Soil Moisture, Crop Yield and Soil Salinity Relocation under Partial Rootzone Drying Irrigation

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Erklärung zur Dissertation

Hierdurch erkläre ich, dass ich meine Dissertation mit dem Titel **'Soil Moisture, Crop Yield and Soil Salinity Relocation under Partial Rootzone Drying Irrigation**' selbständig verfasst und die benutzten Hilfsmittel und Quellen sowie gegebenenfalls die zu Hilfeleistungen herangezogenen Institutionen vollständig angegeben habe.

Die Dissertation wurde nicht schon als Masterarbeit, Diplomarbeit oder andere Prüfungsarbeit verwendet.

Hannover, 20.12.2011

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Abstract

Water supplies are limited worldwide since water use has been growing at more than twice the rate of population increase in the last century, and the numