer. Proc.* **28:** 457-460.

Goldberg, S.D., Ben-Asher, J. & Gornat, B., 1976. Soil and plant water status under sprinkling and trickling. *Agric. Water Manage.* **1:** 33-40.

Goldberg, S.D., Gornat, B. & Bar, Y., 1971. The distribution of roots, water and minerals as a result of trickle irrigation. *J. Amer. Soc. Hort. Sci.* **96:** 645-648.

Goode, J.E., Higges, K.H. & Hyrycz, K.J., 1978. Trickle irrigation of apple trees and the effect of liquid feeding with NO_3^- and K^+ compared with normal manuring. *J. of Hort. Sci.* **53:** 307-316.

Grable, A.R., 1966. Soil aeration and plant growth. *Adv. Agron.* **18:** 57-106.

Harris, D.G. & Van Bavel, C.H.M., 1957. Root respiration of tobacco, corn, and cotton plants. *Agron. J.* **49:** 182-184.

Haynes, R.J., 1985. Principles of fertilizer use for trickle irrigated crops. *Fert. Res.* **6:** 235-255.

Haynes, R.J. & Swift, R.S., 1986. Effects of soil acidification and subsequent leaching on levels of extractable nutrients in a soil. *Plant and Soil* **95:** 327-336.

Haynes, R.J. & Swift, R.S., 1987. Effect of trickle fertigation with three forms of nitrogen on soil pH, levels of extractable nutrients below the emitter and plant growth. *Plant and Soil* **102:** 211-221.

He, Z.L., Alva, A.K., Calvert, D.V., Li, D.J. & Banks, D.J., 1999. Effects of nitrogen fertilization of grapefruit trees on soil acidification and nutrient availability in Riviera fine sand. *Plant and Soil* **206:** 11-19.

Holder, C.B. & Brown, K.W., 1980. The relationship between oxygen and water uptake by roots of intact bean plants. *Soil Sci. Soc. Amer. J.* **44:** 21-25.

Hussain, F., Overstreet R. & Jacobson L., 1954. The influence of hydrogen ion concentration on cation absorption by barley roots. *Plant Physiol.* **29:** 234-237.

Islam, A.K.M.S., Edwards, D.G. & Asher, C.J., 1980. pH optima for crop growth: Results of a flowing nutrient culture experiment with six species. *Plant and Soil* **54:** 339-357.

Itoh, K., Nakamura, Y., Kawata, H., Yamada, T., Ohta, E., & Sakata, M., 1987. Effect of osmotic stress on turgor pressure in mung bean root cells. *Plant Cell Physiol.* **28:** 987-994.

Jacobson, L., Overstreet, R., King, H.M. & Handley, R., 1950. A study of potassium absorption by barley roots. *Plant Physiol.* **25:** 639-647.

Kafkafi. U., 1991. Root growth under stress - Salinity. pp. 375-391. **In**: Waisel,Y., Eshet, A. & Kafkafi, U. (eds.). *Plant roots: The hidden half.* Marcel Dekker, New York.

Kelly, S., 1947. The relationship between respiration and water uptake in the oat coleoptile. *Amer. J. Bot.* **34:** 521-526.

Kerby, E. A. & Knight, A.H., 1977. Influence of the level of nitrate nutrition on ion uptake and assimilation, organic acid accumulation, and cation-anion balance in whole tomato plants. *Plant Physiol.* **60:** 349-353.

Lance, J.C. & Pearson, R.W., 1969. Effect of low concentrations of aluminium on growth and water and nutrient uptake by cotton roots. *Soil Sci. Soc. Amer. Proc.* **33:** 95-98.

Lemon, E.R. & Erickson, A.E., 1955. Principle of the platinum microelectrode as a method of characterizing soil aeration. *Soil Sci.* **79:** 383-392.

Letey, J., Lunt, O.R., Stolzy, L.H. & T.E. Szuszkiewicz, T.E., 1961. Plant growth, water use and nutritional response to rhizosphere differentials of oxygen concentration. *Soil Sci. Soc. Amer. Proc.* **25:** 183-186.

Levin, I., Assaf, R. & Bravdo, B., 1979. Soil moisture and root distribution in an apple orchard irrigated by tricklers. *Plant and Soil* **52:** 31-40.

Levin, I., Assaf, R. & Bravdo, B., 1980. Irrigation, water status and nutrient uptake in an apple orchard. *Acta Hort.* **92:** 255-264.

Lunin, J. & Gallatin, M.H., 1965. Zonal salinization of the root system in relation to plant growth. *Soil Sci. Soc. Amer. Proc.* **29:** 608-612.

Maas, E.V., 1969. Calcium uptake by excised maize roots and interactions with alkali cations. *Plant Physiol.* **44:** 985-989.

Maas, E.V., Moore, D.P. & Mason, B.J., 1968. Manganese absorption by excised barley roots. *Plant Physiol.* **43:** 527-530.

Magistad, O.C., 1925. The aluminium content of the soil solution and its relation to soil reaction and plant growth. *Soil Sci.* **20:** 181-225.

McCart, G.D. & Kamprath, E.J., 1965. Supplying Ca and Mg for cotton on sandy, low cation exchange capacity soils. *Agron. J.* **57:** 404-406.

Meiri, A. & Plaut, Z., 1985. Crop production and management under saline conditions. *Plant and Soil* **89:** 253-271.

Moore, D.P., 1974. Physiological effects of pH on roots. pp. 135-151. **In**: Carson, E.W. (ed.). *The Plant Root a and Its Environment*. University Press of Virginia, Charlottesville.

Moore, D.P., Overstreet, R. & Jacobson, L., 1961. Uptake of magnesium and its interaction with calcium in excised barly roots. *Plant Physiol.* **36:** 290-295.

Neilsen, G.N., Parchomchuk, P., Hogue, E.J., Wolk, W.D. & Lau, O.L., 1994. Response of apple trees to fertigation-induced soil acidification. *Can. J. Plant Sci.* **74:** 347-351.

Nielsen, T.R. & Overstreet, R., 1955. A study of the role of hydrogen ion in the mechanism of potassium absorption by excised barley roots. *Plant Physiol.* **30:** 303-309.

Parchomchuk, P., Neilsen, G.H. & Hogue, E.J., 1993. Effect of drip fertigation of NH^4-N and P on soil pH and cation leaching. *Can. J. Soil Sci.* **73.** 157-164.

Pierre, W.H., Webb, J.R. & Shrader, W.D., 1971. Quantitative effects of nitrogen fertilizer on the development and downward movements of soil acidity in relation to level of fertilization and crop removal in a continuous corn cropping system. *Agron. J.* **63:** 291-297.

Plaut, Z., Carmi, A. & Grava, A., 1988. Cotton growth and production under drip-irrigation restricted soil wetting. *Irrig. Sci.* **9:** 143-156.

Proebsting, E.L., Middleton, J.E. & Roberts, S., 1977. Altered fruiting and growth characteristics of 'Delicious' apple associated with irrigation method. *HortScience* **12:** 349-350.

Rashid, A., Chaudhry, F.M. & Sharif, M., 1976. Micronutrient availability to cereals from calcareous soil. III. Zinc absorption by rice and its inhibition by important ions of submerged soils. *Plant and Soil* **45:** 613-623.

Rawlins, S.L., 1973. Principles of managing high frequency irrigation. *Soil Sci. Soc. Amer. Proc.* **37:** 626-929.

Rickman, R.W., Waldman, S.E. & Klepper, B., 1992. Calculating daily root length density profile by applying elastic theory to agricultural soils. *J. Plant Nutr.* **15:** 661-675.

Rogers, W.S., 1939. Root Studies VIII. Apple root growth in relation to rootsotck, soil, seasonal and climatic factors. *J. Pomol. Hort. Sci.* **17:** 99-130.

Roundy, B.A., 1985. Root penetration and shoot elongation of tall wheatgrass and basin wildrye in relation to salinity. *Can. J. Plant Sci.* **65:** 335-343.

Schwab, A.P., Ransom, M.D. & Owensby, C.E., 1989. Exchange properties of an Argiustoll: Effects of long-term ammonium nitrate fertilization. *Soil Sci. Soc. Amer. J.* **53:**1412-1417.

Silberbush, M., Gornat, B. & Goldberg, D., 1979. Effect of irrigation from a point source (trickling) on oxygen flux and on root extension in the soil. *Plant and Soil* **52:** 507-514.

Singh, S.D., Gupta, J.P. & Singh, P., 1978. Water economy and saline water use by drip irrigation. *Agron. J.* **70:** 948-951.

Taylor, H.M. & Klepper, B., 1974. Water relations of cotton. I. Root growth and water use as related to top growth and soil water content. *Agron. J.* **66:** 584-588.

Taylor, H.M. & Ratliff, L.F., 1969. Root elongation rate of cotton and peanuts as a function of soil strength and soil water content. *Soil Sci.* **108:** 119-119.

Taylor, H.M., Roberson, G.M. & Parker, J.J., 1966. Soil strength-root penetration relations for medium- to coarse-textured soil materials. *Soil Sci.* **102:** 18-22.

Tscheschke, P., Alfaro, J.F., Keller, J. & Hanks, R.J., 1974. Trickle irrigation soil water potential as influenced by management of highly saline water. *Soil Sci.* **117:** 226-231.

Van Breemen, N., Mulder, J. & Driscoll, C.T., 1983. Acidification and alkalinization of soils. *Plant and Soil* **75:** 283-308.

West, D.W., Merrigan, I.F., Taylor, J.A. & Collins, G.M., 1979. Soil salinity gradients and growth of tomato plants under drip irrigation. *Soil Sci.* **127:** 281-291.

West, D.W., Thompson, W.K. and Black, J.D.F., 1970. Polar and lateral transport of water in an apple tree. *Austr. J. Biol. Sci.* **23:** 231-234.

Wiegand, C.L. & Lemon, E.R., 1958. A field study of some plant soil relations in aeration. *Soil Sci. Soc. Amer. Proc.* **22:** 216-221.

Zur, B., 1996. Wetted soil volume as a design objective in trickle irrigation. *Irrig. Sci.* **16:** 101-105.

3. PAPER 1: DRIP FERTIGATION: I. SYSTEM EFFECTS ON WATER MOVEMENT AND ROOT DISTRIBUTION IN SANDY SOILS.

Abstract

The aim of efficient drip irrigation scheduling is to replenish the water deficit within the active root zone while minimizing leaching below this depth. The objective of this study was to determine the water distribution pattern beneath a dripper in sandy soil. EnviroSCAN (Sentek) capacitance probes were installed directly below the dripper and at distances of 20, 40 and 60 cm from the dripper. The continuous monitoring of the soil water content (SWC) beneath the dripper provided a good indication of how the water applied through the dripper is distributed in the soil. In this study a semi-impermeable layer in the soil was detected through observing water accumulation patterns in the SWC. Water accumulated above the layer and SWC values increased to far above the upper level of easily available soil water (EAW_{upper}), while the lower soil layers remained dry. The measurements also show that the horizontal water movement is restricted to 20 cm from the dripper. Specific parameters such as, the lower level of easily available soil water (EAW_{lower}), can be used to determine optimal irrigation management.

Together with the water distribution study, the root distribution beneath a dripper was also investigated. A high concentration of roots in the area beneath the dripper was found, which corresponds with the area wetted by irrigation.

Introduction

The aim of efficient drip irrigation scheduling is to replenish the water deficit within the active root zone while minimizing leaching below this depth. To maintain this, it is necessary to know how water is distributed within the soil after application through a dripper. Knowledge of the shape of wetted volume is important in the design, operation and management of an irrigation system. Together with the knowledge about the wetted volume it is also important to determine the root distribution beneath the dripper, to fine-tune scheduling needs.

The dimensions of the wetted soil volume under a dripper, its width and depth, depend on the hydraulic properties of the soil, the discharge rate of the emitter and the quantity of water applied (Brandt *et al.*, 1971, Bresler *et al.*, 1971). Brandt *et al.* (1971) developed a model to define infiltration and distribution of water into the soil from the dripper. The implication seems to be that at low application rates the wetting pattern will be narrower and deeper than at high application rates.

A system capable of continuously monitoring changes in the soil moisture status, during and after irrigation, at different positions from the dripper makes it possible to investigate the actual water distribution. Such a system is the EnviroSCAN system (EnviroSCAN, Sentek PTY Ltd., South Australia) based on capacitance principles. The capacitance probe measures the apparent dielectric constant of the soil surrounding the sensor in order to measure the water content of the soil-water-air mixture. The dielectric constant of a medium depends upon the polarization of its molecules in an electric field. The dielectric constant of water (80) is larger than that of the soil matrix (<10) or air (1). The soil as a dielectricum is dominated by the water-volume fraction. Therefore, a change of water content will strongly change the dielectric constant of the soil-water-air mixture that will be measured by the sensor. A probe surrounded by soil constitutes the capacitor and measurements of the dielectric constant for soil can be used for estimation of water content. Paltineanu and Starr (1997) have described the EnviroSCAN capacitance probe in more detail.

The aim of this study was to firstly investigate the water distribution beneath a dripper in sandy soils, by means of EnviroSCAN (Sentek) capacitance probes, and secondly to investigate the resulting root distribution in the soil profile.

Materials and methods

The study was conducted on a commercial farm near Gouda in the Western Cape area of South Africa (33.5°S, °19E; mediterranean climate). 'Nules Clementine' mandarin trees (*C. reticulata* Blanco) on 'Troyer' rootstock were established in December 1998. Before the trees were established, the soil was ripped and subsequently ridged with about 30 cm of soil on top of the original ground level. The trees were irrigated using a pressure compensating drip system with one dripper per tree delivering 1.6 $l.h^{-1}$. The dripper was positioned close to the tree stem, as is usually done with young trees. A balanced nutrient solution was applied through the drip system with each irrigation. The dripper line is placed directly on the soil surface so that the area of infiltration is very small compared with the total soil surface.

The soil is classified as a Tukulu (Soil Classification Working Group, 1991) soil and the texture class as a sandy soil. The textural composition of the soil is as follows: 95% sand, 2.8% silt and 2.2% clay content (Table 1), with an average bulk density of 1.57 g.cm^{-3} for the whole profile (Table 2).

[Tables 1 and 2]

Soil water content

Soil water content was monitored using EnviroSCAN capacitance soil moisture probes. Four probes, probe A, B, C, and D were installed at four different measuring positions, respectively 0, 20, 40 and 60 cm away from the dripper, against the row direction. Each probe have five sensors at five measuring depths: 10, 20, 30, 40 and 50 cm beneath soil surface (Figure 1). During installation, the probes were lowered into a PVC access tube, which remained *in situ* permanently for the desired period of time. The PVC access tube was installed into a slightly undersized hole that was hand augered using specially-designed augers for sand and clay textures. Sensors, powered via a solar panel and a storage battery, were programmed to record the soil moisture content at each depth every 10 minutes. Soil water content data was continuously recorded, from 1 April to 31 May 2000, on a data logger, and the data was periodically downloaded to a laptop computer.

[Figure 1]

Percentage volumetric soil water content (Table 3) is the volumetric soil water content multiplied by 100. In this paper the term "soil water content" (SWC) will be used to refer to "percentage volumetric soil water content". The soil in this study was saturated at a SWC value of 40.75 m^{3}.m^{-3} x 100. The SWC at the upper level of easily available water

(EAW_{upper}) or field capacity (FC) for this soil was calculated, using equations from the WRC report no. 144/1/88 (Bennie, 1988), as 15.75 m $m^3.m^{-3}$ x 100 (equation 2.3: $EAW_{upper} = 0.0037 [S + K\%] + 0.139$). Field capacity denotes the amount of water held in the soil against gravity, i.e. after the excess water has been leached following irrigation or rainfall (Veihmeyer and Hendrickson, 1949). The lower level of easily available water (EAW_{lower}) was 14 $m^3.m^{-3}$ x 100, calculated at a matric suction of 100kPa. Between the EAW_{upper} and EAW_{lower} water is easily available for absorption by plant roots. Below EAW_{lower} it becomes difficult for the roots to absorb water from the soil and water stress will occur below this SWC. The permanent wilting point (PWP) for this soil was calculated as 3.17 $m^3.m^{-3}$ x 100 (equation 2.4: $PWP = 0.00385 [S + C\%] + 0.013$). At PWP the plants would be subject to severe moisture stress.

[Table 3]

Three scenarios (treatments) were chosen to investigate what happens with water applied through a dripper: a day with no irrigation, a day with one irrigation pulse and a day with two irrigation pulses. Three consecutive days were chosen for these treatments: 8, 9 and 10 April 2000. On 8 April there was no irrigation, on 9 April there was one irrigation pulse of 100 min and on 10 April there were two irrigation pulses, the first one lasted 60 minutes and the other 50 minutes, with 10 hours of no irrigation in-between.

Root distribution

Three root distribution maps were drawn, one at the exact position where the probes were installed and two in the same row as the EnviroSCAN, one perpendicular and one parallel to the dripper line. Root distribution was quantified using the trench profile method

(Böhm, 1979). Trenches were opened directly beneath the dripper. The roots were exposed by removing a soil layer of approximately 5-10 mm with a knife and water stream using a hand sprayer. A grid with 10 x 10 cm^2 blocks was mapped on the profile wall, using nails. The exposed root cut-off points were then mapped in their natural position.

Results and discussion

Water distribution

Contour graphs were used to provide a visual presentation of the change in SWC at the different measuring positions during the chosen days. Contour graphs are provided for every hour of a 24-hour day, except for the duration of irrigation and one hour thereafter, during which a graph for every 10 minutes is shown. The contour graphs for 8, 9 and 10 April are respectively shown in Figures 2, 3 and 4. Line graphs (Figure 5) provide an overview of the changes in the SWC on the three days.

[Figures 2, 3, 4 and 5]

In Tables 4.1, 5.1 and 6.1 the soil water content values of the three days are given at the chosen times. In Tables 4.2, 5.2 and 6.2 the difference between the consecutive values in Tables 4.1, 5.1 and 6.1 are given. A negative sign indicates a reduction in SWC and positive values represent an increase in SWC. Any increases in SWC in these days were due to the redistribution of irrigation water, since no rainfall occurred. The redistribution of water from one sensor to the other had a reducing effect on the source and an increasing effect on the sink. The reduction in SWC can be ascribed to various possible factors. These factors include transpirational loss via the plant, evaporation from the soil surface, drainage and redistribution from the measured soil volume. It is impossible to quantify which part of the total reduction can be allocated to each factor. Therefore, only the total reduction will be used, which constitutes a combination of all the listed factors.

Firstly the probe closest to the dripper, then the probe 20 cm away and lastly the two probes the furthest away from the dripper will be discussed.

Probe-A (0 cm away from the dripper)

Prior to presenting changes in soil water content, it is necessary to explain some features of the soil profile at the position of probe-A. Between 30 and 40cm beneath the soil surface a semi-impermeable layer was detected, which did not let the water through easily. This can be seen from the high SWC at the 30cm-layer and the sudden drop in SWC at the 40cm-layer. A possible cause of this impermeable layer can be due to a change in soil texture. At this position the percentage coarse sand (2.0-0.5mm) was high, 40.54%, compared to the 33.56%, 30.79% and 29.23%, respectively, at 10, 20, and 30 cm beneath the soil surface (Table 1). It is known that a sudden change in texture can create an impermeable layer for water movement. This layer may be the transition between the ridged soil and the original ground level. This change was visually easy to detect and can be seen in Figure 6. Proof of this accumulation can also be found in the values of SWC. The SWC at field capacity (FC) for this soil is 15.75 $m^3.m^{-3}$ x 100. Above this value the soil becomes saturated and free water will exist in the soil pores that easily moves down to the next soil layer. This could be seen at the 10cm- and 20cm-layers, where the SWC increased above FC and then reduced again as the free water moved to the next layer. In comparison, at the

30cm-layer, the SWC increased to far above FC and remained high while the layer below it showed only a small increase in SWC.

[Figure 4]

On **8 April** there was no irrigation event and the water that was removed from the measured volume was the water applied through the irrigation event on the previous day. The SWC values at the 10cm-, 20cm-, 40cm- and 50cm-layers were below the EAW_{lower} level throughout the day (Table 4.1). At these levels the water was not easily available for absorption by the plant roots. The SWC at the 30cm-layer early on 8 April was above EAW_{upper} at 18.97 $m^3.m^{-3}$ x 100 and decreased to a value of 15.55 $m^3.m^{-3}$ x 100, which was still above EAW_{lower}. Thus, in the 30cm-layer, the plant roots were able to easily absorb water throughout the day. It was also noted that the reduction in SWC was the highest at this layer. The total reduction of the entire volume measured by probe-A was 11.45 $m^3.m^{-3}$ x 100. The reduction of the 10cm-, 20cm-, 30cm-, 40cm- and 50cm-layers were respectively 3.18, 2.80, 3.42, 1.19 and 0.86 $m^3.m^{-3}$ x 100 (Table 4.2).

[Tables 4.1 and 4.2]

On **9 April** there was one irrigation pulse of 100 min (2.66 litres water applied) from 10:20 until 12:00. This pulse was first detected at 10:20 by the sensor in the ***10cm-layer***. The 10cm-layer increased to above EAW_{lower} after 20 minutes of irrigation and increased further to above EAW_{upper} after another 10 minutes. Irrigation stopped at 12:00 and the SWC started to decrease but stayed above EAW_{upper} until 13:00. Between 13:00 until 16:00 the SWC was above EAW_{lower} (Table 5.1). Thus, between 10:40 and 16:00 (320 min) the sensor in the 10cm-layer measured a SWC above EAW_{lower}. During irrigation the

SWC increased by 7.52 $m^3.m^{-3}$ x 100 and decreased afterwards by 5.31 $m^3.m^{-3}$ x 100. Together with the decrease of 0.57 $m^3.m^{-3}$ x 100 before irrigation, the net change in SWC at the 10cm layer during the day was an increase of 1.62 $m^3.m^{-3}$ x 100 (Table 5.2 and 7).

[Tables 5.1, 5.2 and 7]

Twenty minutes after irrigation started, at 10:40, the sensor in the ***20cm-layer*** showed the first increase as the water started to move downwards. Twenty minutes later, at 11:00, the SWC level increased to above EAW_{lower} and within another 10 minutes the values increased to above EAW_{upper}. The SWC stopped to increase at 12:00 but stayed above EAW_{upper} until 12:50. From 13:00 until 15:00 the SWC was above EAW_{lower} (Table 5.1). Thus, between 11:00 and 15:00 (240 min) the sensor in the 20cm-layer measured a SWC above EAW_{lower}. The SWC increase during irrigation was 7.61 $m^3.m^{-3}$ x 100 and afterwards decreased by 5.78 $m^3.m^{-3}$ x 100. Together with the decrease of 0.53 $m^3.m^{-3}$ x 100 before irrigation, the net change in SWC at the 20cm layer was an increase of 1.31 $m^3.m^{-3}$ x 100 (Table 7).

Forty minutes after irrigation started, at 11:00, the ***30cm-layer*** started to show an increase in SWC. This SWC of this layer did not drop below EAW_{lower} before irrigation started. After 10 minutes of irrigation the SWC increased to above EAW_{upper} values. The SWC increased to 22.72 $m^3.m^{-3}$ x 100 before it started to decrease again and stayed above EAW_{upper} for the rest of the day (Table 5.1). Thus, the SWC of this layer was above EAW_{lower} for the whole day. Although irrigation stopped at 12:00 and the reduction was immediately seen in the upper two soil layers, the SWC at this layer and the 40cm- and 50cm-layers still showed an increase. This took place while free water from the upper layers still moved downwards after irrigation had stopped. This soil layer showed the highest increase in SWC as a result of irrigation (7.86 $m^3.m^{-3}$ x 100), but also the highest decrease (5.92 $m^3.m^{-3}$ x 100), after irrigation. This high increase was due to the semi-impermeable layer that caused the water to accumulate at this position. Together with the decrease of 0.69 $m^3.m^{-3}$ x 100 before irrigation, the net change in SWC at the 30cm layer was an increase of 1.24 $m^3.m^{-3}$ x 100 (Table 7).

The sensors in the ***40cm- and 50cm-layers*** started showing an increase in SWC at respectively 11:10 and 12:00. The increase of respectively 2.03 $m^3.m^{-3}$ x 100 and 0.67 $m^3.m^{-3}$ x 100 was small compared to the increase of the top three layers. This was due to the semi-impermeable layer above these sensors that did not readily allow water infiltration. The SWC values did not approximate the EAW_{lower} value (Table 5.1).

The total increase of the entire volume measured by probe-A was 25.70 $m^3.m^{-3}$ x 100, whereas the total reduction after irrigation was 18.47 $m^3.m^{-3}$ x 100. The net change at probe-A on 9 April was an increase of 4.82 $m^3.m^{-3}$ x 100 (Table 7). However, the total cumulative change in SWC from the beginning of 8 April until the end of 9 April was a reduction of 6.63 $m^3.m^{-3}$ x 100. Although the pulse on 9 April increased the SWC on that day, the reduction on 8 April was not fully eliminated by this increase.

On **10 April** there were two irrigation pulses, the first one lasted 60 minutes (1.6 litres water applied) from 7:10 until 8:10 and the second one 50 minutes (1.33 litres water applied) from 17:10 until 18:00. The water applied through these pulses showed the same stepwise downward movement as seen in the pulse of 9 April.

The SWC at the 10cm-layer was above EAW_{lower} from 7:30 until 12:10 (280 min) due to the first pulse and from 17:20 until 23:20 (360 min) as a result of the second pulse. For the same reasons the SWC at the 20cm-layer was above EAW_{lower} from 7:50 until 11:00 (190 min) and from 17:40 until 21:10 (210 min). The SWC at the 30cm-layer was above EAW_{upper} for the entire day. As was the situation on 9 April, the SWC at the 40cm- and 50cm-layer did again not increase to above EAW_{lower} (Table 6.1). As expected, the increases of these pulses were smaller than the increase of the 100min pulse on 9 April. The total increases of the 60 and 50 minute pulses were 17.83 and 14.77 $m^3.m^{-3}$ x 100 (Table 6.2) respectively. The difference between these shorter pulses and the longer pulse on 9 April was that the 30cm-layer did not show the highest increase in SWC, as was the case on 9 April. With both pulses on 10 April, the 20cm-layer showed the highest increase in SWC with the 10cm-layer only slightly lower. A possible explanation can be that the longer pulse on 9 April kept the SWC of the 20cm-layer for a longer period above EAW_{upper}. Thus, more free water was able to freely move down to the 30cm-layer and accumulate there. The total change at probe-A on 10 April was an increase of 5.23 $m^3.m^{-3}$ x 100 (Table 7). The total cumulative change in SWC over the three days was a reduction of 1.40 $m^3.m^{-3}$ x 100. At the end of the three days the SWC was almost the same as it was at the start.

[Tables 6.1 and 6.2]

Probe-B (20cm away from dripper)

The soil profile at this point does not show the same features as at probe-A. The difference is that the accumulation of water at the 30cm-layer of probe-A was instead seen at the 40cm-layer of this probe B. The impermeable layer appears to be broken or more permeable at 30cm and reappear at 40cm. This can be seen from the fact that the SWC at the 40cm-layer was higher than EAW_{upper}, while the SWC at the 50cm-layer was far below that.

On **8 April** there was a total decrease of 6.83 $m^3.m^{-3}$ x 100 from the entire volume measured by probe-B. The 30cm-layer had the largest decrease of 1.73 $m^3.m^{-3}$ x 100 followed by 1.66, 1.40, 1.25 and 0.8 $m^3.m^{-3}$ x 100 for respectively the 10cm-, 20cm-, 40cm- and 50cm-layers (Table 4.2). The SWC of the 10cm-, 20cm- and the 50cm-layers was below EAW_{lower}. The SWC at the 30cm-layer started above EAW_{lower} and stayed there until 10:00, while the SWC at 40cm-layer was above EAW_{upper} for the entire day (Table 4.1).

On **9 April**, with the 100 minute pulse, all the layers showed an increase, but the increases at this probe were much smaller than at probe A (Table 7). The total increase at probe-B was 2.69 $m^3.m^{-3}$ x 100. These small increases at 20cm from the dripper indicate the low unsaturated hydraulic conductivity of this sandy soil. In a sandy soil like this, the horizontal conductivity of micropores is not fast enough to conduct the water horizontally through capillary forces and water moves mainly vertically due to gravitational forces and a difference in soil water potential. The stepwise increase in SWC from the upper layers to the lower layers was also detected at this probe. However, the increase in SWC at the 10cm- layer of probe-B started 50 minutes later than the start of the increase at the 10cm-layer of probe-A. This was the amount of time the water needed to move 20cm in a horizontal direction. Only the SWC at the 40cm-layer was above EAW_{lower} (Table 5.1). This indicates the accumulation of water above the semi-impermeable layer at this position. The increase in SWC at this layer was smaller than at the top three layers, but much larger than the layer below it. The total change at probe-B on 9 April was a small reduction of 0.03 $m^3.m^{-3}$ x 100 (Table 7).

The two pulses on **10 April,** were almost a repetition of the pulse on 9 April, except that the changes were smaller, as expected. The total increases of the 60 and 50 minute pulses were, respectively, 1.55 and 1.68 $m^3.m^{-3}$ x 100 (Table 7), compared with the 2.7 $m^3.m^{-3}$ x 100 of the 100min pulse on 9 April. The total change at Probe-B on 10 April was an increase of 1.45 $m^3.m^{-3}$ x 100 (Table 7). However, the total cumulative change in SWC from the beginning of 8 April until the end of 10 April was a reduction of 5.41 $m^3.m^{-3}$ x 100. Thus, the three shorter pulses on 9 and 10 April were not able to replenish the water removed on 8 April.

Probes C and D (40 and 60cm away from the dripper)

The SWC measured by the sensors on these probes were not affected by an irrigation event and stayed very stable over the three days (Fig 3). The conduction of water through micropores was not fast enough to conduct the water this far horizontally through capillary forces. The SWC values were all below 9 $m^3.m^{-3}$ x 100. At these values there is no easily available water for the plant. The total decreases on 8, 9 and 10 April were, respectively, 0.19, 0.32 and 0.32 $m^3.m^{-3}$ x 100 for probe-C and 0.12, 0.08, and 0.13 $m^3.m^{-3}$ x 100 for probe-D (Table 7). The water that was removed from this volume of soil was water that had entered through rain on earlier days.

Root distribution

The root distribution of the profile where the probes were installed can be seen in Figure 6. The highest root concentration was in the vicinity of the dripper, with 83% of the roots found in an area 20 cm sideways and 60 cm downwards from the dripper, which is about 19% of the total profile wall area. As seen in the results of the water distribution this was also the extent for water distribution. The high concentration of roots in the 40 x 60 cm area beneath the dripper was also found in the other profile walls with 52% and 66% in, respectively, the profile wall parallel (Figure 7) and perpendicular (Figure 8) to the dripper line. There was no evidence of root decay in the soil profile. There was also some root development outside the wetted zone.

[Figure 5 and 6]

Conclusion

The continuous monitoring of the SWC beneath a dripper provided a good indication of how the water applied through a dripper is distributed in the soil. In this study a semi-impermeable layer in the soil was detected through observing water accumulation patterns in the SWC. The impact of a layer like this is clearly seen in this study. Water accumulated above this layer and SWC values increased to far above EAW_{upper}, while the lower soil layers remained dry. There is a risk of a water table developing above the semi-impermeable layer and it is important to take it in consideration with irrigation scheduling. This shows the importance of studying the soil profile, to know whether there are any physical soil factors that will influence the water distribution through the soil. The measurements also show that the horizontal water movement is restricted to 20cm from the dripper. This indicates that the water flow is mainly in a vertical direction. In the event that there is no impermeable layer, leaching losses in a sandy soil like this can be very high. The texture class of the soil should be taken into consideration when designing the irrigation system.

The continuous monitoring of the changes in SWC during and after irrigation can help to determine the optimal irrigation management. Specific parameters like EAW_{upper} and EAW_{lower} can be used to divide SWC into different levels. By analyzing the water distribution patterns, the time that the SWC (in a specific soil layer) will be at a certain level can be calculated. This information can be used to determine when the plant will experience water stress, how much irrigation time is necessary to replenish the SWC to an optimal level and how long after irrigation the SWC will be at this level.

Root distribution studies provide an indication of how effective water and nutrients can be absorbed. In this study, the high root concentration in the 40 x 60 cm area beneath the dripper corresponds with the area wetted by irrigation. However, the dripper was positioned close to the tree stem where the roots of a young tree are expected to be. Therefore, it is difficult to isolate the influence of water distribution on root distribution. It can be concluded that the practice of positioning the dripper at the stem of young trees is correct, because the water is applied to the active root zone. However, it is important to move the dripper line away from the tree stem after the root system have been established to decrease the chances of root disease development, such as *Phytophthora* root rot. The lack of root decay indicates that there was no problem with root diseases or oxygen deficiency. Oxygen controls root respiration and is essential for good root development (Harris and Van Bavel, 1957). It has been reported (Silberbush *et al.*, 1979) that drip irrigation can cause an insufficient oxygen supply in the vicinity of the drippers. In our case, short irrigation pulses probably overcame problems with oxygen deficiencies. By using short pulses, the time of saturation beneath the dripper is shortened and after a pulse air was drawn into the soil pores to aerate the soil again.

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Literature cited

Bennie, A.T.P., Coetzee, M.J., van Antwerpen, R., van Rensburg, L.D. & Burger, R. du T., 1988, *'n Waterbalansmodel vir besproeiing gebaseer op profielwatervoorsieningstempo en gewaswaterbehoefe*s. Verslag 144/1/88 aan die Waternavorsingskommissie, Departement Grondkunde, Universiteit van die Oranje-Vrystaat, Bloemfontein.

Böhm, W., 1976. Methods of studying root systems. 33: 39-76. **In:** Billings, W.D., Golley, F., Lange, O.L. and Olsen, J.S. (eds.). Springer–Verlag, Heidelberg, New York.

Brandt, A. Bresler, E., Diner, N., Ben-Asher, I., Heller, J. & Goldberg, D., 1971. Infiltration from a trickle source: I. Mathematical models. *Soil Sci. Soc. Amer. Proc.* **35:** 671-674.

Bresler, E., Heller, J., Diner, N., Ben-Asher, I., Brandt, A. & Goldberg, D., 1971. Infiltration from a trickle source: II. Experimental data. *Soil Sci. Soc. Amer. Proc.* **35:** 675-682.

Harris, D.G. & Van Bavel, C.H.M., 1957. Root respiration of tobacco, corn, and cotton plants. *Agron. J.* **49:** 182-184.

Paltineanu, I.C. & Starr, J.L., 1997. Real-time soil water dynamics using multisensor capacitance probes: Laboratory Calibration. *Soil. Sci. Soc. Amer. J.* **61:** 1576-1585.

Silberbush, M., Gornat, B. & Goldberg, D., 1979. Effect of irrigation from a point source (trickling) on oxygen flux and on root extension in the soil. *Plant and Soil* **52:** 507-514.

Soil Classification Working Group, 1991. Soil classification - a taxonomic system for South Africa. Memoirs on the Agricultural Natural Resources of South Africa No. 15. Department of Agricultural Development. Pretoria

Veihmeyer, F.J.& Hendrickson A.H., 1949. Methods of measuring field capacity and wilting percentage of soils. *Soil Sci.* **68:**75-94.

Table 1. Percentage particle size distribution analysis for the soil where the EnviroSCAN probes were installed. The samples were taken at the sensors' positions (10, 20, 30, 40 and 50 cm beneath the soil surface) of probe A and C.

Particle size (mm)	Percentage particle size distribution at sample positions.										
	Probe A					Probe C					
	10cm	20cm	30cm	40cm	50cm	10cm	20cm	30cm	40cm	50cm	aver.
sand fraction											
coarse: 2.00 - 0.50	33.56	30.79	29.23	40.54	43.02	32.24	29.54	42.23	36.96	31.99	33.81
medium: 0.50 - 0.25	24.47	30.01	33.46	31.90	20.70	27.58	26.79	23.69	34.07	27.62	28.73
fine: 0.25 - 0.10	28.11	28.26	28.91	20.41	24.30	28.12	30.46	23.84	21.55	27.90	26.69
very fine: 0.10 - 0.05	7.45	6.14	4.82	3.64	6.37	6.42	7.44	5.33	4.05	7.13	5.88
silt + clay fraction											
coarse silt: 0.05 - 0.02	2.15	0.95	0.87	0.03	1.34	1.95	1.60	0.73	0.06	1.60	1.13
fine silt: 0.02 - 0.002	1.41	1.81	0.60	1.80	1.41	1.81	1.81	2.21	2.21	1.61	1.67
clay: < 0.002	2.82	2.01	2.21	1.80	2.82	2.01	2.41	2.21	1.40	2.41	2.21

Table 2. The soil density (g.cm^{-3}) at the position of each sensor.

	Probe			
Depth (cm)	A	B	C	D
10	1.51	1.51	1.60	1.53
20	1.44	1.57	1.56	1.58
30	1.48	1.42	1.61	1.72
40	1.46	1.59	1.67	1.67
50	1.58	1.63	1.74	1.59
Average of the profile				1.57

Table 3. Percentage volumetric soil water content ($m^3.m^{-3}$ x 100) of different soil parameters.

Saturation point	40.75
Easily Available soil Water, upper level (EAW_{upper}) / Field Capacity	15.75
Easily Available soil Water, lower level (EAW_{lower})	14.00
Permanent Wilting Point (PWP)	3.17

Table 4.1. The hourly volumetric soil water content values ($m^3.m^{-3}$ x 100) of the four probes with each measuring depth (10, 20, 30, 40, 50 cm) beneath the soil surface on 8 April (no irrigation event).

Probe	Depth	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
A	10	13.89	13.75	13.61	13.48	13.36	13.25	13.14	13.04	12.95	12.84	12.77	12.73	12.58	12.39	12.18	11.95	11.72	11.49	11.30	11.15	11.04	10.94	10.85	10.78	10.71
	20	13.02	12.84	12.67	12.53	12.40	12.27	12.16	12.05	11.95	11.84	11.73	11.60	11.46	11.32	11.17	11.02	10.86	10.71	10.60	10.52	10.45	10.38	10.33	10.27	10.22
	30	18.97	18.74	18.53	18.32	18.14	17.96	17.80	17.67	17.52	17.39	17.24	17.09	16.93	16.76	16.59	16.43	16.27	16.14	16.02	15.93	15.84	15.77	15.69	15.62	15.55
	40	9.75	9.67	9.60	9.54	9.47	9.42	9.36	9.31	9.26	9.20	9.15	9.08	9.02	8.96	8.90	8.84	8.79	8.74	8.71	8.69	8.66	8.64	8.61	8.59	8.56
	50	7.83	7.77	7.72	7.67	7.62	7.58	7.54	7.50	7.46	7.42	7.37	7.33	7.28	7.23	7.19	7.15	7.11	7.08	7.07	7.05	7.04	7.02	7.00	6.99	6.97
	total	63.46	62.77	62.14	61.54	60.99	60.47	60.00	59.56	59.14	58.70	58.26	57.83	57.27	56.66	56.02	55.38	54.74	54.16	53.69	53.33	53.02	52.74	52.49	52.24	52.02
B	10	11.20	11.12	11.05	10.98	10.92	10.85	10.80	10.75	10.69	10.65	10.61	10.57	10.53	10.47	10.39	10.29	10.19	10.08	9.98	9.88	9.79	9.71	9.65	9.59	9.54
	20	12.76	12.67	12.60	12.52	12.46	12.40	12.34	12.29	12.23	12.18	12.13	12.06	12.01	11.95	11.89	11.82	11.75	11.68	11.63	11.58	11.53	11.48	11.44	11.40	11.36
	30	14.90	14.78	14.67	14.57	14.48	14.39	14.31	14.23	14.16	14.08	14.02	13.95	13.89	13.81	13.75	13.69	13.62	13.56	13.50	13.44	13.38	13.32	13.27	13.21	13.17
	40	16.23	16.15	16.07	16.00	15.93	15.86	15.80	15.75	15.69	15.64	15.60	15.54	15.49	15.44	15.40	15.35	15.31	15.26	15.22	15.18	15.14	15.10	15.06	15.02	14.99
	50	12.67	12.61	12.56	12.51	12.47	12.43	12.39	12.35	12.32	12.28	12.25	12.21	12.18	12.15	12.12	12.08	12.05	12.02	12.00	11.97	11.96	11.93	11.91	11.88	11.86
	total	67.75	67.34	66.96	66.58	66.25	65.93	65.64	65.36	65.09	64.84	64.61	64.35	64.11	63.83	63.54	63.23	62.92	62.60	62.32	62.04	61.80	61.55	61.32	61.11	60.92
C	10	5.45	5.43	5.41	5.38	5.38	5.37	5.36	5.34	5.33	5.34	5.37	5.42	5.49	5.57	5.62	5.65	5.64	5.59	5.56	5.52	5.48	5.45	5.43	5.40	5.38
	20	8.82	8.81	8.80	8.80	8.79	8.78	8.77	8.77	8.77	8.76	8.76	8.77	8.78	8.80	8.82	8.84	8.85	8.86	8.85	8.84	8.83	8.82	8.81	8.79	8.78
	30	8.27	8.27	8.27	8.26	8.26	8.25	8.25	8.24	8.24	8.23	8.23	8.23	8.23	8.23	8.23	8.23	8.23	8.23	8.23	8.23	8.22	8.21	8.20	8.19	8.18
	40	6.61	6.61	6.61	6.61	6.61	6.61	6.60	6.60	6.60	6.60	6.60	6.59	6.59	6.59	6.59	6.60	6.60	6.60	6.60	6.60	6.60	6.60	6.60	6.59	6.58
	50	7.07	7.08	7.08	7.09	7.09	7.09	7.09	7.09	7.10	7.10	7.10	7.10	7.10	7.10	7.10	7.10	7.10	7.10	7.11	7.11	7.11	7.11	7.11	7.10	7.10
	total	35.23	35.19	35.16	35.14	35.12	35.10	35.07	35.04	35.03	35.03	35.06	35.11	35.19	35.29	35.36	35.42	35.43	35.38	35.35	35.29	35.23	35.18	35.14	35.08	35.03
D	10	3.41	3.40	3.39	3.38	3.37	3.36	3.36	3.36	3.35	3.36	3.38	3.42	3.45	3.48	3.50	3.51	3.49	3.46	3.43	3.40	3.38	3.36	3.34	3.33	3.32
	20	4.01	4.00	3.99	3.98	3.97	3.97	3.96	3.95	3.94	3.94	3.94	3.94	3.95	3.97	3.99	4.00	4.02	4.02	4.02	4.01	4.00	4.00	3.98	3.98	3.97
	30	4.94	4.93	4.93	4.92	4.92	4.91	4.90	4.90	4.90	4.89	4.89	4.89	4.89	4.89	4.90	4.90	4.91	4.92	4.92	4.92	4.92	4.92	4.92	4.91	4.91
	40	6.05	6.05	6.04	6.04	6.04	6.04	6.03	6.03	6.03	6.02	6.02	6.02	6.01	6.01	6.01	6.02	6.02	6.03	6.03	6.04	6.04	6.04	6.05	6.05	6.04
	50	7.79	7.79	7.79	7.80	7.80	7.80	7.81	7.81	7.81	7.81	7.81	7.81	7.82	7.81	7.82	7.82	7.83	7.83	7.83	7.83	7.84	7.84	7.85	7.85	7.85
	total	26.20	26.17	26.14	26.12	26.10	26.08	26.06	26.04	26.03	26.02	26.04	26.07	26.12	26.17	26.22	26.25	26.26	26.26	26.24	26.21	26.19	26.16	26.13	26.11	26.09

Table 4.2. The hourly change in volumetric soil water content values ($m^3.m^{-3}$ x 100) between consecutive time intervals on 8 April (no irrigation event).

Probe	Depth	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00	Total
A	10		-0.14	-0.14	-0.13	-0.12	-0.11	-0.10	-0.11	-0.09	-0.10	-0.07	-0.04	-0.15	-0.19	-0.21	-0.23	-0.24	-0.23	-0.19	-0.15	-0.11	-0.10	-0.08	-0.08	-0.07	-3.18
	20		-0.18	-0.16	-0.14	-0.14	-0.12	-0.12	-0.11	-0.10	-0.11	-0.12	-0.13	-0.13	-0.14	-0.15	-0.15	-0.16	-0.15	-0.11	-0.08	-0.07	-0.06	-0.06	-0.06	-0.05	-2.80
	30		-0.23	-0.21	-0.21	-0.19	-0.17	-0.16	-0.14	-0.14	-0.13	-0.15	-0.15	-0.16	-0.17	-0.16	-0.16	-0.16	-0.14	-0.12	-0.09	-0.09	-0.07	-0.07	-0.07	-0.07	-3.42
	40		-0.08	-0.07	-0.06	-0.06	-0.06	-0.06	-0.05	-0.05	-0.06	-0.06	-0.06	-0.06	-0.06	-0.06	-0.06	-0.05	-0.04	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-1.19
	50		-0.06	-0.05	-0.05	-0.05	-0.04	-0.04	-0.04	-0.04	-0.04	-0.05	-0.04	-0.05	-0.04	-0.05	-0.04	-0.04	-0.03	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.86
	total		-0.69	-0.64	-0.59	-0.56	-0.51	-0.48	-0.44	-0.42	-0.44	-0.44	-0.44	-0.56	-0.61	-0.64	-0.64	-0.64	-0.59	-0.46	-0.36	-0.31	-0.28	-0.25	-0.25	-0.22	-11.45
B	10		-0.08	-0.07	-0.07	-0.06	-0.06	-0.05	-0.05	-0.05	-0.04	-0.04	-0.04	-0.04	-0.06	-0.08	-0.10	-0.10	-0.11	-0.10	-0.10	-0.09	-0.08	-0.06	-0.06	-0.05	-1.66
	20		-0.08	-0.07	-0.08	-0.06	-0.06	-0.05	-0.06	-0.05	-0.05	-0.06	-0.06	-0.05	-0.06	-0.07	-0.07	-0.07	-0.07	-0.05	-0.05	-0.05	-0.05	-0.04	-0.04	-0.04	-1.40
	30		-0.11	-0.11	-0.10	-0.09	-0.09	-0.08	-0.08	-0.07	-0.07	-0.07	-0.07	-0.07	-0.07	-0.06	-0.07	-0.07	-0.07	-0.06	-0.06	-0.06	-0.06	-0.05	-0.05	-0.04	-1.73
	40		-0.08	-0.08	-0.07	-0.07	-0.07	-0.06	-0.06	-0.06	-0.05	-0.04	-0.05	-0.05	-0.05	-0.04	-0.05	-0.04	-0.05	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04	-1.25
	50		-0.06	-0.05	-0.05	-0.05	-0.04	-0.04	-0.04	-0.03	-0.04	-0.03	-0.04	-0.03	-0.03	-0.04	-0.03	-0.03	-0.03	-0.03	-0.03	-0.02	-0.03	-0.02	-0.03	-0.02	-0.80
	total		-0.42	-0.38	-0.38	-0.33	-0.32	-0.29	-0.28	-0.26	-0.25	-0.24	-0.26	-0.24	-0.28	-0.29	-0.31	-0.31	-0.32	-0.28	-0.27	-0.25	-0.25	-0.22	-0.21	-0.19	-6.83
C	10		-0.03	-0.02	-0.02	-0.01	-0.01	-0.01	-0.02	-0.01	0.01	0.03	0.05	0.06	0.08	0.05	0.04	-0.01	-0.05	-0.04	-0.04	-0.04	-0.03	-0.02	-0.02	-0.02	-0.07
	20		-0.01	-0.01	0.00	-0.01	0.00	-0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.02	0.01	0.00	0.00	-0.01	-0.01	-0.01	-0.01	-0.02	-0.01	-0.04
	30		0.00	-0.01	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	-0.01	-0.01	-0.01	0.00	-0.09
	40		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	-0.03
	50		0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
	total		-0.03	-0.04	-0.02	-0.02	-0.02	-0.03	-0.03	-0.01	0.00	0.02	0.06	0.08	0.10	0.07	0.06	0.01	-0.04	-0.04	-0.06	-0.06	-0.06	-0.04	-0.06	-0.05	-0.19
D	10		-0.01	-0.01	-0.01	-0.01	-0.01	0.00	0.00	0.00	0.00	0.02	0.04	0.04	0.03	0.02	0.00	-0.02	-0.02	-0.03	-0.03	-0.03	-0.02	-0.02	-0.01	-0.01	-0.09
	20		-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.00	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.05
	30		-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	0.00	-0.01	0.00	-0.01	0.00	0.00	0.01	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	-0.03
	40		0.00	-0.01	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	-0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	-0.01
	50		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.06
	total		-0.03	-0.03	-0.02	-0.02	-0.02	-0.02	-0.02	-0.01	-0.01	0.02	0.03	0.05	0.05	0.05	0.03	0.01	0.00	-0.02	-0.02	-0.02	-0.03	-0.03	-0.02	-0.03	-0.12

Table 5.1. Hourly volumetric soil water content values ($m^3.m^{-3}$ x 100) of the four probes with each measuring depth (10, 20, 30, 40, 50 cm) beneath the soil surface on 9 April. During an irrigation cycle and for the first hour thereafter, 10-minute values are indicated. The irrigation event is marked by ** and the hour thereafter by *. Shaded values show an increase due to irrigation.

Probe	Depth	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	10:10	** 10:20	** 10:30	** 10:40	** 10:50	** 11:00	** 11:10	** 11:20	** 11:30	** 11:40	** 11:50	** 12:00	* 12:10	* 12:20	* 12:30	* 12:40	* 12:50	* 13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
A	10	10.71	10.65	10.59	10.54	10.48	10.44	10.39	10.35	10.31	10.25	10.14	10.12	10.16	12.50	14.94	16.22	16.79	17.08	17.24	17.37	17.48	17.56	17.64	17.41	16.84	16.46	16.20	15.99	15.81	15.02	14.48	14.03	13.65	13.34	13.12	12.92	12.75	12.60	12.45	12.33
	20	10.22	10.17	10.12	10.08	10.03	10.00	9.96	9.92	9.89	9.84	9.76	9.75	9.73	9.69	9.99	12.12	14.38	15.83	16.49	16.83	17.07	17.20	17.30	17.21	16.85	16.47	16.15	15.88	15.66	14.68	14.00	13.45	13.01	12.66	12.40	12.17	11.98	11.81	11.67	11.53
	30	15.55	15.49	15.43	15.36	15.31	15.25	15.20	15.15	15.11	15.05	14.96	14.95	14.92	14.89	14.88	14.86	14.96	15.96	18.05	19.90	21.17	21.97	22.48	22.72	22.59	22.31	22.01	21.73	21.48	20.36	19.60	19.01	18.53	18.15	17.84	17.58	17.35	17.15	16.96	16.80
	40	8.56	8.54	8.51	8.49	8.47	8.45	8.42	8.40	8.38	8.35	8.30	8.29	8.28	8.27	8.26	8.25	8.24	8.24	8.26	8.43	8.74	9.12	9.52	9.91	10.15	10.25	10.28	10.27	10.24	10.02	9.82	9.66	9.52	9.42	9.34	9.27	9.20	9.15	9.09	9.04
	50	6.97	6.95	6.94	6.92	6.90	6.89	6.87	6.86	6.84	6.82	6.78	6.77	6.77	6.76	6.75	6.75	6.74	6.73	6.73	6.71	6.70	6.70	6.70	6.74	6.83	6.94	7.05	7.14	7.22	7.37	7.38	7.35	7.31	7.29	7.27	7.24	7.22	7.20	7.18	7.15
	total	52.02	51.79	51.59	51.39	51.20	51.02	50.84	50.69	50.53	50.31	49.94	49.89	49.86	52.11	54.81	58.20	61.12	63.85	66.77	69.25	71.16	72.56	73.65	73.99	73.25	72.43	71.69	71.01	70.40	67.45	65.28	63.48	62.01	60.88	59.96	59.19	58.50	57.90	57.35	56.84
B	10	9.54	9.49	9.44	9.40	9.36	9.33	9.29	9.27	9.23	9.21	9.18	9.17	9.17	9.17	9.17	9.16	9.16	9.16	9.17	9.18	9.20	9.24	9.30	9.37	9.46	9.55	9.63	9.69	9.75	9.92	9.95	9.95	9.92	9.87	9.83	9.80	9.76	9.72	9.69	9.66
	20	11.36	11.32	11.28	11.25	11.21	11.18	11.15	11.12	11.09	11.06	11.01	11.00	10.99	10.99	10.98	10.97	10.97	10.96	10.95	10.95	10.95	10.94	10.94	10.95	10.97	11.00	11.04	11.08	11.13	11.35	11.45	11.49	11.49	11.49	11.48	11.47	11.45	11.42	11.40	11.38
	30	13.17	13.12	13.07	13.03	12.98	12.94	12.89	12.85	12.82	12.78	12.74	12.74	12.73	12.73	12.72	12.71	12.70	12.70	12.68	12.68	12.67	12.67	12.67	12.69	12.73	12.81	12.88	12.96	13.03	13.30	13.40	13.42	13.40	13.37	13.34	13.31	13.28	13.24	13.20	13.16
	40	14.99	14.95	14.92	14.87	14.85	14.81	14.78	14.74	14.72	14.69	14.66	14.66	14.66	14.65	14.64	14.63	14.63	14.61	14.61	14.60	14.60	14.59	14.59	14.59	14.59	14.59	14.60	14.63	14.65	14.82	14.92	14.96	14.98	14.99	14.99	14.98	14.96	14.95	14.93	14.90
	50	11.86	11.84	11.82	11.79	11.78	11.75	11.73	11.71	11.70	11.67	11.65	11.64	11.64	11.63	11.63	11.63	11.62	11.61	11.61	11.61	11.60	11.60	11.59	11.59	11.59	11.59	11.59	11.58	11.59	11.63	11.70	11.74	11.77	11.78	11.79	11.80	11.80	11.79	11.79	11.78
	total	60.92	60.71	60.53	60.35	60.17	60.01	59.85	59.69	59.55	59.41	59.24	59.21	59.19	59.17	59.13	59.09	59.07	59.05	59.03	59.02	59.02	59.05	59.09	59.19	59.34	59.54	59.75	59.95	60.16	61.02	61.42	61.55	61.56	61.50	61.44	61.34	61.24	61.12	61.00	60.89
C	10	5.38	5.36	5.35	5.34	5.32	5.31	5.30	5.30	5.29	5.30	5.34	5.34	5.36	5.36	5.37	5.38	5.39	5.40	5.42	5.43	5.44	5.44	5.45	5.47	5.47	5.49	5.50	5.50	5.51	5.57	5.60	5.61	5.58	5.54	5.50	5.47	5.44	5.41	5.38	5.36
	20	8.78	8.77	8.76	8.75	8.74	8.73	8.72	8.72	8.71	8.70	8.70	8.70	8.70	8.70	8.70	8.70	8.70	8.70	8.70	8.71	8.71	8.71	8.71	8.71	8.72	8.72	8.72	8.72	8.73	8.74	8.76	8.77	8.78	8.77	8.77	8.76	8.75	8.73	8.72	8.71
	30	8.18	8.17	8.16	8.15	8.14	8.13	8.12	8.12	8.11	8.11	8.10	8.10	8.10	8.09	8.09	8.09	8.09	8.09	8.09	8.09	8.09	8.09	8.09	8.09	8.09	8.09	8.09	8.09	8.09	8.09	8.09	8.09	8.09	8.09	8.09	8.09	8.08	8.07	8.07	8.06
	40	6.58	6.58	6.58	6.57	6.56	6.56	6.55	6.55	6.54	6.54	6.53	6.53	6.53	6.53	6.53	6.53	6.53	6.53	6.53	6.53	6.53	6.53	6.53	6.53	6.53	6.53	6.53	6.53	6.53	6.53	6.53	6.53	6.53	6.53	6.53	6.53	6.53	6.52	6.52	6.52
	50	7.10	7.10	7.10	7.10	7.10	7.09	7.09	7.09	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.07	7.07	7.07	7.07	7.07	7.07	7.07	7.07	7.07	7.07	7.07	7.07	7.07	7.07	7.07	7.06	7.07	7.06	7.06
	total	35.03	34.99	34.95	34.91	34.86	34.82	34.79	34.77	34.73	34.72	34.75	34.76	34.77	34.77	34.78	34.79	34.80	34.80	34.82	34.83	34.84	34.85	34.86	34.87	34.88	34.91	34.92	34.91	34.93	35.00	35.04	35.07	35.04	35.00	34.96	34.91	34.86	34.80	34.75	34.71
D	10	3.32	3.31	3.30	3.30	3.29	3.29	3.29	3.29	3.29	3.29	3.32	3.32	3.32	3.33	3.34	3.34	3.35	3.35	3.36	3.37	3.37	3.38	3.38	3.39	3.39	3.40	3.40	3.41	3.41	3.43	3.43	3.43	3.41	3.38	3.35	3.33	3.31	3.29	3.27	3.26
	20	3.97	3.95	3.95	3.94	3.93	3.92	3.92	3.91	3.91	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.92	3.92	3.93	3.93	3.93	3.95	3.97	3.98	3.99	3.99	3.99	3.98	3.97	3.96	3.95	3.94
	30	4.91	4.90	4.90	4.89	4.89	4.88	4.88	4.88	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.88	4.89	4.89	4.90	4.90	4.90	4.90	4.90	4.90	4.90
	40	6.04	6.04	6.04	6.04	6.04	6.03	6.03	6.03	6.02	6.02	6.02	6.02	6.02	6.02	6.02	6.02	6.02	6.02	6.02	6.02	6.02	6.02	6.02	6.02	6.01	6.02	6.02	6.02	6.02	6.02	6.02	6.02	6.03	6.03	6.04	6.04	6.05	6.05	6.05	6.05
	50	7.85	7.85	7.85	7.85	7.85	7.85	7.85	7.85	7.85	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.85	7.85	7.85	7.85	7.85	7.85	7.85	7.86
	total	26.09	26.06	26.04	26.02	26.00	25.98	25.96	25.95	25.94	25.93	25.95	25.95	25.95	25.95	25.97	25.97	25.97	25.97	25.98	25.99	25.99	26.00	26.00	26.02	26.04	26.05	26.05	26.07	26.07	26.11	26.14	26.16	26.17	26.15	26.13	26.10	26.08	26.05	26.03	26.01

Table 5.2. The hourly change in volumetric soil water content values ($m^3.m^{-3}$ x 100) between consecutive time intervals on 9 April. During an irrigation cycle and for the first hour thereafter, 10-minute changes are indicated. The irrigation event is marked by ** and the hour thereafter by *. Shaded values show an increase due to irrigation.

Probe	Depth	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	10:10	** 10:20	** 10:30	** 10:40	** 10:50	** 11:00	** 11:10	** 11:20	** 11:30	** 11:40	** 11:50	** 12:00	* 12:10	* 12:20	* 12:30	* 12:40	* 12:50	* 13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00	Total
A	10		-0.06	-0.06	-0.05	-0.05	-0.05	-0.05	-0.04	-0.03	-0.07	-0.11	-0.02	0.04	2.33	2.44	1.28	0.57	0.29	0.16	0.13	0.11	0.08	0.07	-0.22	-0.57	-0.37	-0.26	-0.21	-0.18	-0.79	-0.54	-0.45	-0.38	-0.30	-0.23	-0.19	-0.17	-0.16	-0.14	-0.12	1.62
	20		-0.05	-0.04	-0.05	-0.04	-0.03	-0.04	-0.03	-0.03	-0.05	-0.08	-0.01	-0.02	-0.04	0.30	2.14	2.26	1.45	0.66	0.34	0.23	0.14	0.10	-0.09	-0.37	-0.38	-0.32	-0.26	-0.22	-0.98	-0.68	-0.56	-0.44	-0.34	-0.27	-0.23	-0.19	-0.17	-0.15	-0.14	1.31
	30		-0.07	-0.06	-0.06	-0.05	-0.06	-0.05	-0.05	-0.05	-0.05	-0.09	-0.01	-0.03	-0.03	-0.01	-0.02	0.11	1.00	2.09	1.85	1.27	0.80	0.51	0.24	-0.13	-0.28	-0.30	-0.28	-0.25	-1.12	-0.76	-0.59	-0.48	-0.38	-0.31	-0.26	-0.23	-0.20	-0.19	-0.17	1.24
	40		-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.03	-0.05	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	0.02	0.16	0.32	0.38	0.40	0.39	0.24	0.10	0.03	-0.01	-0.02	-0.22	-0.20	-0.17	-0.14	-0.09	-0.08	-0.07	-0.07	-0.06	-0.06	-0.05	0.47
	50		-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.01	-0.02	-0.02	-0.04	0.00	0.00	-0.01	-0.01	0.00	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	0.00	0.04	0.09	0.12	0.11	0.09	0.07	0.15	0.01	-0.03	-0.04	-0.02	-0.03	-0.02	-0.02	-0.02	-0.02	-0.03	0.18
	total		-0.23	-0.21	-0.20	-0.19	-0.18	-0.18	-0.16	-0.15	-0.22	-0.37	-0.06	-0.02	2.24	2.71	3.39	2.92	2.73	2.92	2.48	1.92	1.40	1.08	0.34	-0.74	-0.81	-0.74	-0.68	-0.61	-2.95	-2.17	-1.79	-1.48	-1.13	-0.92	-0.77	-0.68	-0.61	-0.55	-0.51	4.82
B	10		-0.05	-0.05	-0.04	-0.04	-0.03	-0.04	-0.03	-0.03	-0.03	-0.03	0.00	0.00	0.00	0.00	-0.01	0.00	0.01	0.00	0.01	0.02	0.04	0.06	0.08	0.09	0.09	0.08	0.06	0.06	0.16	0.03	0.00	-0.03	-0.05	-0.04	-0.04	-0.04	-0.04	-0.04	-0.02	0.12
	20		-0.04	-0.03	-0.03	-0.04	-0.03	-0.03	-0.03	-0.03	-0.03	-0.05	-0.01	-0.01	0.00	-0.01	-0.01	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.04	0.04	0.05	0.22	0.10	0.03	0.00	0.00	0.00	-0.01	-0.02	-0.02	-0.02	-0.02	0.02
	30		-0.05	-0.05	-0.04	-0.05	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.01	0.02	0.04	0.07	0.08	0.08	0.07	0.27	0.10	0.02	-0.02	-0.03	-0.03	-0.03	-0.03	-0.04	-0.04	-0.04	-0.01
	40		-0.04	-0.03	-0.04	-0.03	-0.04	-0.03	-0.04	-0.03	-0.02	-0.03	-0.01	0.00	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	0.00	0.01	0.01	0.02	0.02	0.17	0.10	0.05	0.02	0.01	0.00	-0.01	-0.01	-0.02	-0.02	-0.02	-0.08
	50		-0.03	-0.02	-0.03	-0.02	-0.03	-0.02	-0.02	-0.02	-0.02	-0.03	-0.01	-0.01	-0.01	-0.01	0.00	-0.01	-0.01	0.00	-0.01	-0.01	0.00	-0.01	0.00	-0.01	0.00	0.00	-0.01	0.01	0.04	0.07	0.04	0.03	0.02	0.01	0.01	0.00	-0.01	-0.01	-0.01	-0.09
	total		-0.21	-0.18	-0.18	-0.17	-0.16	-0.16	-0.15	-0.14	-0.14	-0.17	-0.03	-0.02	-0.03	-0.03	-0.04	-0.03	-0.02	-0.02	-0.01	0.00	0.02	0.05	0.10	0.15	0.20	0.21	0.20	0.21	0.86	0.40	0.13	0.00	-0.05	-0.07	-0.09	-0.10	-0.12	-0.12	-0.11	-0.03
C	10		-0.02	-0.01	-0.01	-0.02	-0.01	-0.01	0.00	-0.01	0.00	0.04	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.00	0.01	0.06	0.03	0.01	-0.03	-0.04	-0.04	-0.04	-0.03	-0.03	-0.03	-0.02	-0.02
	20		0.00	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.02	0.01	0.01	0.00	0.00	-0.01	-0.01	-0.02	-0.01	-0.01	-0.07
	30		-0.01	-0.01	0.00	-0.02	-0.01	-0.01	0.00	-0.01	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	0.00	-0.01	-0.12
	40		0.00	0.00	-0.01	0.00	-0.01	0.00	-0.01	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.06
	50		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.05
	total		-0.04	-0.04	-0.04	-0.05	-0.04	-0.03	-0.03	-0.03	-0.01	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	-0.01	0.01	0.07	0.04	0.02	-0.02	-0.04	-0.04	-0.05	-0.05	-0.06	-0.05	-0.04	-0.32
D	10		-0.01	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.00	0.00	0.01	0.01	0.00	0.01	0.00	0.01	0.01	0.00	0.01	0.00	0.02	0.00	0.01	0.00	0.01	0.00	0.02	0.01	-0.01	-0.02	-0.03	-0.03	-0.03	-0.02	-0.02	-0.01	-0.01	-0.06
	20		-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.01	0.00	0.02	0.02	0.01	0.01	0.00	0.00	-0.01	-0.01	-0.01	-0.01	-0.01	-0.02
	30		0.00	-0.01	-0.01	0.00	-0.01	-0.01	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	-0.01
	40		0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01
	50		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
	total		-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.01	-0.01	-0.01	0.02	0.00	0.00	0.01	0.01	0.00	0.01	0.00	0.01	0.01	0.00	0.01	0.00	0.02	0.02	0.01	0.01	0.01	0.00	0.04	0.03	0.02	0.01	-0.02	-0.02	-0.03	-0.02	-0.03	-0.03	-0.02	-0.08

Table 6.1. Hourly volumetric soil water content values (m^3.m^{-3} x 100) of the four probes with each measuring depth (10, 20, 30, 40, 50 cm) beneath the soil surface on 10 April. During an irrigation cycle and for the first hour thereafter, 10-minute values are indicated. The irrigation event is marked by ** and the hour thereafter by *. Shaded values show an increase due to irrigation.

Probe	Depth	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	** 7:10	** 7:20	** 7:30	** 7:40	** 7:50	** 8:00	** 8:10	* 8:20	* 8:30	* 8:40	* 8:50	* 9:00	* 9:10	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	** 17:10	** 17:20	** 17:30	** 17:40	** 17:50	** 18:00	* 18:10	* 18:20	* 18:30	* 18:40	* 18:50	* 19:00	20:00	21:00	22:00	23:00	24:00
A	10	12.33	12.22	12.11	12.00	11.91	11.82	11.74	11.66	11.71	13.73	15.74	16.66	17.13	17.40	17.46	16.81	16.45	16.18	15.98	15.80	15.64	15.05	14.54	14.12	13.74	13.38	13.21	12.87	12.54	13.63	15.48	16.35	16.82	17.13	17.25	16.91	16.48	16.19	15.98	15.80	15.66	15.04	14.64	14.33	14.08	13.86
	20	11.53	11.40	11.29	11.18	11.09	11.01	10.92	10.84	10.83	10.79	11.40	13.65	15.39	16.29	16.76	16.55	16.24	15.97	15.74	15.54	15.35	14.65	14.02	13.50	13.07	12.67	12.31	11.99	11.71	11.64	11.80	13.39	15.06	16.00	16.48	16.43	16.17	15.91	15.67	15.48	15.31	14.57	14.07	13.69	13.35	13.09
	30	16.80	16.64	16.50	16.39	16.27	16.15	16.06	15.96	15.94	15.91	15.90	15.92	16.61	18.46	20.06	20.71	20.78	20.70	20.59	20.46	20.35	19.79	19.23	18.77	18.35	17.97	17.63	17.30	17.02	16.96	16.92	16.88	17.24	18.60	20.06	20.77	20.91	20.83	20.71	20.58	20.44	19.78	19.30	18.92	18.59	18.32
	40	9.04	8.99	8.95	8.90	8.86	8.82	8.79	8.75	8.75	8.74	8.73	8.72	8.72	8.76	8.96	9.23	9.43	9.56	9.62	9.66	9.67	9.63	9.53	9.42	9.31	9.21	9.11	9.03	8.96	8.94	8.93	8.92	8.92	8.93	9.08	9.31	9.51	9.64	9.72	9.76	9.78	9.76	9.69	9.61	9.53	9.46
	50	7.15	7.13	7.11	7.09	7.07	7.05	7.03	7.01	7.01	7.00	7.00	6.99	6.99	6.98	6.97	6.96	6.96	6.98	7.01	7.04	7.08	7.17	7.21	7.20	7.17	7.14	7.11	7.07	7.04	7.04	7.04	7.04	7.03	7.02	7.02	7.02	7.02	7.05	7.09	7.12	7.16	7.30	7.35	7.35	7.35	7.34
	total	56.84	56.38	55.96	55.57	55.20	54.85	54.53	54.22	54.23	56.18	58.77	61.95	64.84	67.88	70.20	70.26	69.86	69.40	68.94	68.50	68.09	66.29	64.53	63.01	61.65	60.38	59.37	58.26	57.27	58.22	60.17	62.58	65.07	67.68	69.89	70.43	70.08	69.63	69.16	68.75	68.35	66.45	65.05	63.91	62.90	62.07
B	10	9.66	9.64	9.61	9.59	9.56	9.54	9.52	9.50	9.50	9.50	9.50	9.50	9.51	9.52	9.55	9.60	9.65	9.71	9.76	9.81	9.85	9.98	10.06	10.08	10.06	10.01	9.95	9.89	9.82	9.81	9.80	9.79	9.79	9.80	9.84	9.89	9.95	10.01	10.06	10.09	10.13	10.22	10.24	10.23	10.22	10.20
	20	11.38	11.36	11.33	11.31	11.28	11.26	11.24	11.22	11.22	11.22	11.22	11.21	11.21	11.21	11.20	11.21	11.21	11.22	11.24	11.26	11.28	11.40	11.48	11.51	11.51	11.50	11.46	11.42	11.38	11.37	11.37	11.36	11.36	11.35	11.35	11.36	11.37	11.39	11.42	11.45	11.48	11.64	11.71	11.74	11.74	11.73
	30	13.16	13.13	13.10	13.06	13.03	13.00	12.96	12.94	12.93	12.93	12.92	12.91	12.91	12.89	12.89	12.89	12.90	12.92	12.95	12.99	13.03	13.19	13.29	13.32	13.31	13.29	13.25	13.21	13.16	13.15	13.15	13.14	13.13	13.12	13.12	13.12	13.13	13.16	13.20	13.24	13.29	13.48	13.55	13.57	13.56	13.53
	40	14.90	14.89	14.86	14.84	14.82	14.80	14.78	14.76	14.75	14.75	14.74	14.74	14.73	14.72	14.72	14.72	14.72	14.71	14.72	14.72	14.73	14.79	14.86	14.89	14.90	14.90	14.89	14.87	14.85	14.85	14.84	14.83	14.83	14.82	14.82	14.82	14.82	14.82	14.82	14.83	14.85	14.94	15.01	15.05	15.06	15.05
	50	11.78	11.77	11.75	11.74	11.73	11.72	11.70	11.69	11.69	11.69	11.68	11.68	11.67	11.67	11.67	11.67	11.66	11.66	11.66	11.66	11.66	11.66	11.69	11.71	11.72	11.72	11.71	11.71	11.70	11.70	11.69	11.69	11.69	11.69	11.69	11.69	11.69	11.68	11.68	11.69	11.69	11.72	11.76	11.79	11.81	11.82
	total	60.89	60.78	60.66	60.54	60.43	60.32	60.21	60.10	60.08	60.07	60.05	60.04	60.03	60.02	60.04	60.08	60.14	60.22	60.33	60.44	60.55	61.03	61.36	61.51	61.50	61.42	61.27	61.10	60.91	60.88	60.85	60.82	60.79	60.79	60.82	60.87	60.95	61.05	61.18	61.31	61.43	61.99	62.26	62.38	62.39	62.34
C	10	5.36	5.35	5.33	5.31	5.30	5.29	5.28	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.30	5.35	5.41	5.47	5.52	5.53	5.52	5.51	5.52	5.50	5.49	5.49	5.48	5.48	5.46	5.46	5.45	5.44	5.45	5.44	5.41	5.37	5.33	5.31	5.29
	20	8.71	8.70	8.69	8.68	8.67	8.67	8.66	8.64	8.64	8.64	8.64	8.64	8.64	8.64	8.64	8.64	8.64	8.64	8.64	8.64	8.63	8.63	8.64	8.64	8.66	8.67	8.69	8.69	8.70	8.70	8.70	8.70	8.70	8.70	8.70	8.70	8.69	8.69	8.69	8.69	8.69	8.68	8.67	8.66	8.64	8.63
	30	8.06	8.05	8.05	8.04	8.04	8.04	8.03	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.01	8.02	8.02	8.01	8.01	8.01	8.01	8.01	8.00	8.01	8.01	8.01	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.01	8.00	8.00	7.99
	40	6.52	5.51	5.51	5.50	5.50	5.49	5.49	5.49	5.49	5.49	5.49	5.49	5.49	5.49	5.48	5.48	5.48	5.48	5.48	5.48	5.48	5.48	5.48	5.47	5.47	5.47	5.47	5.47	5.48	5.48	5.48	5.48	5.48	5.48	5.48	5.48	5.48	5.48	5.48	5.48	5.48	5.48	5.47	5.47	5.47	5.46
	50	7.06	7.06	7.05	7.05	7.05	7.05	7.04	7.04	7.04	7.04	7.04	7.04	7.04	7.04	7.04	7.04	7.04	7.04	7.04	7.04	7.04	7.04	7.03	7.03	7.03	7.02	7.02	7.02	7.02	7.02	7.02	7.02	7.03	7.02	7.02	7.03	7.02	7.02	7.02	7.02	7.02	7.02	7.02	7.02	7.02	7.02
	total	34.71	34.67	34.63	34.59	34.57	34.53	34.50	34.47	34.47	34.47	34.45	34.45	34.45	34.44	34.44	34.44	34.44	34.44	34.44	34.44	34.43	34.46	34.50	34.56	34.63	34.68	34.72	34.73	34.73	34.74	34.72	34.71	34.71	34.70	34.70	34.69	34.67	34.66	34.66	34.66	34.64	34.60	34.54	34.48	34.44	34.39
D	10	3.26	3.25	3.24	3.24	3.24	3.23	3.23	3.23	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.23	3.23	3.23	3.23	3.23	3.25	3.29	3.32	3.34	3.36	3.36	3.35	3.34	3.33	3.33	3.32	3.32	3.31	3.31	3.30	3.30	3.29	3.29	3.28	3.28	3.25	3.23	3.21	3.19	3.18
	20	3.94	3.93	3.93	3.92	3.91	3.91	3.90	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.88	3.89	3.88	3.88	3.88	3.88	3.89	3.90	3.91	3.93	3.95	3.96	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.96	3.95	3.94	3.93	3.92
	30	4.90	4.89	4.89	4.89	4.88	4.88	4.88	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.86	4.87	4.86	4.86	4.86	4.86	4.86	4.87	4.88	4.88	4.89	4.89	4.89	4.89	4.89	4.89	4.90	4.90	4.90	4.90	4.90	4.90	4.90	4.90	4.90	4.90	4.89	4.89
	40	6.05	6.05	6.05	6.05	6.04	6.04	6.04	6.04	6.04	6.04	6.04	6.03	6.03	6.03	6.03	6.03	6.03	6.03	6.03	6.03	6.03	6.03	6.03	6.03	6.02	6.03	6.03	6.03	6.04	6.04	6.04	6.04	6.04	6.04	6.04	6.04	6.04	6.05	6.04	6.05	6.05	6.05	6.05	6.06	6.05	6.05
	50	7.86	7.85	7.85	7.85	7.85	7.85	7.85	7.85	7.85	7.85	7.85	7.85	7.85	7.85	7.85	7.85	7.85	7.85	7.85	7.85	7.85	7.85	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.84	7.85	7.85	7.85	7.85	7.85	7.85
	total	26.01	25.98	25.96	25.95	25.93	25.90	25.89	25.87	25.87	25.87	25.87	25.87	25.86	25.86	25.86	25.86	25.86	25.86	25.86	25.86	25.86	25.87	25.91	25.95	25.98	26.02	26.05	26.07	26.07	26.08	26.07	26.07	26.06	26.06	26.06	26.06	26.05	26.05	26.04	26.04	26.03	26.00	25.97	25.94	25.91	25.88

Table 6.2. The hourly change in volumetric soil water content values (m^3.m^{-3} x 100) between consecutive time intervals on 10 April. During an irrigation cycle and for the first hour thereafter, 10-minute changes are indicated. The irrigation event is marked by ** and the hour thereafter by *. Shaded values show an increase due to irrigation.

Probe	Depth	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	** 7:10	** 7:20	** 7:30	** 7:40	** 7:50	** 8:00	** 8:10	* 8:20	* 8:30	* 8:40	* 8:50	* 9:00	* 9:10	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	** 17:10	** 17:20	** 17:30	** 17:40	** 17:50	** 18:00	* 18:10	* 18:20	* 18:30	* 18:40	* 18:50	* 19:00	20:00	21:00	22:00	23:00	24:00	Total
A	10		-0.11	-0.11	-0.10	-0.09	-0.09	-0.08	-0.08	0.05	2.03	2.01	0.92	0.47	0.27	0.05	-0.64	-0.37	-0.26	-0.21	-0.18	-0.16	-0.75	-0.51	-0.41	-0.38	-0.36	-0.17	-0.34	-0.32	1.09	1.85	0.87	0.47	0.30	0.13	-0.35	-0.43	-0.28	-0.22	-0.18	-0.14	-0.62	-0.40	-0.30	-0.25	-0.22	1.53
	20		-0.12	-0.11	-0.11	-0.09	-0.09	-0.09	-0.07	-0.01	-0.03	0.61	2.26	1.74	0.90	0.47	-0.21	-0.31	-0.27	-0.24	-0.20	-0.18	-0.89	-0.62	-0.52	-0.43	-0.40	-0.36	-0.32	-0.28	-0.07	0.16	1.59	1.67	0.94	0.48	-0.04	-0.27	-0.26	-0.24	-0.19	-0.17	-0.74	-0.49	-0.38	-0.34	-0.26	1.56
	30		-0.15	-0.14	-0.12	-0.12	-0.11	-0.10	-0.09	-0.02	-0.03	-0.01	0.02	0.69	1.84	1.61	0.65	0.06	-0.07	-0.12	-0.13	-0.11	-0.67	-0.56	-0.47	-0.42	-0.38	-0.34	-0.33	-0.28	-0.06	-0.04	-0.03	0.35	1.37	1.46	0.71	0.14	-0.07	-0.12	-0.13	-0.14	-0.66	-0.48	-0.38	-0.33	-0.28	1.52
	40		-0.05	-0.04	-0.04	-0.04	-0.04	-0.04	-0.03	0.00	-0.01	-0.01	-0.01	0.00	0.03	0.20	0.27	0.21	0.13	0.06	0.03	0.01	-0.02	-0.11	-0.11	-0.11	-0.10	-0.10	-0.08	-0.08	-0.01	-0.01	-0.01	0.00	0.01	0.15	0.23	0.20	0.13	0.08	0.04	0.02	-0.02	-0.07	-0.08	-0.08	-0.07	0.43
	50		-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	0.00	-0.01	0.00	-0.01	0.00	-0.01	-0.01	-0.01	0.00	0.02	0.03	0.03	0.03	0.13	0.03	-0.01	-0.03	-0.03	-0.03	-0.04	-0.03	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.01	0.03	0.03	0.04	0.04	0.14	0.05	0.00	0.00	-0.01	0.19
	total		-0.46	-0.43	-0.39	-0.37	-0.35	-0.33	-0.30	0.01	1.95	2.59	3.18	2.89	3.04	2.31	0.06	-0.40	-0.46	-0.47	-0.44	-0.41	-2.21	-1.76	-1.51	-1.36	-1.27	-1.01	-1.11	-0.99	0.95	1.95	2.41	2.49	2.62	2.21	0.54	-0.35	-0.45	-0.47	-0.42	-0.40	-1.90	-1.40	-1.14	-0.98	-0.85	5.23
B	10		-0.03	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	0.00	0.00	0.00	0.00	0.00	0.02	0.03	0.05	0.06	0.05	0.05	0.05	0.04	0.17	0.07	0.02	-0.02	-0.05	-0.06	-0.06	-0.07	-0.01	-0.01	-0.01	0.00	0.01	0.04	0.05	0.06	0.06	0.05	0.04	0.03	0.09	0.02	0.00	-0.01	-0.02	0.54
	20		-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.02	0.02	0.14	0.08	0.03	0.00	-0.01	-0.03	-0.04	-0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.03	0.03	0.03	0.16	0.08	0.03	0.01	-0.01	0.36
	30		-0.04	-0.03	-0.04	-0.03	-0.03	-0.04	-0.03	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	-0.01	0.01	0.02	0.03	0.04	0.04	0.20	0.10	0.03	-0.01	-0.02	-0.04	-0.04	-0.05	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	0.01	0.03	0.04	0.04	0.04	0.19	0.07	0.02	-0.01	-0.03	0.37
	40		-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.01	0.00	-0.01	-0.01	-0.01	-0.01	0.00	-0.01	0.00	-0.01	0.01	0.00	0.01	0.07	0.07	0.04	0.01	-0.01	-0.01	-0.02	-0.02	0.00	-0.01	-0.01	-0.01	-0.01	0.00	0.00	-0.01	0.00	0.01	0.01	0.01	0.10	0.07	0.04	0.01	-0.01	0.15
	50		-0.01	-0.02	-0.01	-0.02	-0.01	-0.02	-0.01	-0.01	0.00	-0.01	0.00	-0.01	0.00	-0.01	0.00	-0.01	0.00	-0.01	0.00	0.00	0.01	0.02	0.02	0.01	0.01	-0.01	-0.01	-0.01	0.00	-0.01	0.00	-0.01	0.00	0.00	0.00	0.00	-0.01	0.00	0.01	0.00	0.03	0.04	0.03	0.03	0.01	0.05
	total		-0.11	-0.12	-0.12	-0.11	-0.11	-0.11	-0.10	-0.03	-0.01	-0.02	-0.02	-0.01	-0.01	0.02	0.04	0.07	0.08	0.11	0.11	0.11	0.59	0.34	0.14	-0.01	-0.08	-0.15	-0.17	-0.19	-0.02	-0.04	-0.03	-0.03	0.00	0.03	0.06	0.07	0.10	0.13	0.13	0.12	0.56	0.27	0.11	0.02	-0.05	1.45
C	10		-0.02	-0.02	-0.02	-0.01	-0.01	-0.01	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.05	0.06	0.05	0.05	0.02	-0.01	-0.01	0.01	-0.01	-0.01	0.00	-0.01	0.00	-0.02	0.00	-0.01	-0.01	0.00	-0.01	-0.04	-0.04	-0.03	-0.02	-0.03	-0.08
	20		-0.01	-0.01	-0.01	0.00	-0.01	-0.01	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	-0.01	-0.01	-0.01	-0.01	-0.08
	30		-0.01	0.00	-0.01	0.00	-0.01	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	0.00	-0.01	-0.07
	40		0.00	-0.01	-0.01	0.00	-0.01	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	-1.05
	50		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.04
	total		-0.04	-0.04	-0.05	-0.01	-0.04	-0.04	-0.03	0.00	0.00	-0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	-0.01	0.00	0.00	0.02	0.05	0.05	0.07	0.05	0.04	0.00	0.00	0.01	-0.01	-0.01	0.00	-0.01	0.00	-0.01	-0.01	-0.01	-0.01	0.00	-0.02	-0.04	-0.06	-0.06	-0.04	-0.05	-0.32
D	10		-0.01	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.04	0.03	0.02	0.02	0.00	-0.01	-0.02	0.00	0.00	-0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	-0.01	0.00	-0.03	-0.02	-0.02	-0.02	-0.01	-0.08
	20		-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	-0.01	-0.01	-0.01	-0.01	-0.03
	30		-0.01	0.00	0.00	-0.01	-0.01	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	-0.01
	40		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	50		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01
	total		-0.02	-0.02	-0.02	-0.02	-0.02	-0.01	-0.02	-0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.04	0.03	0.04	0.03	0.01	0.01	0.00	-0.01	0.00	-0.01	0.00	0.00	0.00	-0.01	0.00	-0.01	0.00	0.00	-0.03	-0.03	-0.03	-0.04	-0.03	-0.13

Table 7. Summarized volumetric soil water content (SWC) values and differences ($m^3.m^{-3}$ x 100) observed from Tables 4-6. The days with irrigation events are divided in different times: time of SWC decrease before a pulse; time of increase and time of decrease after a pulse. The values at the beginning and end of this time are given and the difference between these values. In the case of no irrigation event or the event having no direct effect on a sensor only the total change during the whole day will be shown.

Day		8 April			9 April										10 April															
		Whole day			Before pulse			Result of pulse			After pulse			Total diff	Before pulse			Result of pulse 1			After pulse 1			Result of pulse 2			After pulse 2			Total/ day
Probe	Depth	Begin	End	Diff.	Begin	End	Diff.	Begin	End	Diff.	Begin	End	Diff.		Begin	End	Diff.	Begin	End	Diff.	Begin	End	Diff.	Begin	End	Diff.	Begin	End	Diff.	
1	10	13.89	10.71	-3.18	10.71	10.12	-0.59	10.12	17.64	7.52	17.64	12.33	-5.31	1.62	12.33	11.66	-0.67	11.66	17.46	5.80	17.46	12.54	-4.91	12.54	17.25	4.71	17.25	13.86	-3.39	1.53
	20	13.02	10.22	-2.80	10.22	9.69	-0.53	9.69	17.30	7.61	17.30	11.53	-5.78	1.31	11.53	10.79	-0.73	10.79	16.76	5.96	16.76	11.64	-5.12	11.64	16.48	4.84	16.48	13.09	-3.39	1.56
	30	18.97	15.55	-3.42	15.55	14.86	-0.69	14.86	22.72	7.86	22.72	16.80	-5.92	1.24	16.80	15.90	-0.89	15.90	20.78	4.88	20.78	16.88	-3.89	16.88	20.91	4.02	20.91	18.32	-2.59	1.52
	40	9.75	8.56	-1.19	8.56	8.24	-0.32	8.24	10.28	2.03	10.28	9.04	-1.24	0.47	9.04	8.72	-0.31	8.72	9.67	0.95	9.67	8.92	-0.75	8.92	9.78	0.86	9.78	9.46	-0.32	0.43
	50	7.83	6.97	-0.86	6.97	6.70	-0.27	6.70	7.38	0.68	7.38	7.15	-0.23	0.18	7.15	6.96	-0.19	6.96	7.21	0.25	7.21	7.02	-0.19	7.02	7.35	0.34	7.35	7.34	-0.02	0.19
	Total			-11.45			-2.41			25.70			-18.47	4.82			-2.80			17.83			-14.87			14.77			-9.70	5.23
2	10	11.20	9.54	-1.66	9.54	9.16	-0.39	9.16	9.95	0.80	9.95	9.66	-0.29	0.12	9.66	9.50	-0.16	9.50	10.08	0.57	10.08	9.79	-0.29	9.79	10.24	0.45	10.24	10.20	-0.04	0.54
	20	12.76	11.36	-1.40	11.36	10.94	-0.42	10.94	11.49	0.55	11.49	11.38	-0.11	0.02	11.38	11.21	-0.17	11.21	11.51	0.31	11.51	11.35	-0.16	11.35	11.74	0.39	11.74	11.73	-0.01	0.36
	30	14.90	13.17	-1.73	13.17	12.67	-0.50	12.67	13.42	0.75	13.42	13.16	-0.25	-0.01	13.16	12.89	-0.27	12.89	13.32	0.43	13.32	13.12	-0.20	13.12	13.57	0.45	13.57	13.53	-0.04	0.37
	40	16.23	14.99	-1.25	14.99	14.59	-0.40	14.59	14.99	0.40	14.99	14.90	-0.08	-0.08	14.90	14.72	-0.19	14.72	14.90	0.19	14.90	14.82	-0.09	14.82	15.06	0.24	15.06	15.05	-0.01	0.15
	50	12.67	11.86	-0.80	11.86	11.58	-0.28	11.58	11.80	0.21	11.80	11.78	-0.02	-0.09	11.78	11.66	-0.11	11.66	11.72	0.06	11.72	11.68	-0.04	11.68	11.82	0.14	11.82	11.82	0.00	0.05
	Total			-6.83			-1.98			2.70			-0.75	-0.03			-0.91			1.55			-0.78			1.68			-0.09	1.45
		Whole day									Whole day																Whole day			Total
3	10	5.45	5.38	-0.07							5.38	5.36		-0.02													5.36	5.29		-0.08
	20	8.82	8.78	-0.04							8.78	8.71		-0.07													8.71	8.63		-0.08
	30	8.27	8.18	-0.09							8.18	8.06		-0.12													8.06	7.99		-0.07
	40	6.61	6.58	-0.03							6.58	6.52		-0.06													6.52	6.46		-0.05
	50	7.07	7.10	0.03							7.10	7.06		-0.05													7.06	7.02		-0.04
	Total			-0.19										-0.32																-0.32
4	10	3.41	3.32	-0.09							3.32	3.26		-0.06													3.26	3.18		-0.08
	20	4.01	3.97	-0.05							3.97	3.94		-0.02													3.94	3.92		-0.03
	30	4.94	4.91	-0.03							4.91	4.90		-0.01													4.90	4.89		-0.01
	40	6.05	6.04	-0.01							6.04	6.05		0.01													6.05	6.05		0.00
	50	7.79	7.85	0.06							7.85	7.86		0.01													7.86	7.85		-0.01
	Total			-0.12										-0.08																-0.13
Total of all the probes/day				-18.59										4.39																6.28

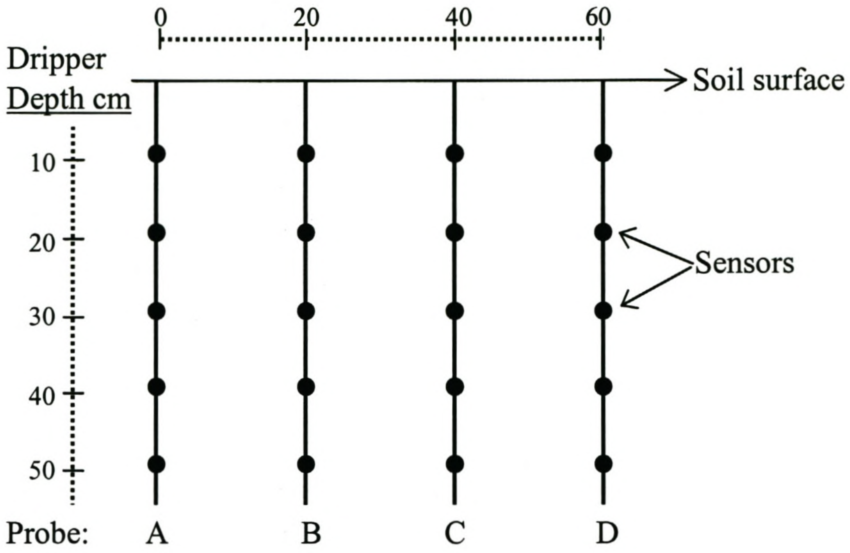


Figure 1. Illustration of the different positions of the EnviroSCAN probes in the soil profile in the field. Four probes, probe A, B, C, and D were installed at four different measuring positions, respectively 0, 20, 40 and 60cm away from the dripper. Each probe has 5 sensors at five measuring depths: 10, 20, 30, 40 and 50cm beneath soil surface.

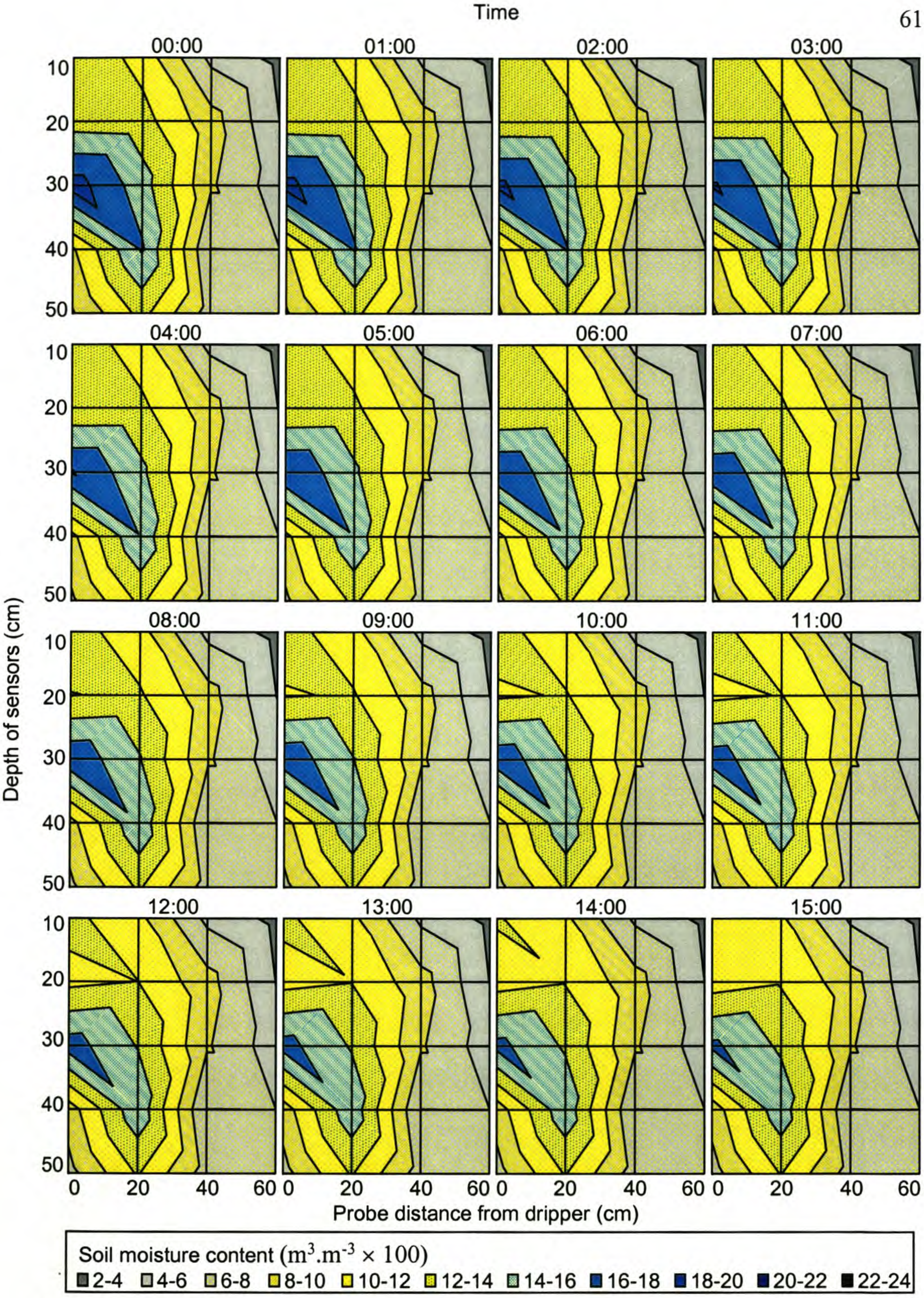


Figure 2. Contour graphs of the soil profile beneath a single dripper at different times during 8 April 2000. Soil moisture content ($m^3.m^{-3}$ × 100) is shown in different colours according to the legend.

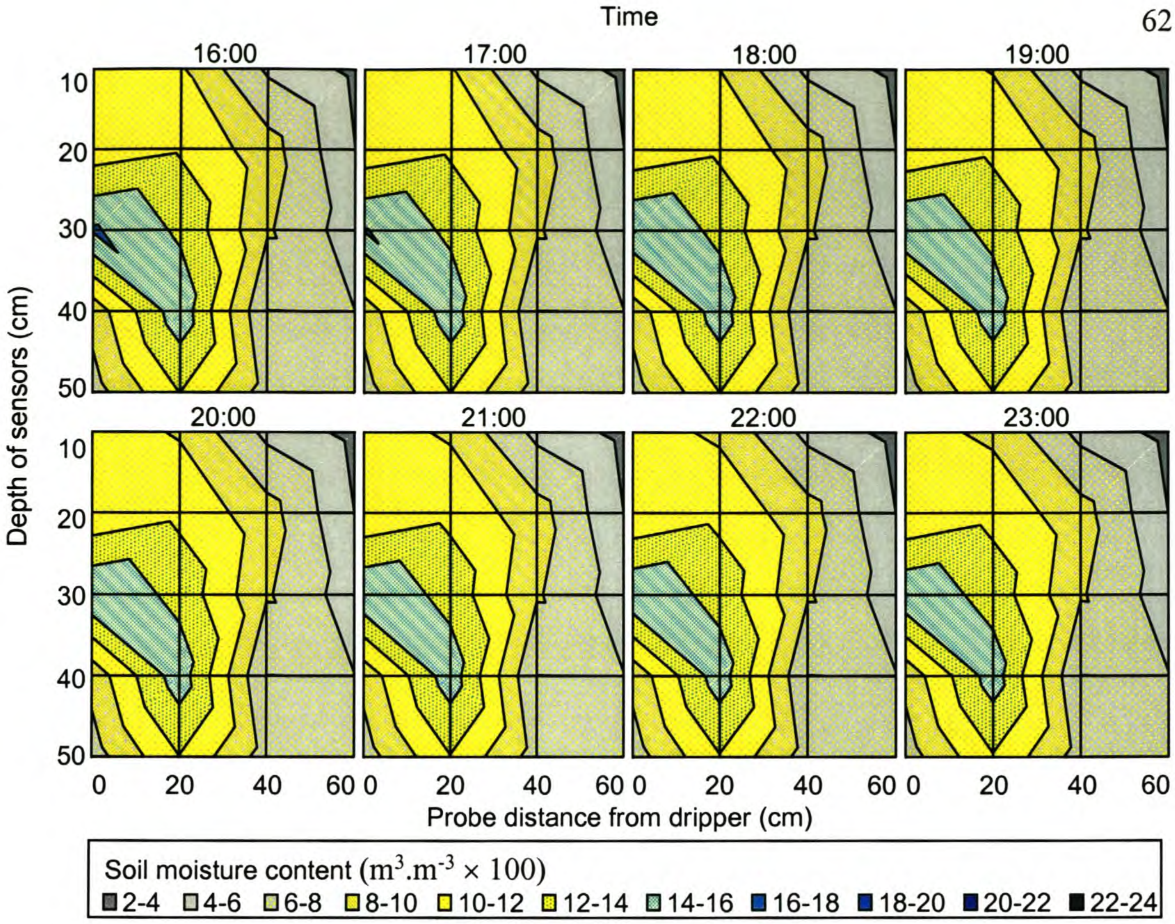


Figure 2. (continued)

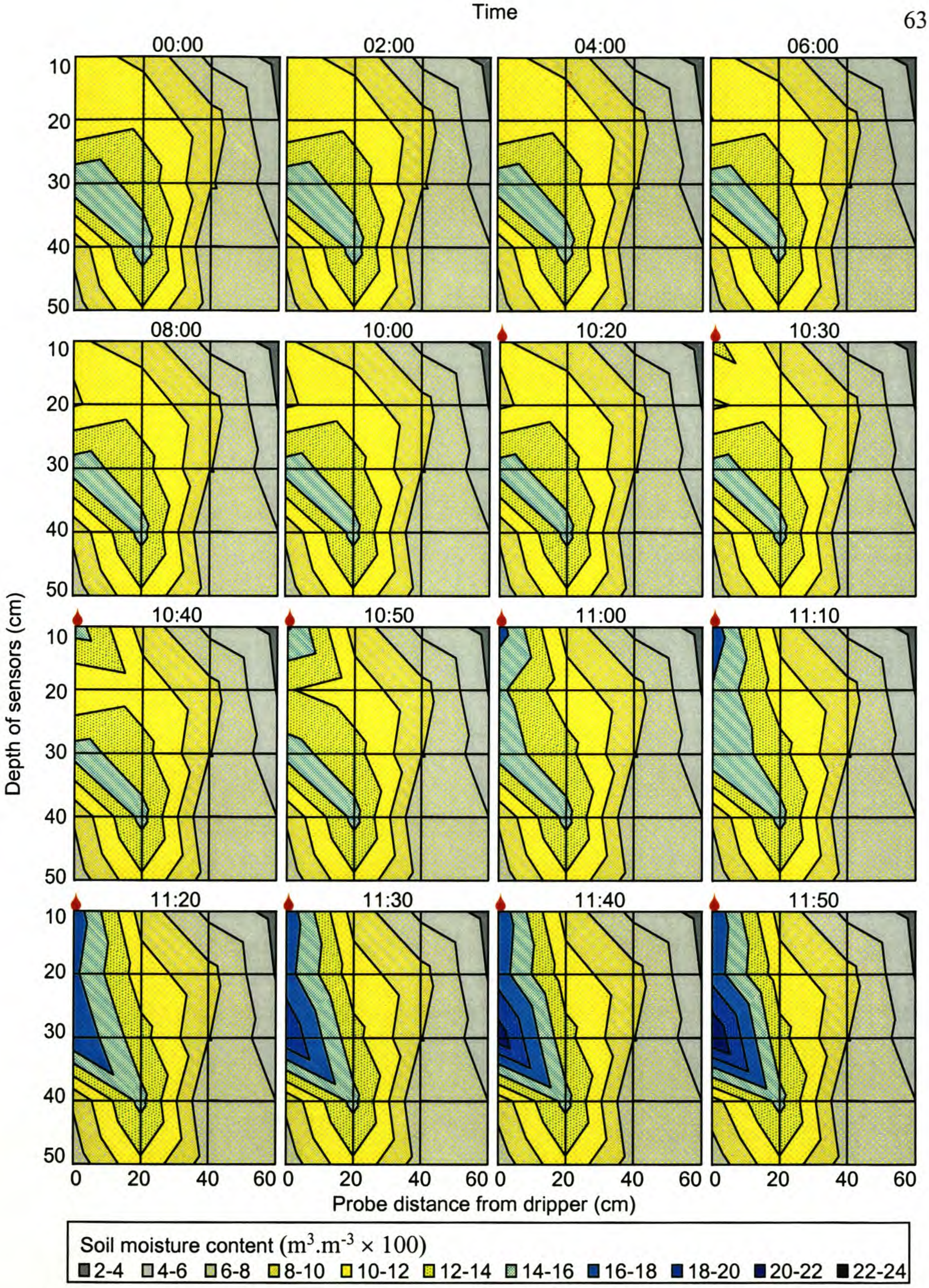


Figure 3. Contour graphs of the soil profile beneath a single dripper at different times during 9 April 2000. Soil moisture content ($m^3.m^{-3} \times 100$) is shown in different colours according to the legend. The position of the dripper as well as an irrigation event are indicated by a red drop at the right, above each relevant graph.

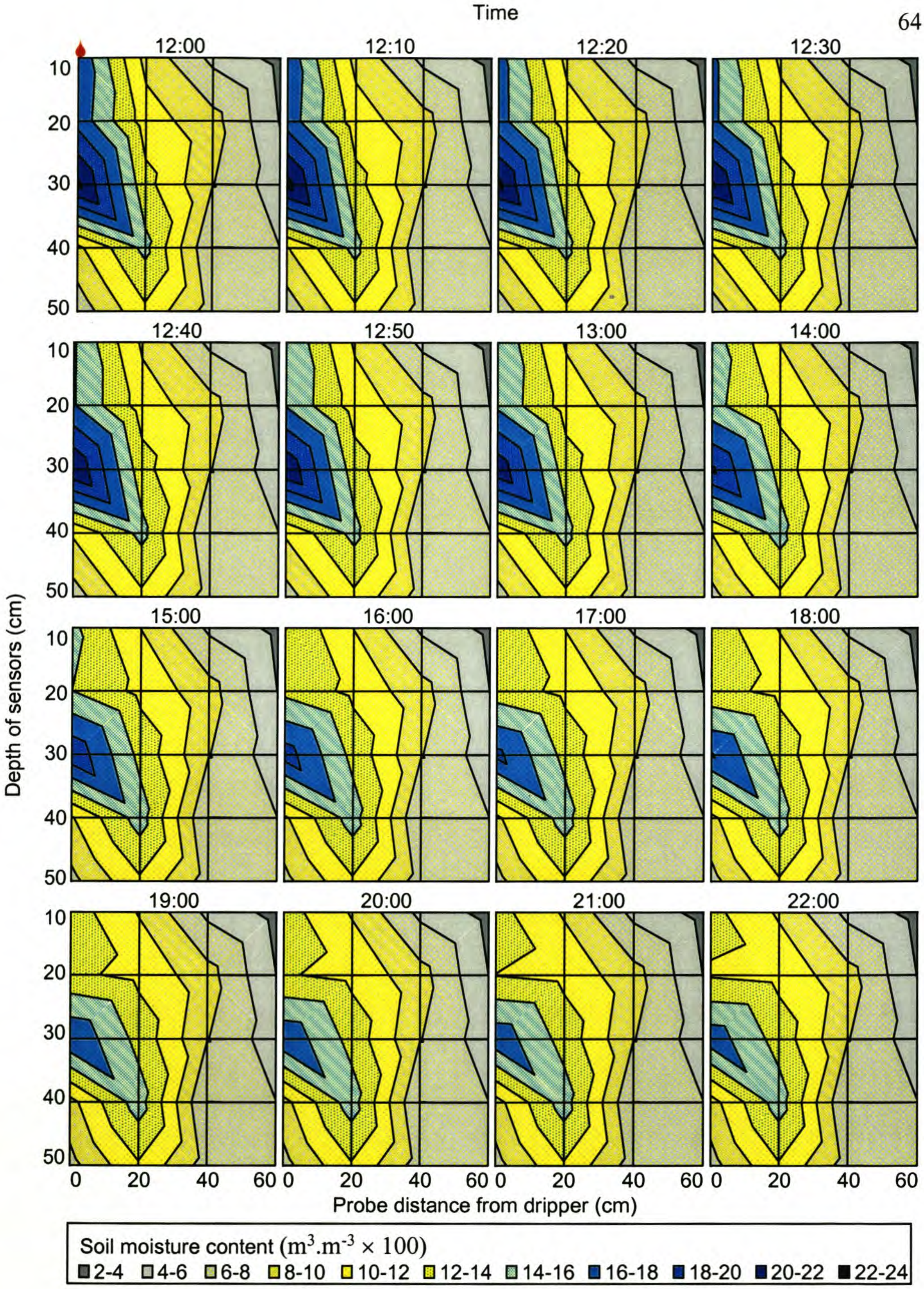


Figure 3. (continued)

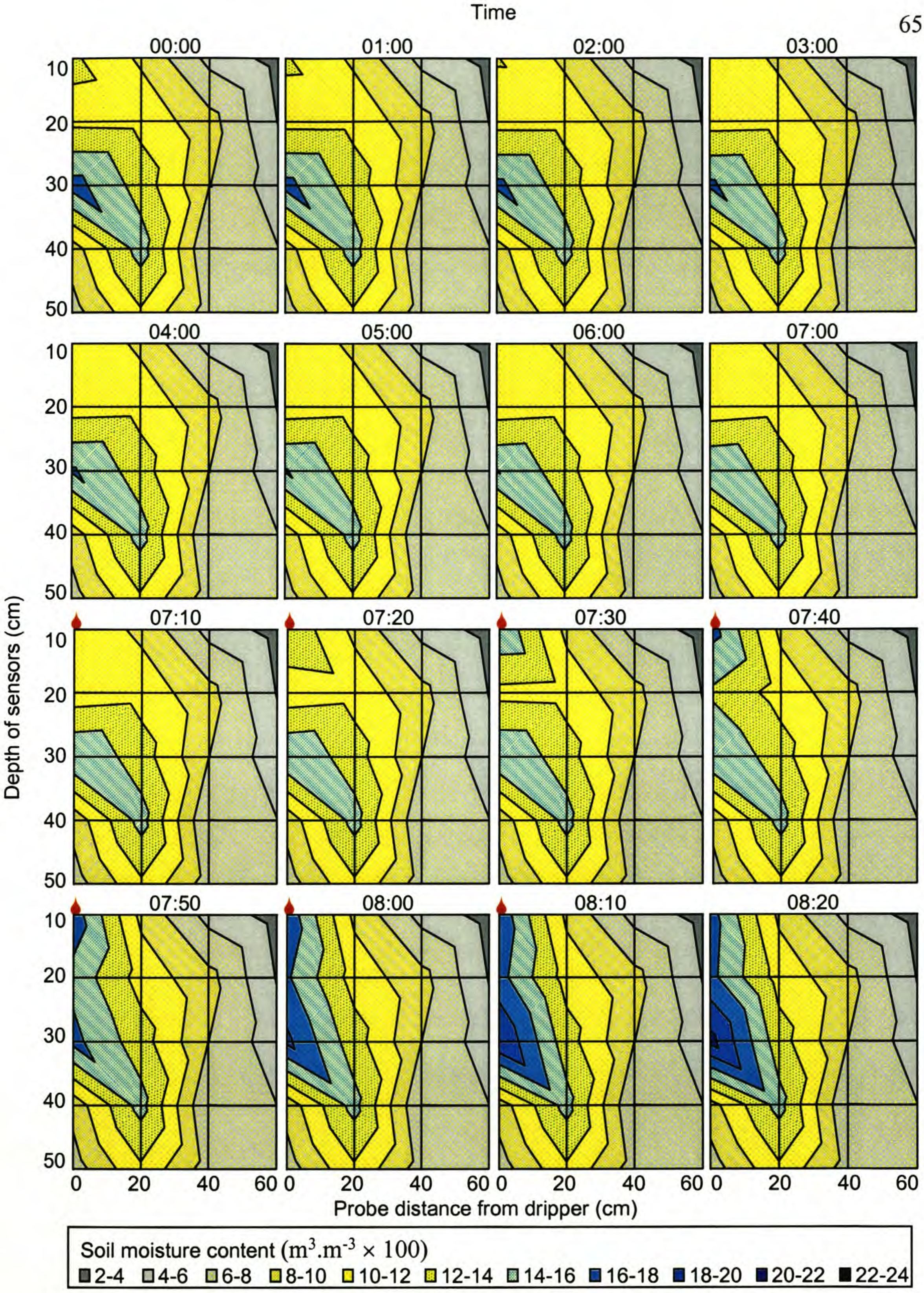


Figure 4. Contour graphs of the soil profile beneath a single dripper at different times during 10 April 2000. Soil moisture content ($m^3.m^{-3} \times 100$) is shown in different colours according to the legend. The position of the dripper as well as an irrigation event are indicated by a red drop at the right, above each relevant graph.

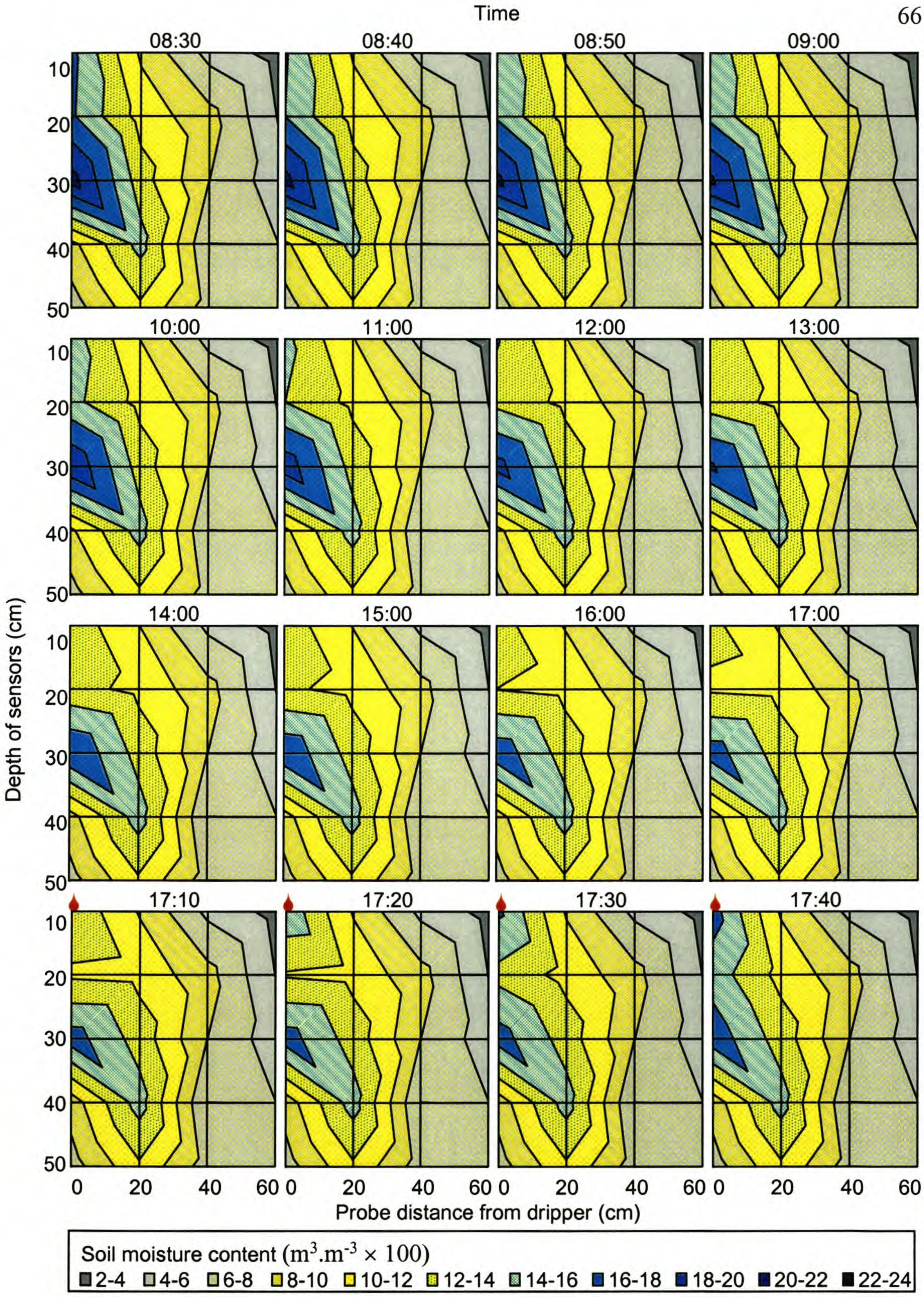


Figure 4. (continued)

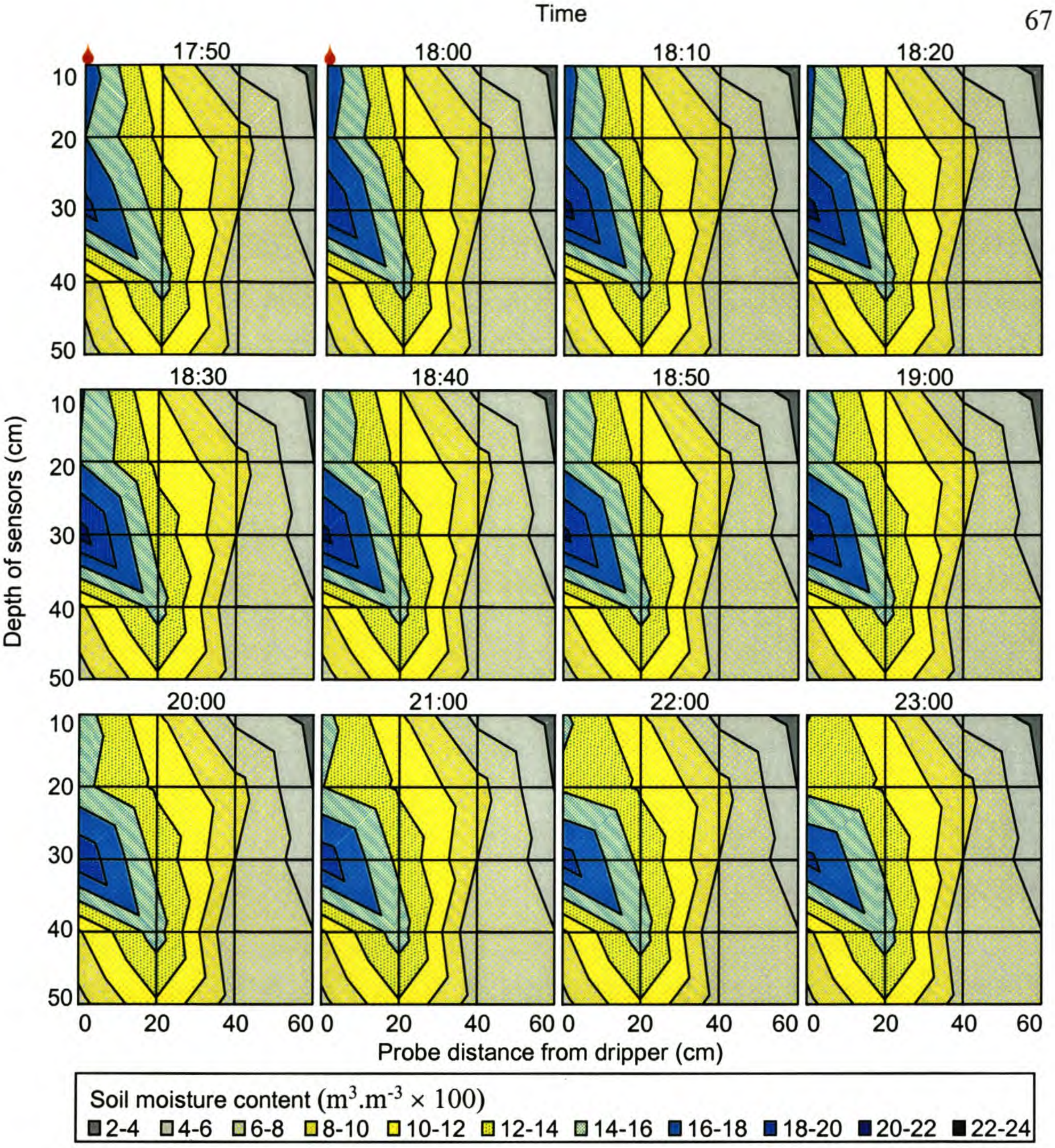


Figure 4. (continued)

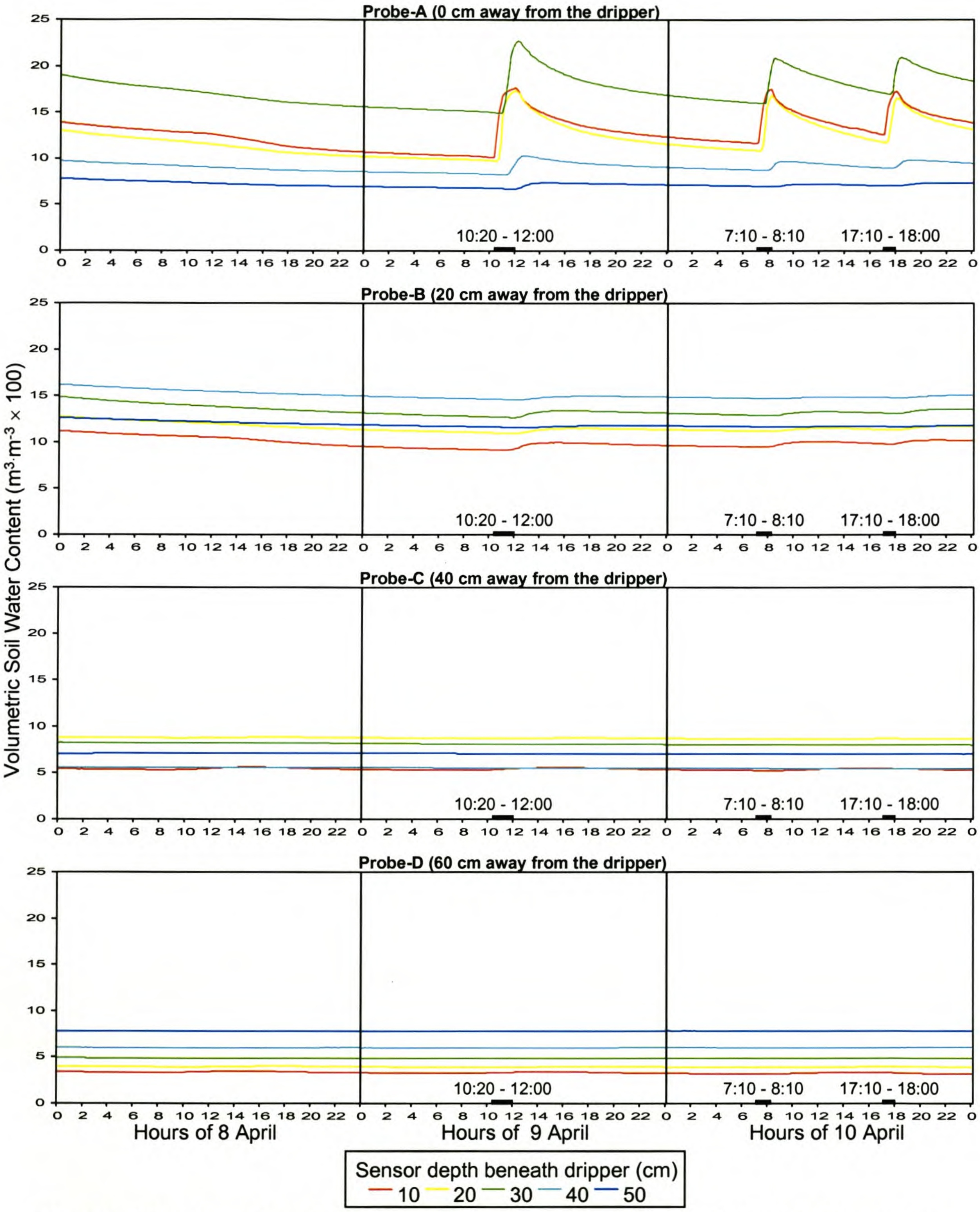


Figure 5. The change in volumetric soil water content (cm^3.cm^{-3} ×100) of the four probes with each measuring depth (10, 20, 30, 40, 50 cm) beneath the dripper on 8, 9, 10 April. The irrigation events are indicated by a thick line on the x-axis.

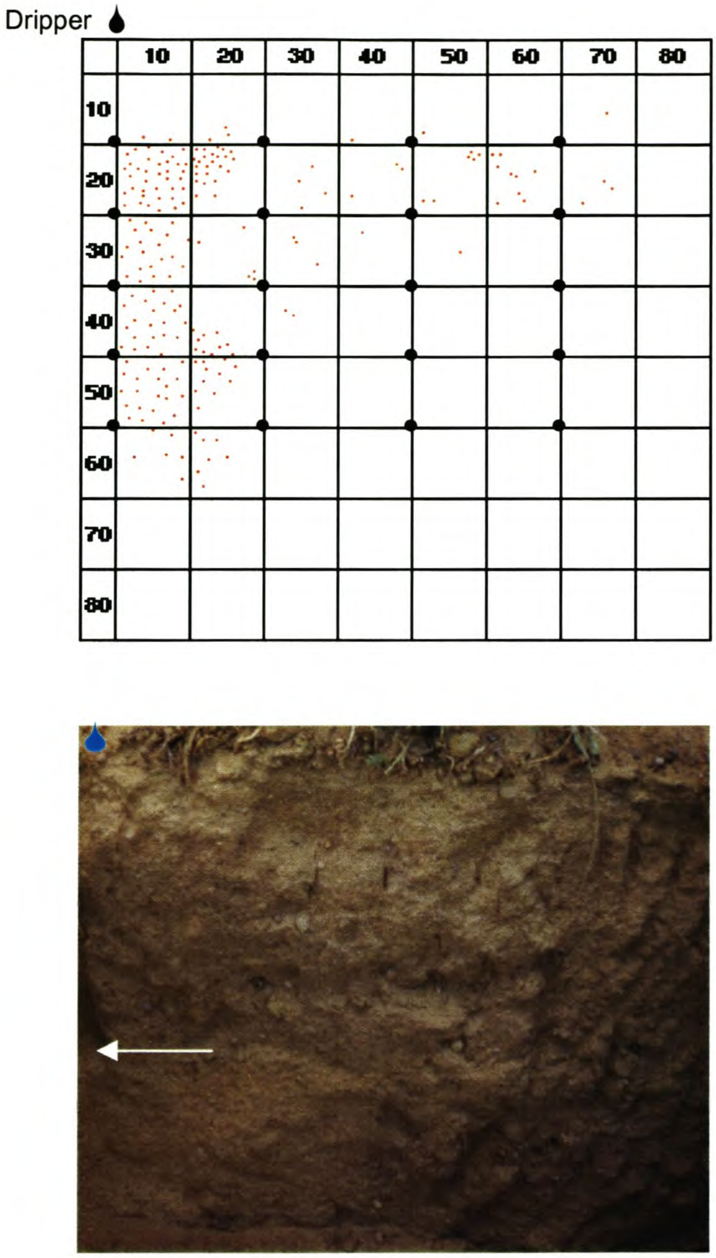


Figure 6. The root distribution of the soil profile where the probes were installed. The profile wall was perpendicular to the dripper line. The blocks represent an area of 10x10cm on the profile wall and the small red dots represent the fine roots (<1mm). The droplet indicates the position of the dripper, which was positioned close to the tree stem. The larger black dots indicate the position of the sensors. The photograph was taken from the soil profile and the arrow indicates the visual change in soil texture that can be the cause for the semi-impermeable layer.

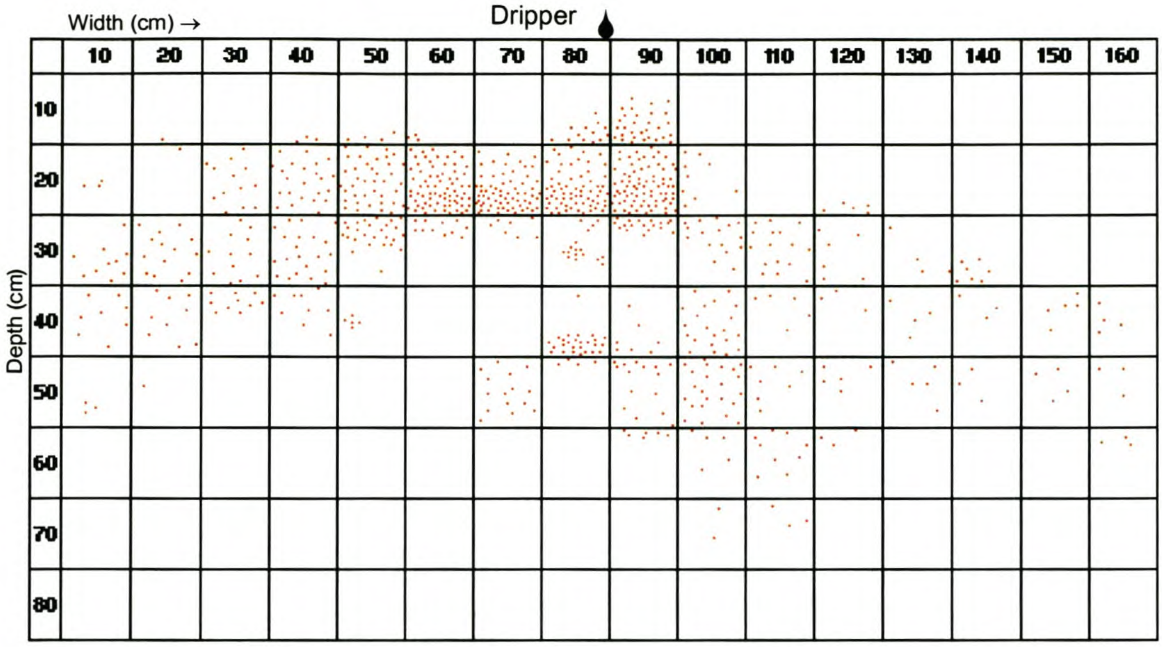
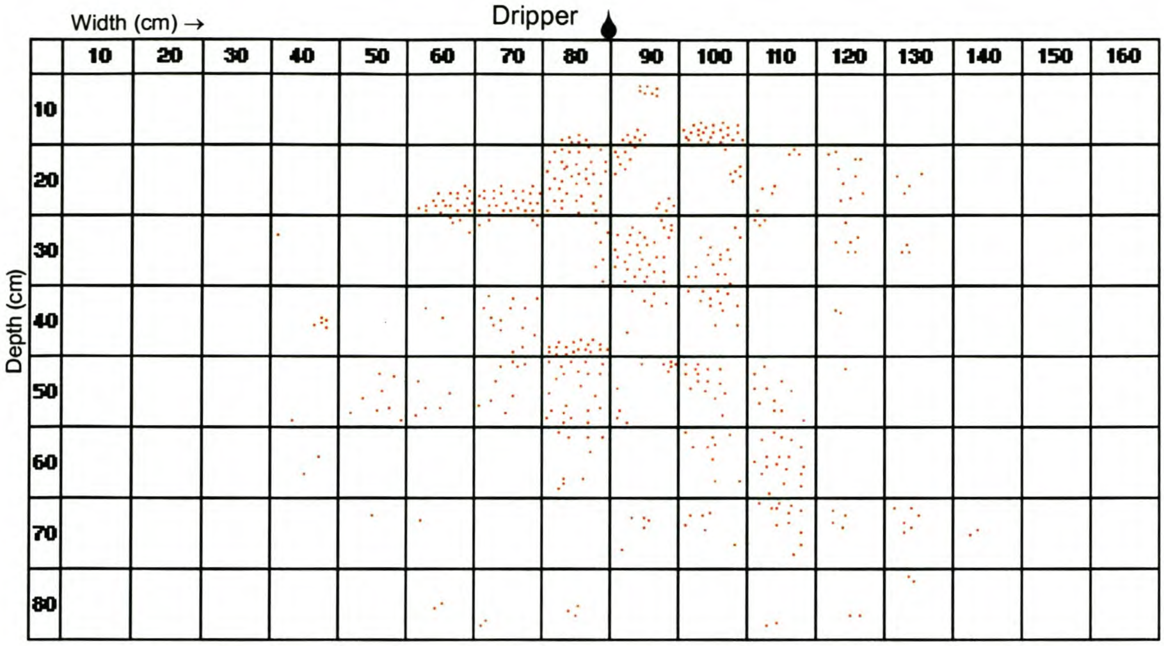


Figure 7. The root distribution of a soil profile made in the same row as where the EnviroSCAN was installed. The profile wall is parallel to the dripper line. The blocks represent an area of 10x10cm on the profile wall and the small red dots represent the fine roots (<1mm). The droplet indicates the position of the dripper, which was positioned close to the tree stem. The photograph corresponds with the soil profile.



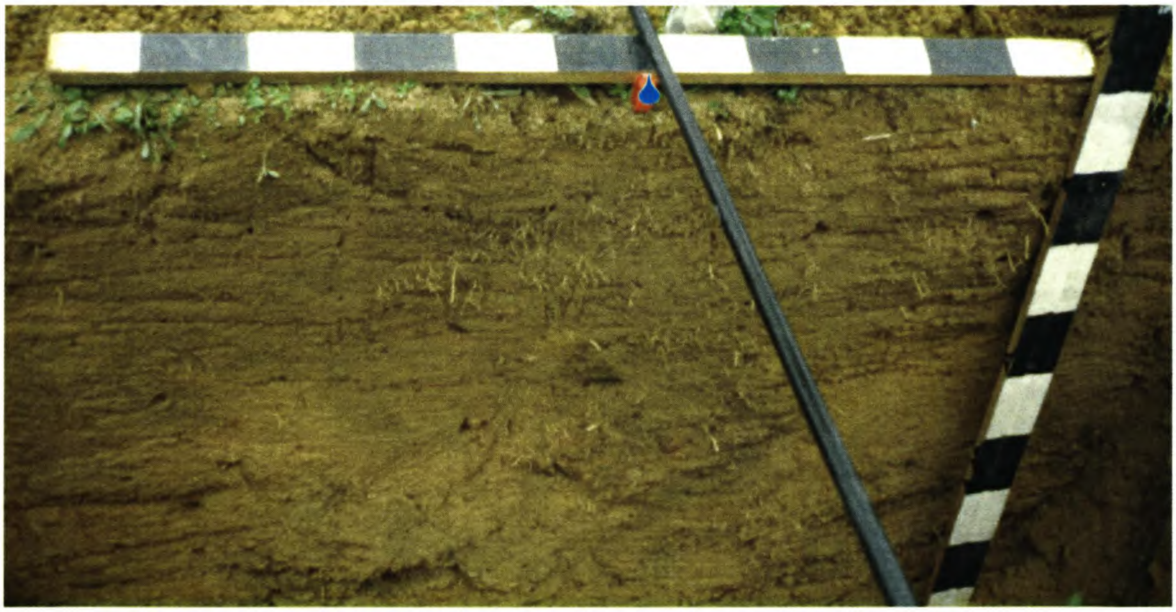


Figure 8. The root distribution of a soil profile made in the same row as where the EnviroSCAN was installed. The profile wall is perpendicular to the dripper line. The blocks represent an area of 10x10cm on the profile wall and the small red dots represent the fine roots (<1mm). The droplet indicates the position of the dripper, which was positioned close to the tree stem. The photograph corresponds with the soil profile.

4. PAPER 2: DRIP FERTIGATION: II. SYSTEM EFFECTS ON SOIL CHARACTERISTICS AND ROOT DISTRIBUTION.

Abstract

Three irrigation/fertigation treatments were investigated to ascertain the influence on soil characteristics and root distribution. These were: micro irrigation (MI) (micro-spinner irrigation with broadcast granular fertilization), conventional drip fertigation (CDF) (daily drip irrigation with daily or weekly fertigation with a unbalanced nutrient solution, containing macronutrients only) and daily drip fertigation (DDF) (daily fertigation of a balanced nutrient solution, containing macro- and micronutrients). The study was conducted in two locations, viz. in the Western Cape Province, on sandy soil, and in the Eastern Cape Province, on silt loam soil.

Micro Irrigation: A wide and even root distribution in the entire wetted volume was found on the sandy and silt loam soil. On the sandy soil, the soil $pH_{(KCl)}$ directly beneath the spinner was significantly lower than the $pH_{(KCl)}$ at positions farther away from the spinner.

Conventional Drip Fertigation: Root studies on sandy soil indicate a poor root development beneath the dripper, with a high concentration of roots in the area between the drippers. The poor root development directly beneath the dipper may be due to oxygen deficiency and/or acidification beneath the dripper. The soil $pH_{(KCl)}$ values were significantly lower directly beneath the dripper than farther away. In comparison to the sandy soil, the roots developed well beneath a dripper in a silt loam soil. It appears as if soil acidity and/or oxygen deficiency was not a problem on this soil type. The rest of the

root system was also well developed. This may be due to this soil's higher water holding capacity which creates a bigger wetted zone.

Daily Drip Fertigation: In the sandy soil it seems that the roots developed in a continuous column beneath the dripper line, with little root development farther than 20 cm from the dripper line. Where over-irrigation occurred it caused a poor root development, in a small area, directly beneath the dripper. The root density in this treatment was much higher than in the other two treatments. The use of a balanced nutrient solution and pulse irrigation may be reasons for the better root development. In a silt loam soil a very high concentration of roots was found beneath the dripper and the rest of the root system was also well developed. As with the CDF treatment, it appears as if oxygen deficiency was not a problem on this soil type.

Introduction

Irrigation and fertilization are two of the most important factors through which farmers can manage their crops. The application of fertilizers through irrigation water (fertigation) brought new possibilities to control nutrient supplies to the plant. Irrigation through drippers further increases fertigation efficiency by applying water and nutrients to a restricted wetted zone. However, the presence of roots in this restricted wetted zone is very important. This raises the following question: How does the root system adapt to this smaller wetted soil volume? Reports in the literature suggest that the root system adapts to wetting of only a portion of the soil volume by the proliferation of roots in the wetted zone (Bar-Yosef, 1977; Levin *et al.*, 1980; Goode *et al.*,1978).

Fertigation also influences soil acidity, salinity and oxygen availability beneath the dripper. These factors, in turn, have an influence on root growth and distribution. It is known that a low soil pH value may cause root growth reduction (Islam *et al.*, 1980) and Al toxicity (Magistad, 1925). A saline environment imposes osmotic (Itoh *et al.*, 1987) and ionic (Kafkafi, 1991) stress on roots which may cause a reduction in root elongation (Roundy, 1985). The root system also responds immediately to a reduction in oxygen supply, by cessation of new root initiation and retardation of root extension (Lemon and Erickson, 1955).

Root distribution studies can determine the concentration of fine roots in and around the wetted volume. The distribution of fine roots provides an indication of how effective the water and nutrients can be absorbed. It also indicates whether soil acidity, salinity and oxygen supply are problems. Understanding the root distribution under different irrigation treatments can assist in determining appropriate irrigation management. This is particularly true with drip treatments, since it is widely believed that drip irrigation may limit the extent of root development.

The objective of this study is to quantify the influence of different irrigation and fertigation treatments on root distribution, soil acidity and salinity.

Materials and methods

The study was conducted in two locations, viz. in the Western Cape Province (32,5°S, 19°E; mediterranean climate) and in the Eastern Cape Province (34°S, 25,5°E; summer rainfall climate) of South Africa.

In the Western Cape Province the study was conducted in the Citrusdal area on commercial farms. It was not possible to use the same plant material and soil type for all three treatments. Different orchards, on different commercial farms with randomly picked trees were used. Details of the orchards are provided in Table 1. In two treatments the soil type was classified as a Kroonstad (Soil Classification Working Group, 1991) form and in the other treatment as a Clovelly (Soil Classification Working Group, 1991) form. For all three treatments the texture class was a sandy soil. In the Eastern Cape Province, the study was conducted near Addo, on a Research Farm of the Agricultural Research Council, Institute for Tropical and Subtropical Crops. The study was done on an existing randomized block design experiment, containing the three treatments used. 'Midknight' Valencia trees (*C. sinensis* L. Osbeck) planted in May 1991 on rough lemon rootstock, spaced at 6,6 x 4,0 m were used. The soil was classified as an Oakleaf (Soil Classification Working Group, 1991) form and the texture class a silt loam soil.

[Table 1]

Three treatments, each consisting of a different irrigation/fertigation system where chosen to investigate the influence of irrigation/fertigation on soil characteristics and root distribution. The exact nutrient content in each fertigation treatment is unknown and only the fertigation concepts will be discussed. The description of the treatments and irrigation scheduling used, are the same for Citrusdal and Addo, unless otherwise mentioned.

Irrigation/fertigation methods:

Micro Irrigation (MI): Micro-spinner irrigation with broadcast fertilization. Irrigation scheduling was done according to soil water content measured with neutron moisture probes.

Conventional Drip Fertigation (CDF): Daily fertigation in Citrusdal and weekly fertigation in Addo of a unbalanced nutrient solution containing macronutrients only. In Citrusdal the scheduling was done with an evaporation pan and adjustments made according to soil water content measured with neutron moisture probes. In Addo, irrigation scheduling was done according to soil water content measured with neutron moisture probes. The irrigation requirement per day was applied in one pulse.

Daily Drip Fertigation (DDF): Daily fertigation of a balanced nutrient solution containing macro- and micronutrients. In Citrusdal, irrigation scheduling was done according to soil water content measured with EnviroSCAN capacitance probes (Sentek) and in Addo with neutron moisture probes. In Citrusdal, the irrigation requirement per day was applied in a few shorter pulses. In Addo the irrigation requirement was applied in one pulse.

Soil pH and resistance:

To determine whether acidification and salt accumulation occured beneath the drippers/spinners, soil $pH_{(KCl)}$ and electrical resistance were measured. In Citrusdal, soil samples for $pH_{(KCl)}$ and electrical resistance analyses were taken with a soil auger, at different positions from randomly picked drippers/spinners in the field. The samples were taken directly below the dripper and at distances of 20, 40 and 60 cm from the dripper at 0-20, 20-40 and 40-60 cm depths below the soil surface. For analysis of variance the treatments were taken as distances away from the dripper with four replications in a complete randomized design. The soil samples were air-dried, ground and passed through a 2-mm sieve. Soil pH was measured in water and 1*M* KCl solution at a soil:solution ratio of 1:1 using a pH meter. The soil resistance was measured with a resistance meter (YSI 3200 Conductivity instrument) on the same saturated water and soil paste used for the pH measurements.

Statistical analyses were performed with the SAS statistical package (SAS Institute Inc., 1990).

In Addo, only two samples were taken for each treatment, one directly beneath the dripper/spinner and one 30 cm away from the dripper/spinner at 30 cm beneath the soil surface. Only the soil $pH_{(KCl)}$ of the soil was measured, not the resistance. No analysis of variance was done on these samples

Root distribution

Root distribution was quantified using the trench profile method (Böhm, 1979). Trenches were opened perpendicular and parallel to the dripper line, directly beneath the dripper/spinner. The roots were exposed by removing a soil layer of approximately 5-10 mm with a knife and water stream using a hand sprayer. A grid with 10 x 10 cm blocks was mapped on the profile wall, using nails. The exposed root cut-off points were then mapped in their natural position.

Water content distribution measurements in a sandy soil, by EnviroSCAN probes, indicated that the extent of horizontal water movement was confined to a radius of about

20 cm from the dripper (Paper 1). The wetted volume is the area where most of the water and nutrients, applied by fertigation, are present. However, the area directly beneath the dripper is also the area with the biggest risk for soil acidity and oxygen deficiency. The distribution of fine roots in and around this wetted volume provides an indication of how effective the water and nutrients can be absorbed. It also shows whether soil acidity, salinity and oxygen deficiency were a problem.

On the profile wall, two zones were identified (Figure 1). The first zone was the area 20 cm to each side of the dripper and 60 cm downwards, zone A. The second zone, zone B, was the 20 x 60 cm area on both sides of zone A. Although the wetted volume in the silt loam soil was expected to be larger, the zone dimensions were kept the same for both soil types. The number of root points in zones A and B were calculated as a percentage of the total amount of roots in these two zones to indicate the relative root distribution in these two zones. The profile walls perpendicular and parallel are indicated separately. Where more than one dripper was available for a treatment, the average number of root points was used.

[Figure 1]

Results and discussion

Sandy soils

Micro Irrigation (MI)

Soil acidity and salinity: In the 0-20 cm soil layer the position directly below the spinner showed a significant ($P < 0.05$) lower $\mathrm{pH}_{(\mathrm{KCl})}$ value than the positions 40 and 60 cm away from the dripper (Figure 2). A significant difference ($P < 0.05$) in electrical resistance measurements was found in the 0-20 cm and 20-40 cm soil layers (Figure 3). The resistance at 60 cm away from the spinner was significantly higher than the resistance at the other positions. This indicates a lower salt concentration further away from the spinner. In the micro irrigation treatment the water was evenly spread over the soil surface with a radius of 1.75 m. Therefore the water application would not be expected to influence acidification or salt accumulation beneath the spinner. However, the reason for the differences in $pH_{(KCl)}$ and resistance values may be due to uneven broadcast application of ammonium-containing fertilizer or lime.

[Figures 2 and Figure 3]

Root distribution: Since the water was evenly spread over the soil surface it would be expected that the roots would be distributed evenly in the entire wetted area. Theoretically, both zones A and B, which both occupied 50% of the total zone, should contain 50% of the total number of roots. The relative root distribution in the profile walls parallel to the dripper line (Figure 4b), were almost the same in the two zones. This indicates an even root distribution. In Figure 4a it can be seen that the relative distribution in the profile walls perpendicular to the dripper line was somewhat lower in zone A than in zone B. This is probably due to natural variation, for there is no pattern in the root distribution that can be correlated with the irrigation pattern. The root distribution patterns can be seen in Figures 5 and 6.

[Figures 4, 5 and 6]

Conventional Drip Fertigation (CDF)

Soil acidity and salinity: At 20-40 cm beneath the soil surface the position directly below the dripper showed a significant lower soil $pH_{(KCl)}$ value than the 40 cm- and 60 cm-positions (Figure 2). The low $pH_{(KCl)}$ value beneath the dripper may be due to ammonium-containing fertilizers which are applied through the irrigation water and known to cause acidification. These results are in accordance with results by Parchomchuk *et al.* (1993), who found that acidification was most severe directly beneath the dripper. The electrical resistance directly below the dripper was significantly higher ($P < 0.05$) than positions further away form the dripper (Figure 3). The high resistance below the dripper indicates a low salt concentration. The salts were possibly leached from directly below the dipper or laterally moved with the water-front.

Root distribution: In drip irrigation, point source water spreads from the dripper in a three-dimensional flow. It creates an onion-shaped mass of wetted soil. The soil is saturated in the zone below the dripper while the rest of the volume is unsaturated. In the saturated zone, lack of oxygen and anaerobic conditions can develop which is detrimental for root development. As can be seen in Figures 7 and 8, there is a low concentration of roots beneath all the drippers. The roots are generally concentrated around the wetted area and between the drippers. The soil would have been drier and better aerated with oxygen in the area between the drippers. For the profile wall perpendicular to the dripper line, the relative distribution of roots in zone A and zone B was, respectively, 18% and 82% (Figure 4a). In the profile wall parallel to the dripper line, the relative distribution of roots in zone A and zone B was, respectively, 28 and 72% (Figure 4b). The lack of roots directly beneath the dripper can be due to a low soil pH and/or low oxygen concentration beneath the dripper. As seen in Figure 2, the soil $pH_{(KCl)}$ values in the 20-40 cm soil layer was significantly lower beneath the dripper than further away. This indicates that acidification beneath the dripper may have contributed to the poor root development beneath the dripper. In this treatment, the irrigation requirement was applied in one pulse, which does not allow time for air to be drawn into the soil. Therefore, lower oxygen concentrations beneath the dripper would be expected, compared to the DDF treatment, where the water was applied in pulses.

[Figures 7 and 8]

Daily Drip Fertigation (DDF)

Soil acidity and salinity: No significant difference ($P < 0.05$) was found in the $pH_{(KCl)}$ values at the different measuring positions (Figure 2). The lack of significant difference between the position directly beneath the dipper and the positions further away from the dripper, indicates the absence of acidification beneath the dripper. The balanced nutrient solution used in the DDF treatment may be responsible for preventing acidification beneath the dripper. The resistance values (Figure 3) indicate a gradual increase in salt concentration with increasing distance from the dripper. The salts were possibly leached from directly below the dipper or laterally moved with the water-front.

Root distribution: It is important to mention that due to a calculation error this orchard was over irrigated before our root study started. The correction was only made days before Figure 9a and Figure 10a were drawn. Figure 9c and Figure 10b were drawn three months later and Figure 9e and Figure 10e six months later.

The root distribution perpendicular to dripper line, Figure 9a and 9c, both show a high concentration of roots beneath the dripper, but with a small area in the middle where almost no roots were found. This may be due to oxygen deficiency, which was caused by the over-irrigation. At the periphery of this area there was a very high concentration of roots, probably at the point where oxygen became more available. There is no difference between the soil $pH_{(KCl)}$ value below the dripper, where the root concentration was low, and the soil $pH_{(KCl)}$ value where the root concentration was high (Figure 2). This indicates that a low soil pH beneath the dripper was not the reason for the low root concentration. The root distribution parallel to the dripper line (Figure 10b) shows almost the same distribution pattern as in Figures 9a and 9c. There is a small area with a very low concentration of roots in the vicinity of each dripper, with the highest concentration between the two drippers. Figure 10a show a localized concentration of roots on one side of the dripper with very few roots on the other side. Figure 9e and Figure 10e drawn 6 months after the irrigation scheduling was rectified. A better oxygen supply to the roots below the dripper, due to better irrigation scheduling, would most likely be the reason for the improved root development beneath the dripper.

[Figures 9 and 10]

The relative distribution between zone A and zone B in the profile walls perpendicular to the dripper line was 67% in zone A and 33% in zone B (Figure 4a). This indicates that the roots were concentrated around the dripper, with little root development further away than 20 cm from the dripper line. The difference in relative distribution between zone A and zone B in the profile walls parallel to the dripper line was not as large, with 54% in zone A and 46% in zone B (Figure 4b). Therefore, it seems that the roots developed in a continuous column beneath the dripper line, except where over-irrigation caused poor root development directly beneath the dripper.

The use of pulse irrigation in this treatment compared to the one irrigation pulse in the CDF treatment, may also be a reason for the better root development beneath the dripper. When water application is ceased after a pulse, air will be drawn in from the atmosphere causing aeration of wetted zone. The next pulse will push the oxygen downward and this may improve root development in the wetted zone beneath the dripper.

Silt loam soils

Soil acidity: Although the soil $pH_{(KCl)}$ measurements in all three treatments at the Addo experimental site, indicated a slight acidification beneath the dipper (Table 2), the soil $pH_{(KCl)}$ values was still above the optimal soil $pH_{(KCl)}$ of 6.5 (Miller and Gardiner, 199x). In this soil, a low $pH_{(KCl)}$ value beneath the dripper will not be a reason for poor root development.

[Table 2]

Micro irrigation (MI)

The root distribution under MI treatment on the silt loam is very similar to the even root distribution on the sandy soil (Figures 11a and 11b) . The relative root distribution in the two zones in both the profile wall parallel and perpendicular to the irrigation line are close to 50% (Figure 4c).

[Figure 11]

Conventional Drip Fertigation (CDF)

The profile wall perpendicular to the dripper line (Figure 12a) shows a higher relative root distribution in zone A, with 60% than in zone B, with 40% (Figure 4c). This is the opposite from what was seen on the sandy soils. It appears as if soil acidity and/or oxygen deficiency was not a problem on this soil type. Loamy soils, with a higher clay content than sandy soils, have a better acidification buffer capacity than sandy soil, because clay colloids have larger amounts of cation exchange sites than do sands (Miller and Gardiner, 199x). Loam soil also contains more micropores, which may keep the soil more aerated and prevents oxygen deficiency. The profile wall parallel to the dripper line (Figure 12b) shows a more even root distribution. The relative root distribution in zone A (54%) is not much higher than in zone B (46%) (Figure 4d). The higher water holding capacity of this soil cause a larger wetted soil volume beneath the dripper. The roots have a large volume of wetted soil to proliferate in, and can develop further away from the dripper

[Figure 12]

Daily Drip Fertigation (DDF)

These trees were changed over to the DDF treatment one year prior to the study being done. Before the change the trees were under a micro irrigation system for 8 years. At this site the rate of application exceeded the ability of the soil to absorb water and ponding at the dripper was observed. To decrease run-off water, a small depression was made around the dripper as indicated in Figure 13. Figures 13a and 13b clearly show a high concentration of roots around the depression. In both the profile walls, perpendicular and parallel, the relative root distribution in zone A is higher than in zone B (Figures 4c and 3d). There is no indication of the small area without roots, which was found beneath the drippers on the sandy soil. It appears as if soil acidity and oxygen deficiency was not a problem with this treatment on this soil type. The rest of the root system in Figure 13a and 13b is also well developed. This may be due to a bigger wetted zone in this soil with a high water holding capacity. Another explanation can also be that these roots are the remains of the root treatment under the previous micro irrigation system.

[Figure 13]

Conclusion

Micro Irrigation: A wide and even root distribution in the entire wetted volume was found on the sandy and silt loam soil. On the sandy soil, the soil $pH_{(KCl)}$ directly beneath the spinner was significantly lower than the $pH_{(KCl)}$ at positions further away from the spinner. This may be due to uneven broadcast application of ammonium-containing fertilizers or lime.

Conventional Drip Fertigation: Root distribution studies on the sandy soil indicate a poor root development beneath the dripper, with a high concentration of roots in the area between the drippers. The poor root development directly beneath the dipper may be due to oxygen deficiency and/or acidification beneath the dripper. The irrigation requirement was applied in one pulse, which does not allow time for air to be drawn into the soil. Therefore, low oxygen concentrations beneath the dripper would be expected. The soil $pH_{(KCl)}$ values were significantly lower directly beneath the dripper than farther away. In comparison to the sandy soil, the roots developed well beneath a dripper in a silt loam soil. It appears as if soil acidity and oxygen deficiency was not a problem on this soil type. Loam soils have a better buffer capacity than sandy soils to prevent acidification and contain more micropores that may keep the soil more aerated and prevent oxygen deficiency. The rest of the root system was also well developed. This may be due to this soil's higher water holding capacity that creates a big wetted zone.

Daily Drip Fertigation: Root distribution studies on the sandy soil, perpendicular to the dripper line, indicate that the roots were concentrated around the dripper with little root development further away than 20 cm from the dripper line. Where over-irrigation occurred, a small area with little root development was observed directly beneath the dripper. The root distribution studies parallel to the dripper line indicate a high root concentration between the drippers. Therefore, is seems that roots developed in a continuous column beneath the dripper line, except where over-irrigation caused poor root development directly beneath the dripper. The root density in this treatment was much higher than in the other two treatments. The use of a balanced nutrient solution and pulse irrigation may be reasons for the better root development. In a silt loam soil a very high concentration of roots was found beneath the dripper and the rest of the root system was also well developed. As with the CDF treatment, it appears as if oxygen deficiency and acidification was not a problem on this soil type.

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Literature cited

Bar-Yosef, B., 1977. Trickle irrigation and fertilization of tomatoes in sand dunes: Water, N, and P distribution in the soil and uptake by plants. *Agron. J.* **69:** 486-491.

Böhm, W., 1979. Methods of studying root systems. 33: 39-76. **In:** Billings, W.D., Golley, F., Lange, O.L. and Olsen, J.S. (eds.). Springer–Verslag, Heidelberg, New York.

Goode, J.E., Higges, K.H. & Hyrycz, K.J., 1978. Trickle irrigation of apple trees and the effect of liquid feeding with NO_3^- and K^+ compared with normal manuring. *J. Hort. Sci.* **53:** 307-316.

Islam, A.K.M.S., Edwards, D.G. & Asher, C.J., 1980. pH optima for crop growth: Results of a flowing nutrient culture experiment with six species. *Plant and Soil* **54:** 339-357.

Itoh, K., Nakamura, Y., Kawata, H., Yamada, T., Ohta, E., & Sakata, M., 1987. Effect of osmotic stress on turgor pressure in mung bean root cells. *Plant Cell Physiol.* **28:** 987-994.

Kafkafi. U., 1991. Root growth under stress - Salinity. pp. 375-391. **In**: Waisel,Y., Eshet, A. & Kafkafi, U. (eds.). *Plant roots: The hidden half.* Marcel Dekker, New York.

Lemon, E.R. & Erickson, A.E., 1955. Principle of the platinum microelectrode as a method of characterizing soil aeration. *Soil Science* **79:** 383-392.

Levin, I., Assaf, R. & Bravdo, B., 1980. Irrigation, water status nutrient uptake in an apple orchard. *Acta Hort.* **92:** 255-264.

Magistad, O.C., 1925. The aluminum content of the soil solution and its relation to soil reaction and plant growth. *Soil Science* **20:** 181-225.

Miller, R.W. & Gardiner, D. T., 199x. Acidic soil and their management. pp. 265-283. **In:** Miller, R.W. & Gardiner, D. T. (eds.). *Soil in our environment*. Eight Edition. Prentice Hall, Upper Saddle River, New Jersey.

Parchomchuk, P., Neilsen, G.H. & Hogue, E.J., 1993. Effect of drip fertigation of NH_4^--N and P on soil pH and cation leaching. *Can. J. Soil Sci.* **73.** 157-164.

Roundy, B.A., 1985. Root penetration and shoot elongation of tall wheatgrass and basin wildrye in relation to salinity. *Can. J. Plant Sci.* **65:** 335-343.

SAS Institute Inc. 1990. SAS User's guide, Version 6, 4th ed., Vol, 1 Cary, N.C., 1-1290.

Soil Classification Working Group, 1991. Soil classification - a taxonomic system for South Africa. Memoirs on the Agricultural Natural Resources of South Africa No. 15. Department of Agricultural Development. Pretoria

Table 1. Plant material and the soil type of the experimental sites. In Citrusdal the study was conducted on different orchards of commercial farms. In Addo an existing randomized block design experiment, containing the three treatments, was used.

Plant material and soil type	Treatment			
	Citrusdal			Addo
	MI*	CDF*	DDF*	MI, CDF and DDF
Cultivar	'Nules Clementine' (*C. reticulata* Blanco)	'Nules Clementine' (*C. reticulata* Blanco)	'Midknight' Valencia (*C. sinensis* L. Osbeck)	'Midknight' Valencia (*C. sinensis* L. Osbeck)
Rootstock	'Troyer'	'Troyer'	'Troyer'	Rough Lemon
Age	7 yr.	4 yr.	5 yr.	9 yr.
Row direction	N-S	E-W	N-S	N-S
Spacing (m)	5 x 2	5.5 x 3	5 x 2	6.6 x 4
Soil form	Kroonstad	Clovelly	Kroonstad	Oakleaf
Texture class	Sandy	Sandy	Sandy	Silt loam

*MI = Micro Irrigation, CDF = Conventional Drip Fertigation, DDF = Daily Drip Fertigation

Table 2. The soil $pH_{(KCl)}$ beneath the dripper/spinner on a silt loam soil at the Addo experimental site. Two samples were taken, one directly beneath the dripper/spinner and one 30 cm away from the dripper/spinner at 30 cm beneath the soil

Treatment	Distance away from dripper/spinner	
	0 cm	30 cm
Micro Irrigation (MI)	6.7	7.7
Conventional Drip Fertigation (CDF)	7.4	7.7
Daily Drip Fertigation (DDF)	6.6	7.3

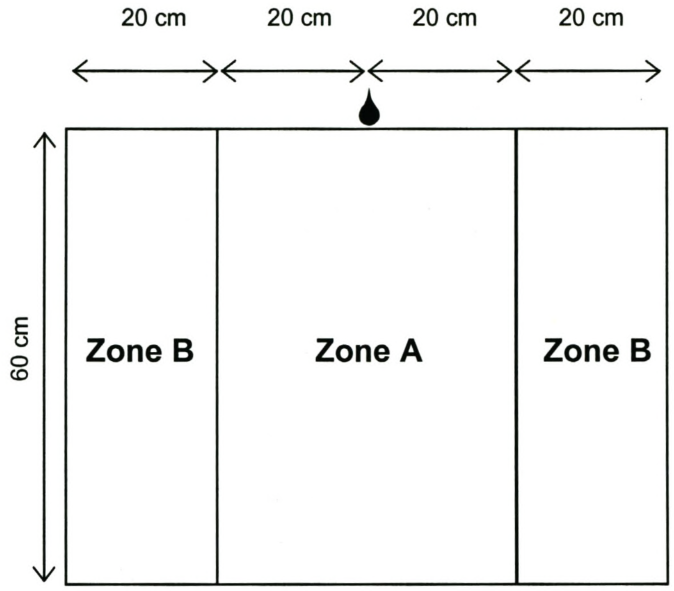


Figure 1. On the profile wall, two zones were identified. Zone A is the area 20 cm to each side of the dripper and 60 cm downwards and zone B is the 20 x 60 cm area on both sides of zone A.

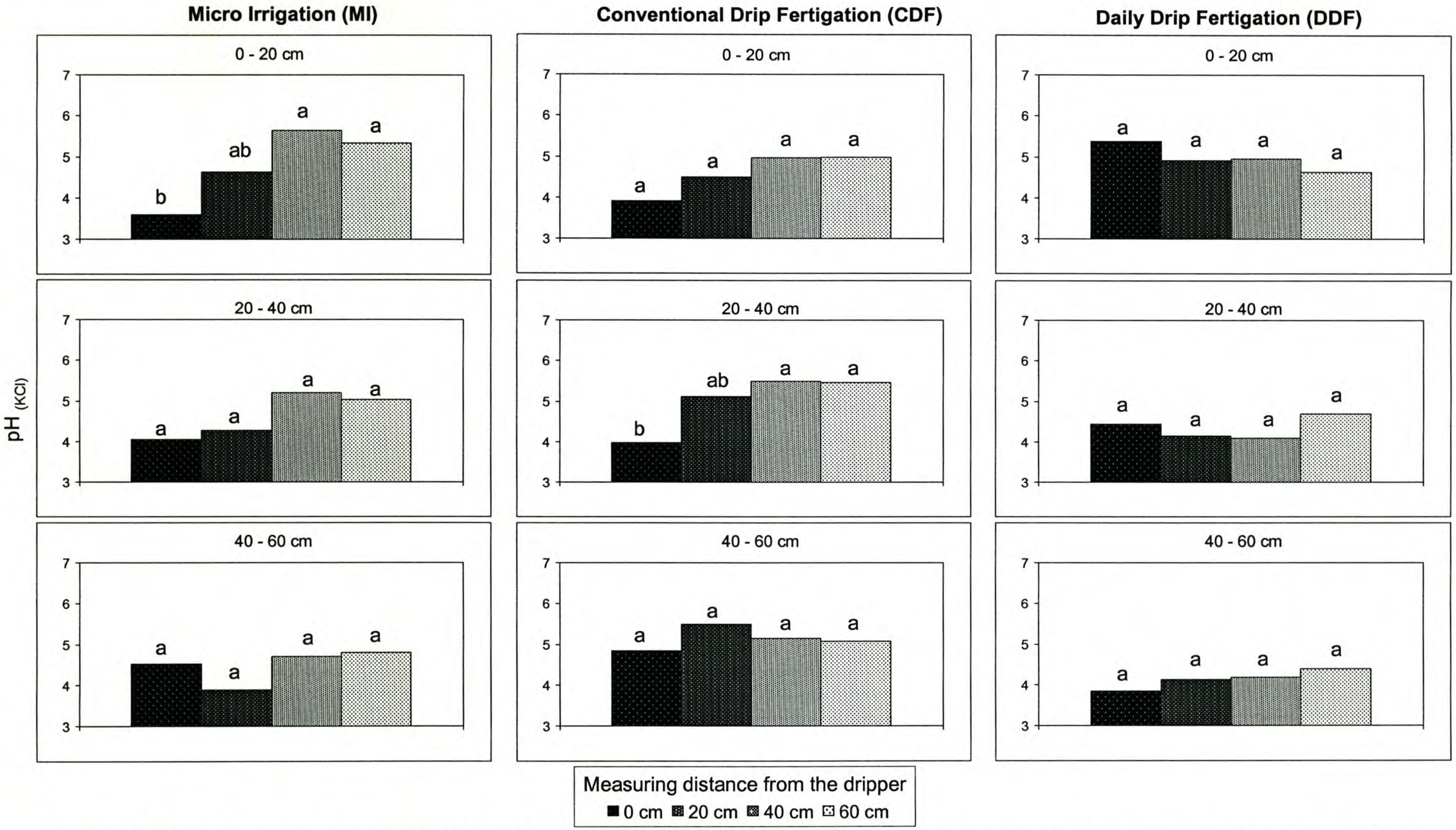


Figure 2. The soil $pH_{(KCl)}$ measurements of the three irrigation systems at Citrusdal. Each graph represent a measuring depth (0-20, 20-40 and 40-60 cm) beneath the soil surface. The measuring distance from the dripper is shown in different shades according to the legend. Columns following by the same letter are not significantly different ($P < 0.05$).

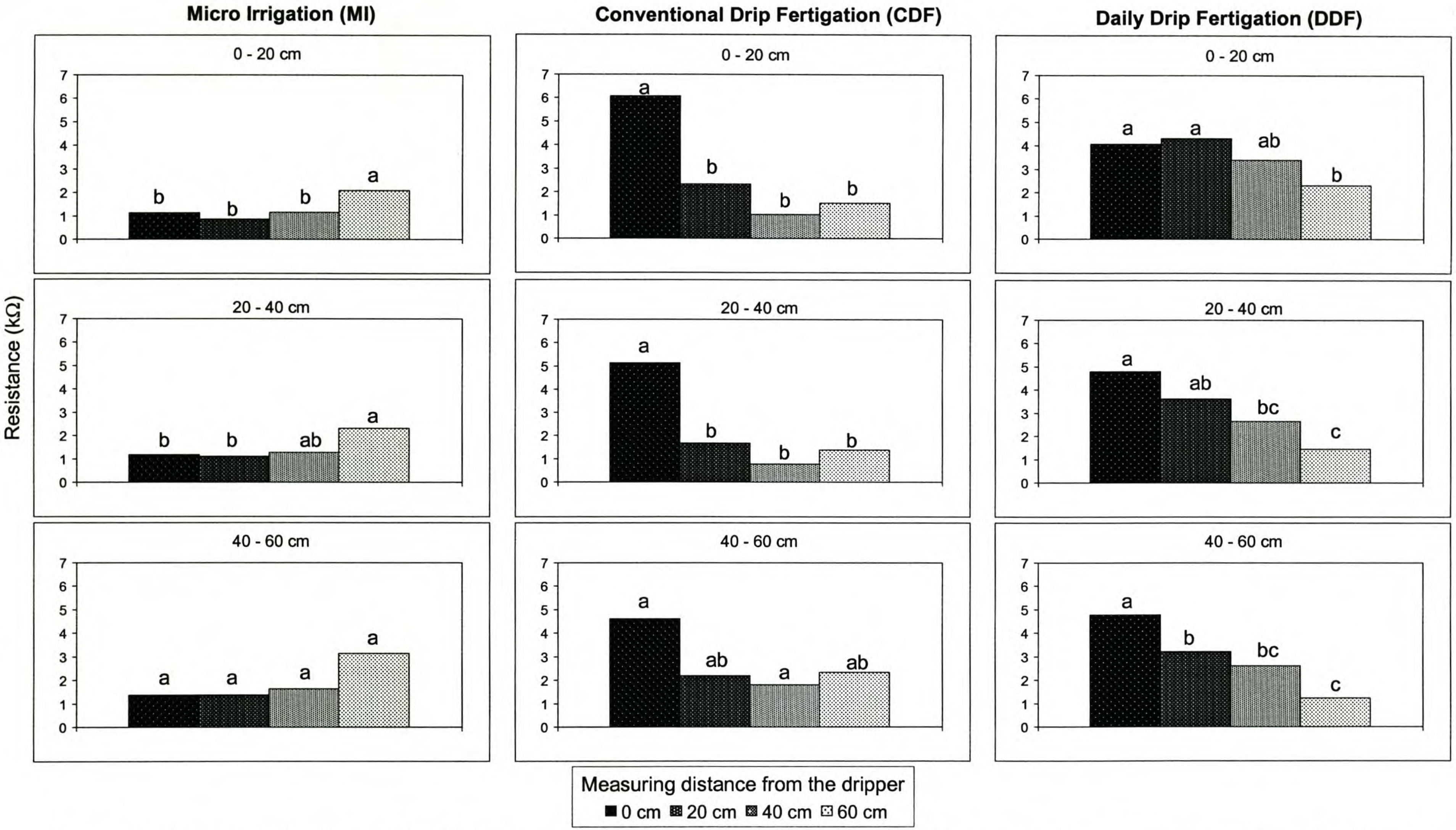


Figure 3. The soil electrical resistance measurements (kΩ) of the three irrigation systems at Citrusdal. Each graph represent a measuring depth (0-20, 20-40 and 40-60 cm) beneath the soil surface. The measuring distance from the dripper is shown in different shades according to the legend. Columns following by the same letter are not significantly different (*P* < 0.05).

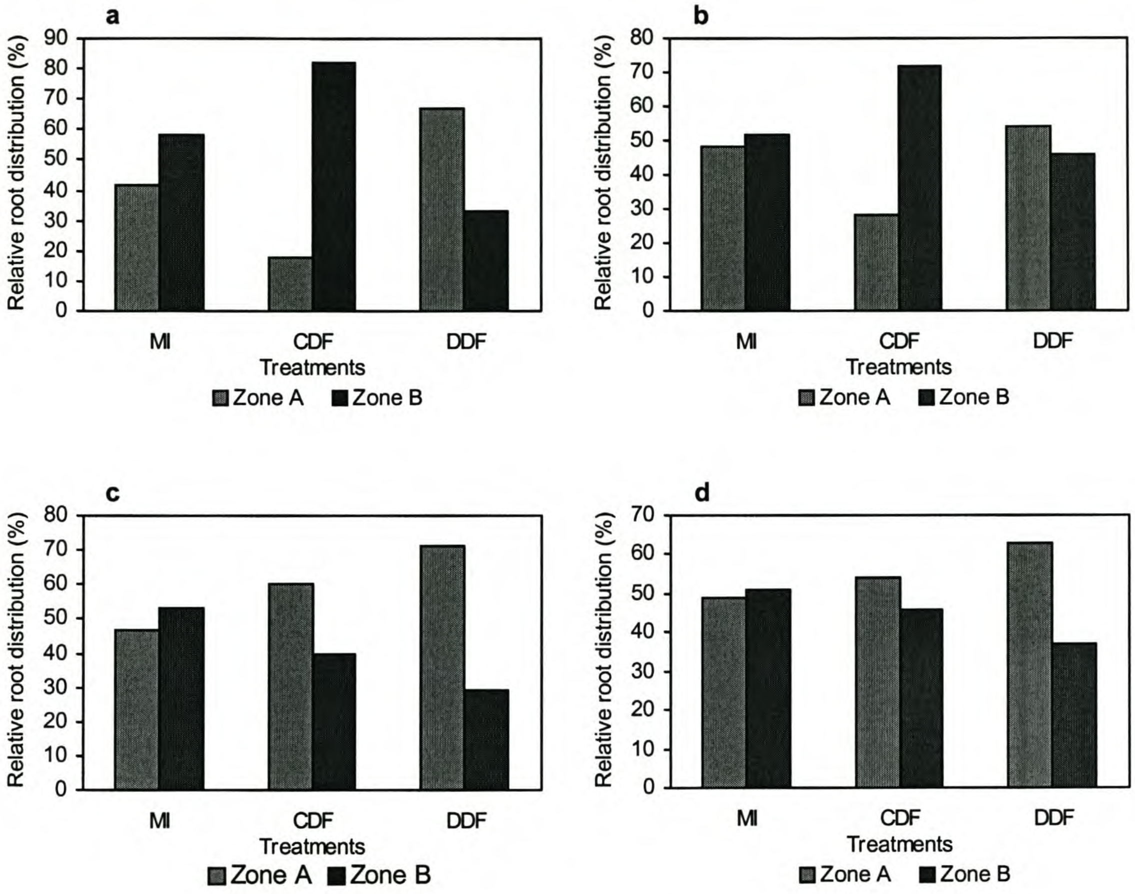


Figure 4. The relative root distribution of zone A and zone B in each treatment (MI = micro irrigation, CDF = conventional drip fertigation, DDF = daily drip fertigation). Zone A is the area 20 cm to each side of the dripper and 60 cm downwards and zone B was the 20x60 cm area on both sides of zone A. Graphs (a) and (b) represent the profile pits made in Citrusdal, with (a) perpendicular and (b) parallel to the dripper line. Graphs (c) and (d) represent the profile pits made in Addo, with (c) perpendicular and (d) parallel to the dripper line.

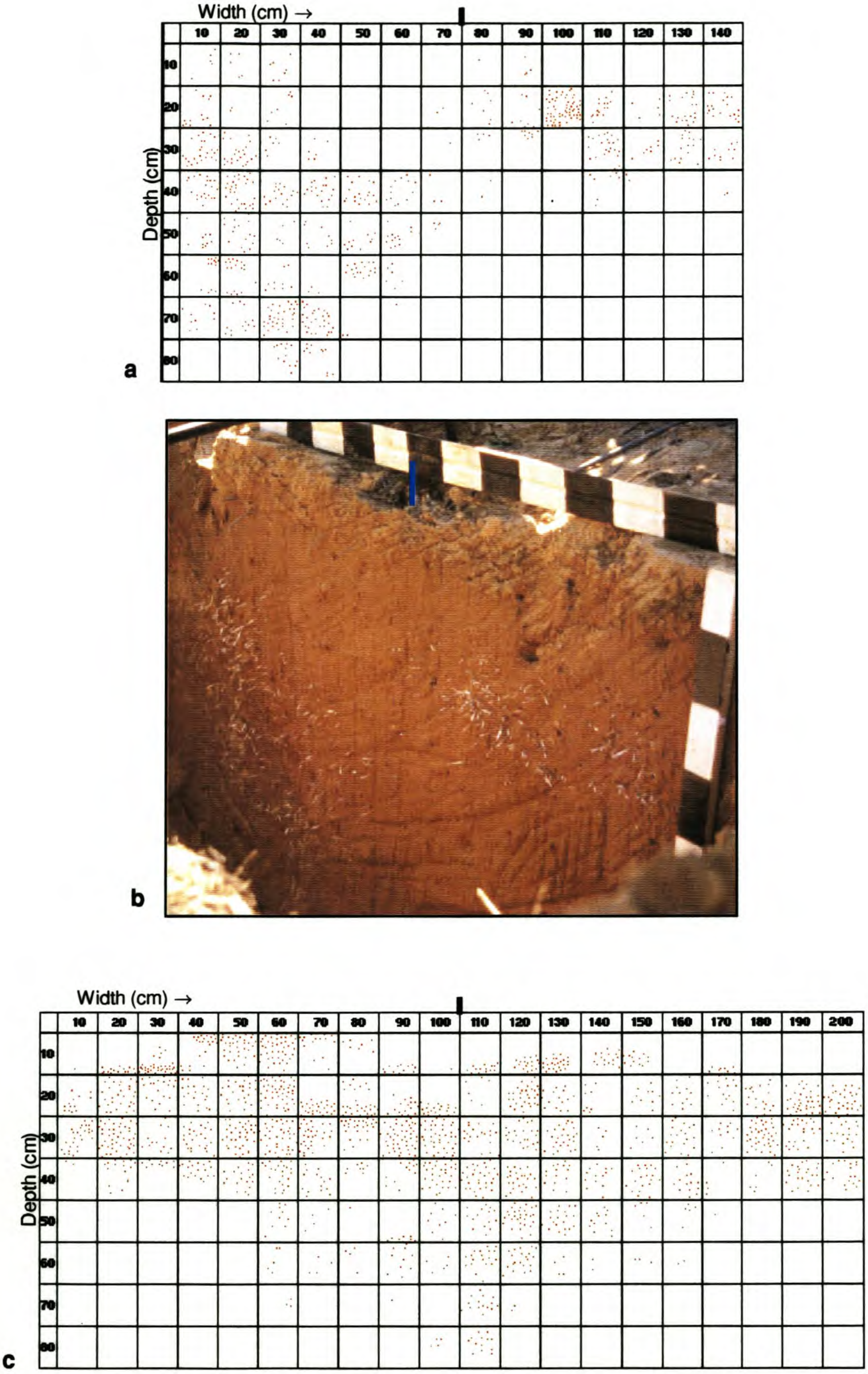


Figure 5. The root distribution patterns of the Micro Irrigation treatment at Citrusdal, with the profile walls perpendicular to the dripper line. In the rootmaps (a and c) the blocks represent an area of 10x10cm on the profile wall and the small dots represent the fine roots (<1mm). A small rectangle indicates the position of the spinner, which was exactly between two trees. The photo (b) corresponds with the rootmap in (a).

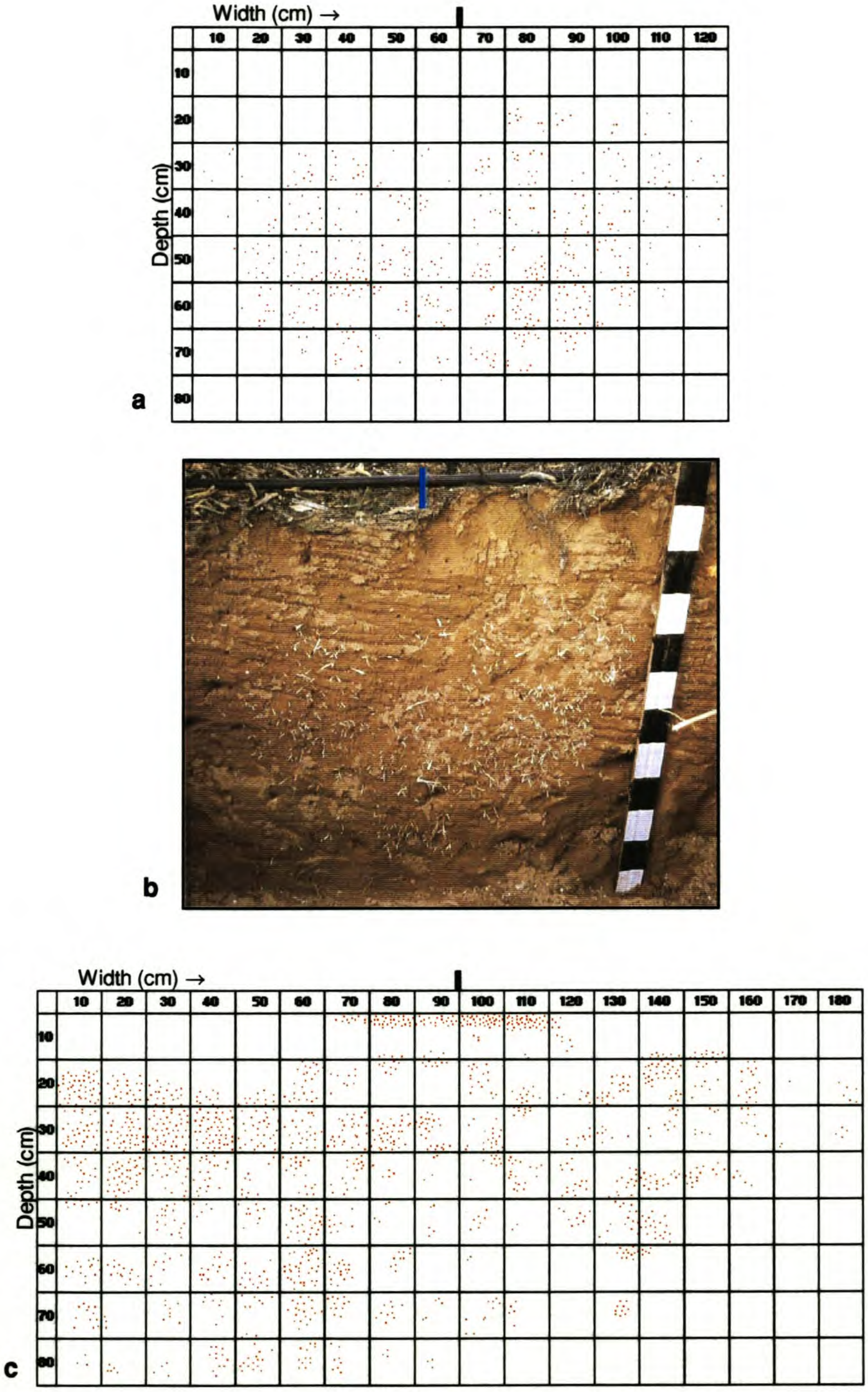


Figure 6. The root distribution patterns of the micro irrigation treatment at Citrusdal, with the profile walls parallel to the dripper line. In the rootmaps (a and c) the blocks represent an area of 10x10cm on the profile wall and the small dots represent the fine roots (<1mm). A small rectangle indicates the position of the spinner, which was exactly between two trees. The photo (b) corresponds with the rootmap in (a).

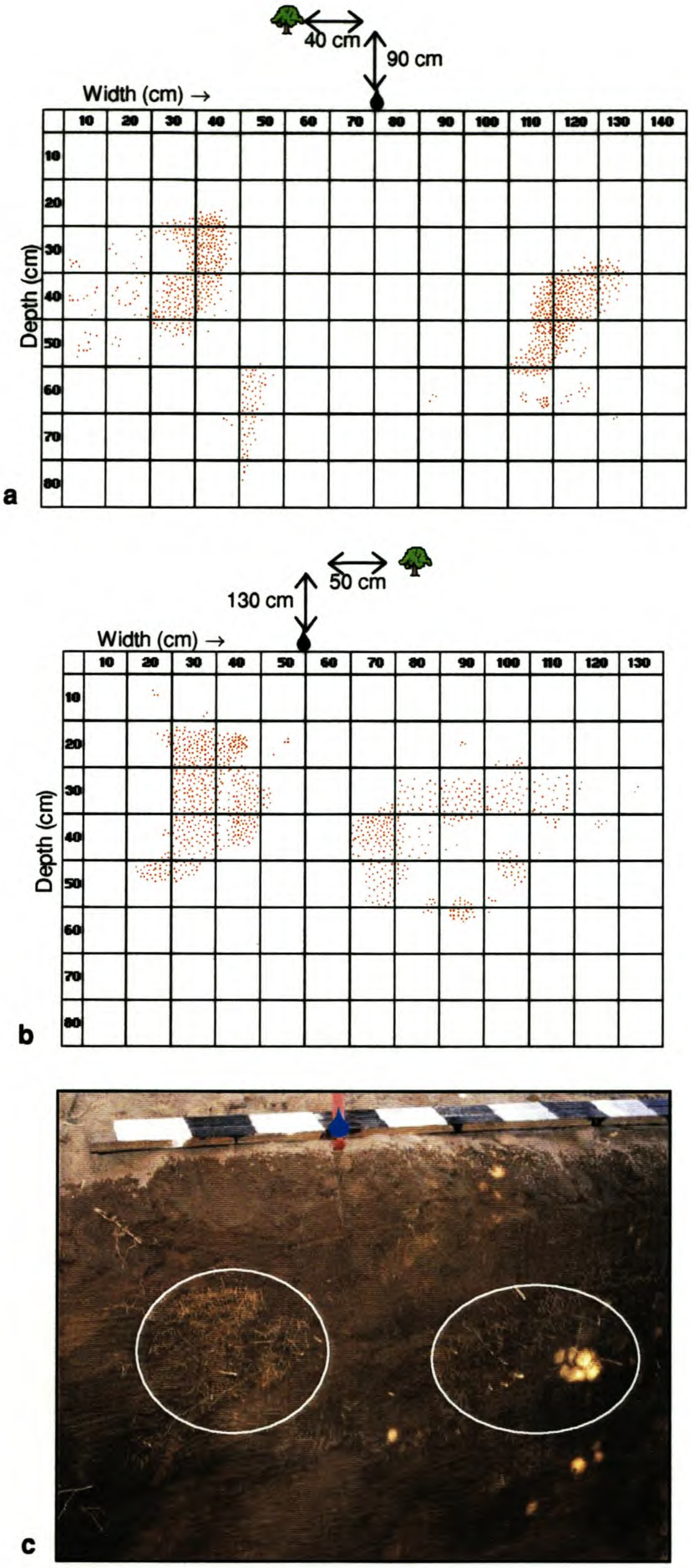


Figure 7. The root distribution patterns of the Conventional Drip Fertigation treatment at Citrusdal, with the profile walls perpendicular to the dripper line. In the rootmaps (a and b) the blocks represent an area of 10x10cm on the profile wall and the small dots represent the fine roots (<1mm). A small drop indicates the position of the dripper, and arrows indicate the position of the tree in relation to the dripper. The photo (c) corresponds with the rootmap in (b).

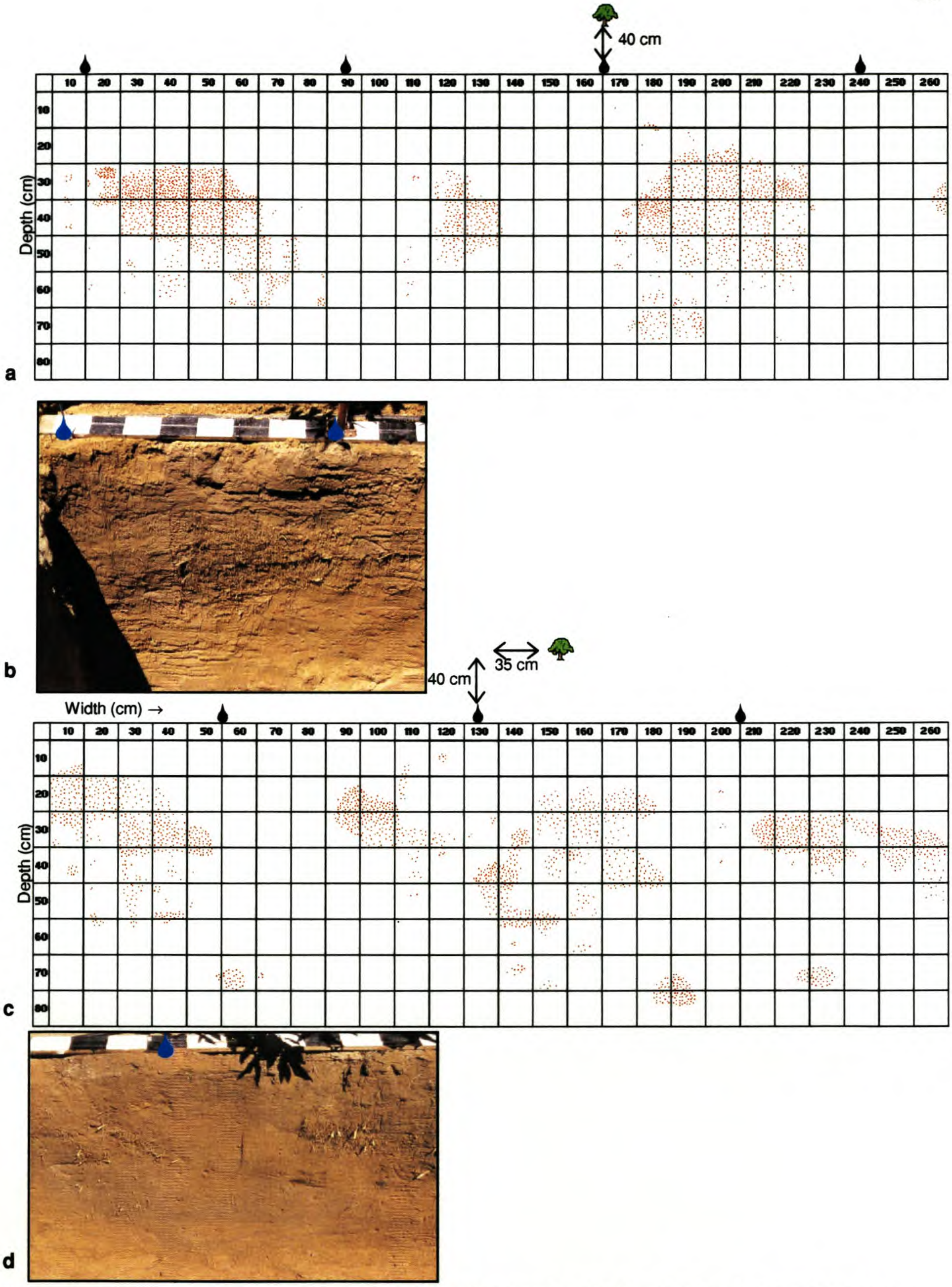
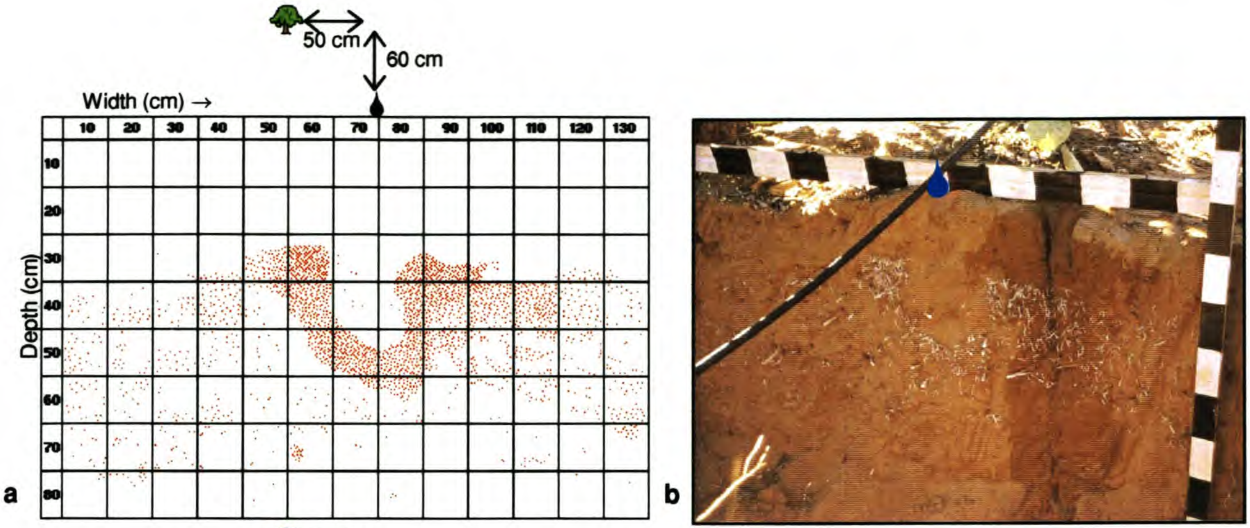
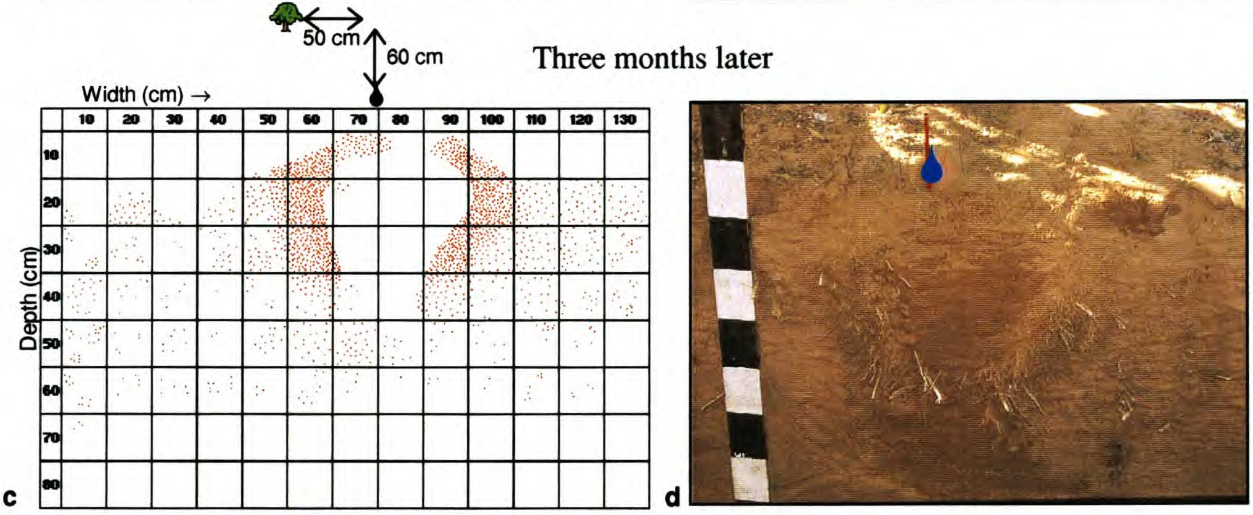


Figure 8. The root distribution patterns of the Conventional Drip Fertigation treatment at Citrusdal, with the profile walls parallel to the dripper line. In the rootmaps (a and c) the blocks represent an area of 10x10cm on the profile wall and the small dots represent the fine roots (<1mm). A small drop indicates the position of the dripper, and arrows indicate the position of the tree in relation to the dripper. The photos (b) and (d) correspond with the first dripper of the rootmaps, in respectively (a) and (c).



Three months later



Six months later

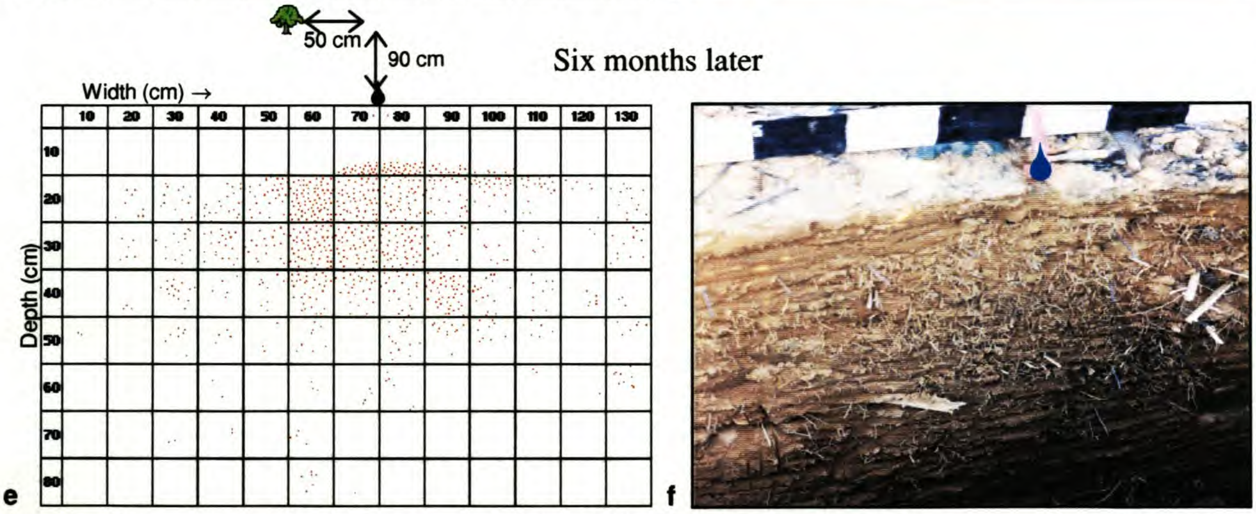


Figure 9. The root distribution patterns of the Daily Drip Fertigation treatment at Citrusdal, with the profile walls perpendicular to the dripper line. In the rootmaps (a, c and e) the blocks represent an area of 10x10cm on the profile wall and the small dots represent the fine roots (<1mm). A small drop indicates the position of the dripper, and arrows indicate the position of the tree in relation to the dripper. The photos (b), (d) and (f) correspond with the rootmaps in (a), (c) and (e). Over-irrigation was rectified only days before the first rootmap (a) was drawn, (c) was drawn three months later and (e) six months later. The wet soil in (b) does not indicate the position of the dripper, the dripper line was accidentally moved during digging of the profile pit.

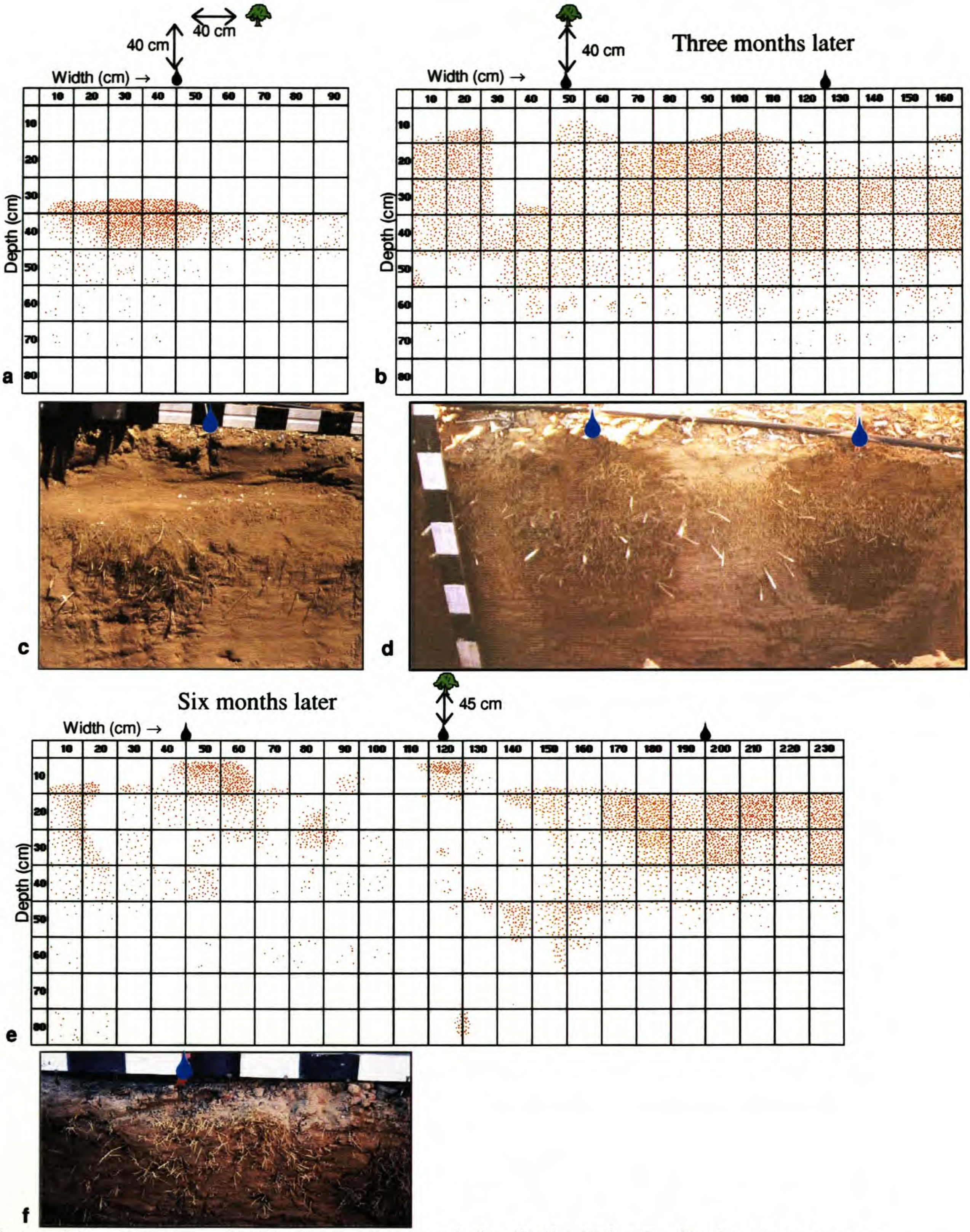


Figure 10. The root distribution patterns of the Daily Drip Fertigation treatment at Citrusdal, with the profile walls parallel to the dripper line. In the rootmaps (a, b and e) the blocks represent an area of 10x10cm on the profile wall and the small dots represent the fine roots (<1mm). A small drop indicates the position of the dripper, and arrows indicate the position of the tree in relation to the dripper. The photos (c), (d) and (f) correspond with the rootmaps in respectively (a), (b) and (e). Over-irrigation was rectified only days before the first rootmap (a) was drawn, (b) was drawn three months later and (e) six months later.

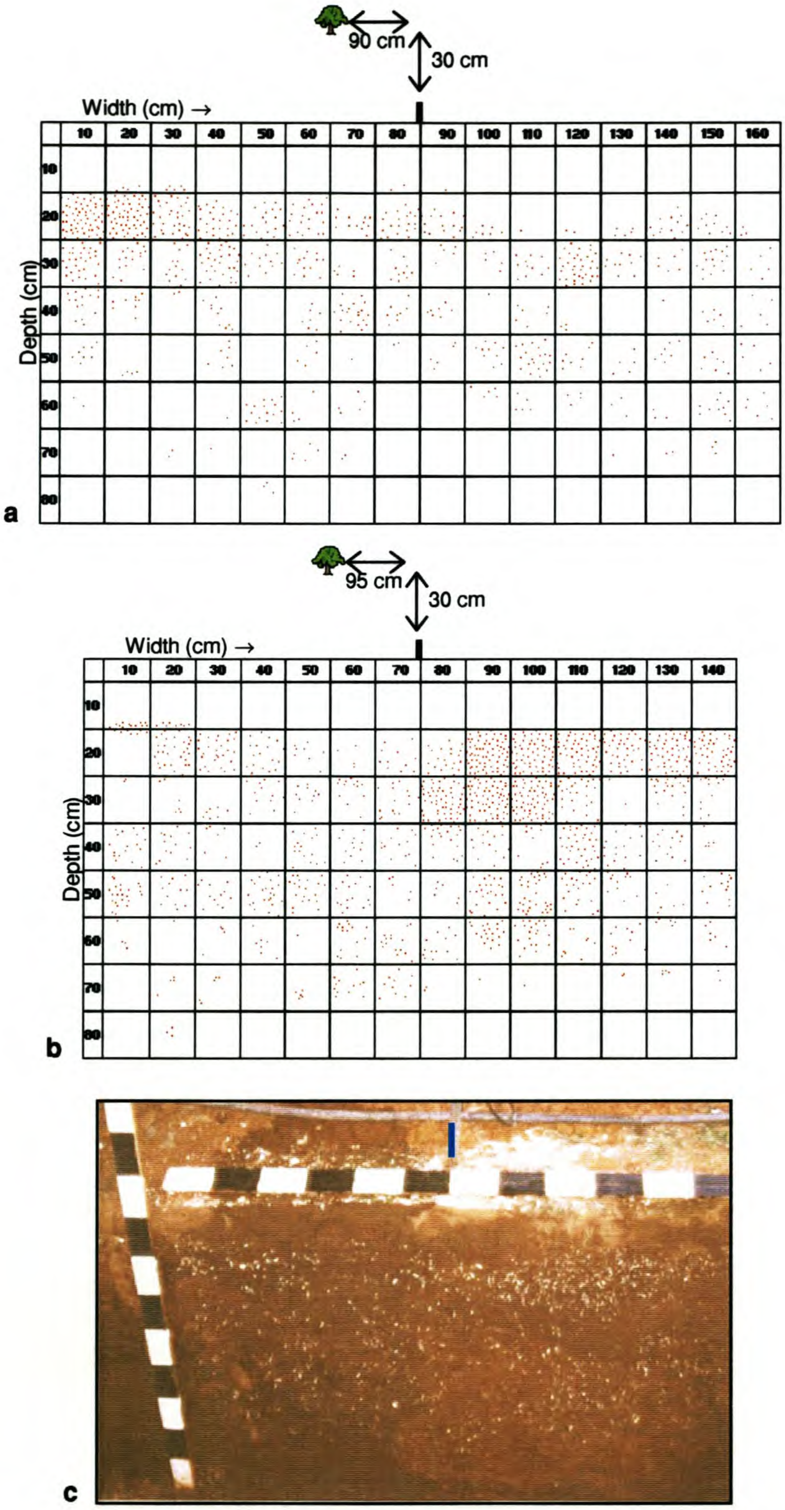


Figure 11. The root distribution patterns of the Micro Irrigation treatment at Addo. In (a) the profile wall is perpendicular to the dripper line and in (b) the wall is parallel to the dripper line. In the rootmaps (a and b) the blocks represent an area of 10x10cm on the profile wall and the small dots represent the fine roots (<1mm). A small rectangle indicates the position of the spinner, and arrows indicate the position of the tree in relation to the spinner. The photo (c) corresponds with the rootmap in (b).

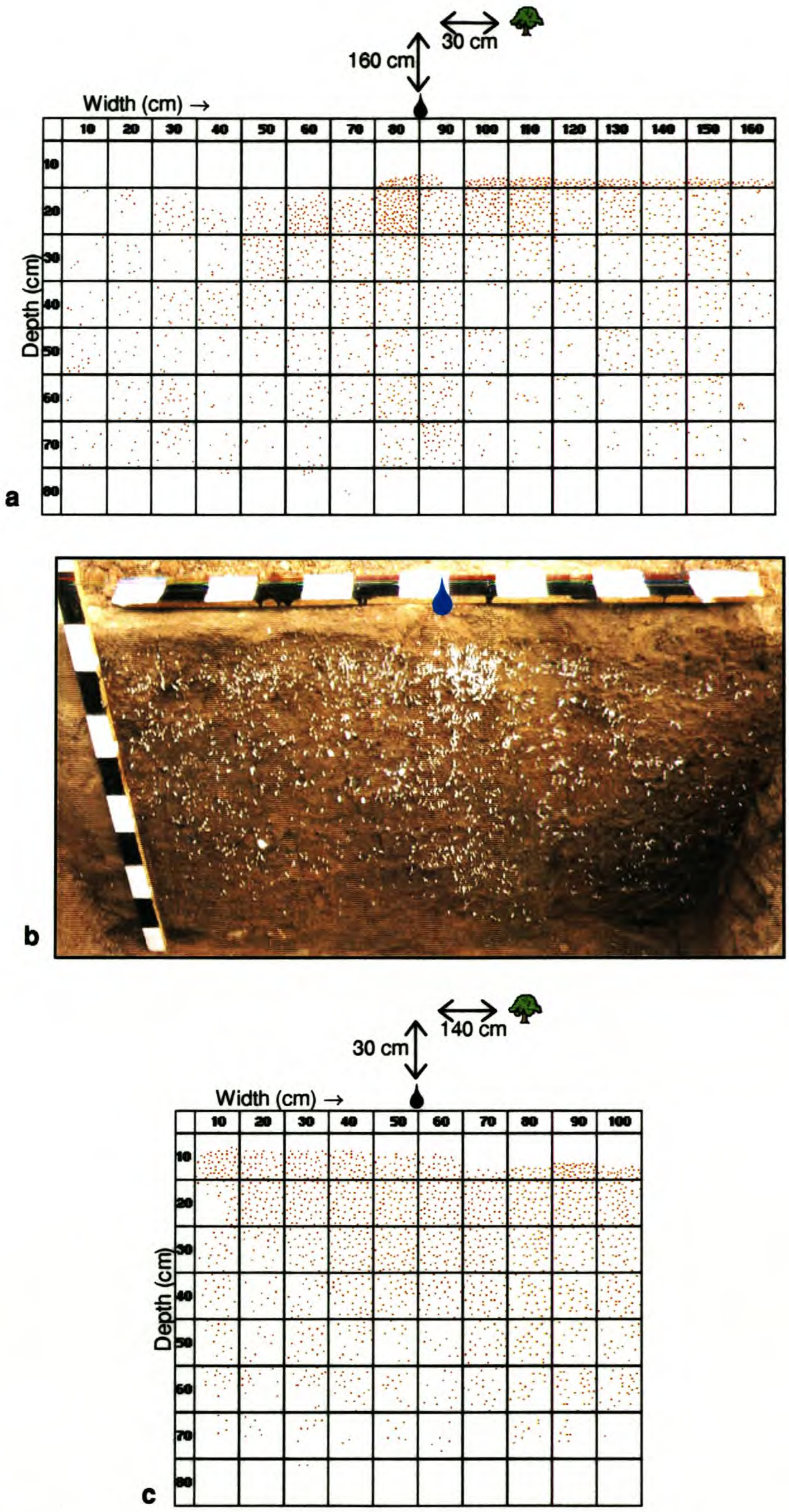


Figure 12. The root distribution patterns of the Conventional Drip Fertigation treatment at Addo. In (a) the profile wall is perpendicular to the dripper line and in (c) the wall is parallel to the dripper line. In the rootmaps (a and c) the blocks represent an area of 10x10cm on the profile wall and the small dots represent the fine roots (<1mm). A small drop indicates the position of the dripper, and arrows indicate the position of the tree in relation to the dripper. The photo (b) corresponds with the rootmap in (a).

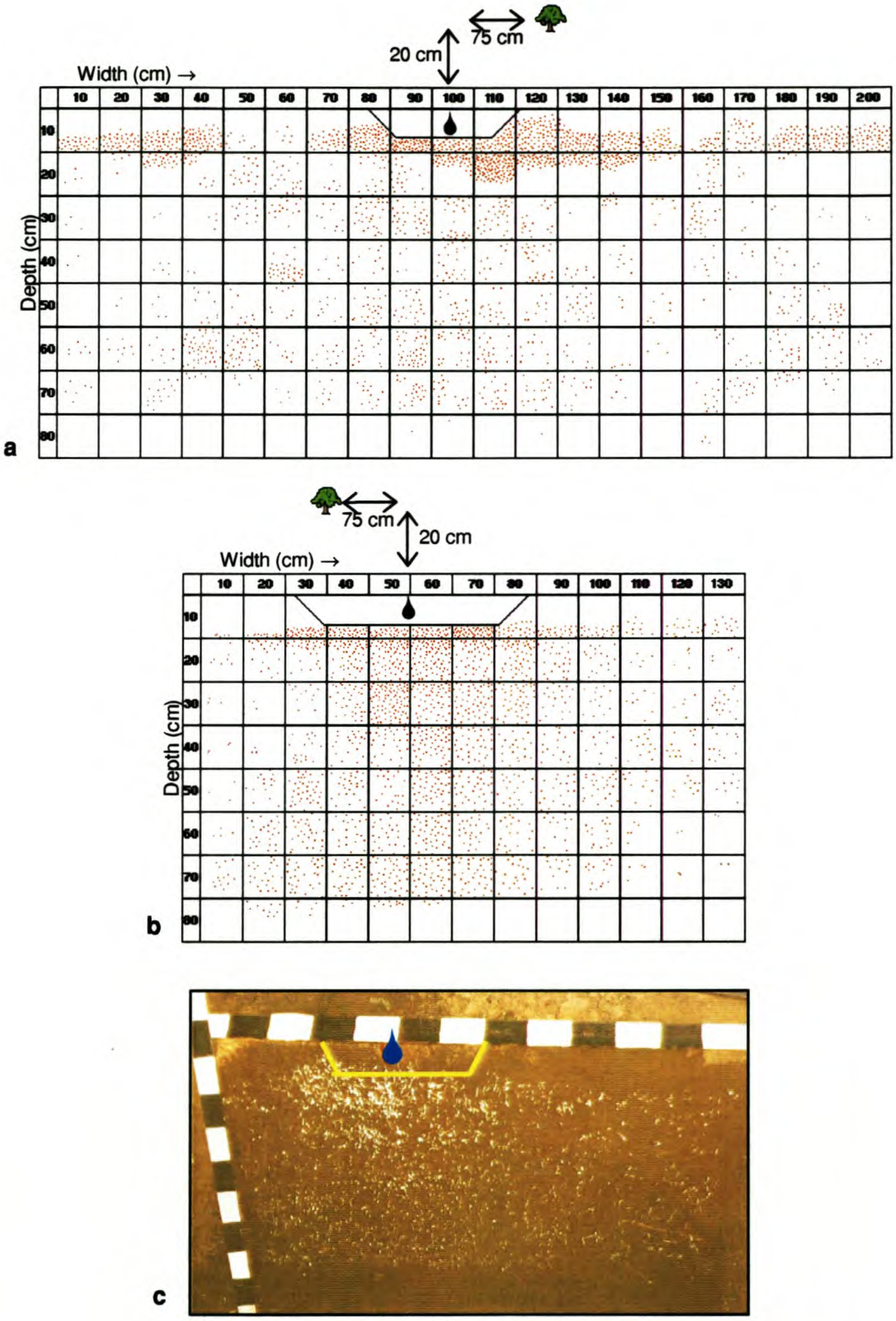


Figure 13. The root distribution patterns of the Daily Drip Fertigation treatment at Addo. In (a) the profile wall is perpendicular to the dripper line and in (b) the wall is parallel to the dripper line. In the rootmaps (a and b) the blocks represent an area of 10x10cm on the profile wall and the small dots represent the fine roots (<1mm). A small drop indicates the position of the dripper, and arrows indicate the position of the tree in relation to the dripper. The photo (c) corresponds with the rootmap in (b).

5. GENERAL DISCUSSION AND CONCLUSION

First study: The continuous monitoring of the soil water content (SWC) beneath a dripper gave a good indication of how water applied through a dripper is distributed in a sandy soil. The measurements show that the horizontal water movement is restricted to 20cm from the dripper. This indicates that the water flow is mainly in a vertical direction. In this study a semi-impermeable layer in the soil was detected through observing water accumulation patterns in the SWC. In the event that there is no impermeable layer, leaching losses in a sandy soil like this can be very high. This indicates that the texture class of the soil should be taken in consideration when designing the irrigation system. Further studies on soils with a higher clay content are needed and the influence of different dripper delivery rates also need to be tested.

In this study, only the total reduction in SWC was discussed, which constitutes a combination of various factors. By separately measuring transpiration and drainage together with SWC, it may be possible to quantify the contribution of these factors to the total reduction in SWC.

In the second study, the effect of fertigation on soil characteristics and root distribution was determined. On the sandy soil, roots developed poorly directly beneath the dripper of the conventional drip fertigation treatment (CDF). This may be due to oxygen deficiency and/or acidification beneath the dripper. Under the daily drip fertigation treatment (DDF), with pulse irrigation, roots developed well beneath the drippers, and no acidification of the soil was found. In a silt loam soil, roots developed well beneath the dripper of both the

CDF and DDF treatment and the rest of the root system was also well developed. It appears as if soil acidity and/or oxygen deficiency was not a problem on this soil type.

In sandy soil, with a poor buffer capacity, the use of a balanced nutrient solution is advisable, for it may slow down the acidification process. More research is needed on the topic of acidification beneath drip irrigation and how it can be rectified. The use of pulse irrigation, where the total irrigation requirement is divided into short pulses, is also a recommendable practice on sandy soil to increase the oxygen supply to the roots. Further research on this topic is necessary to fine-tune irrigation scheduling on sandy soils. In such studies the oxygen levels beneath a dripper should be monitored. In soils with higher clay content the need for a balanced nutrient solution and pulse irrigation is not as big. This is because clay colloids have a better acidification buffer capacity than sandy soil and clay soils contain more micro pores to keep the soil aerated.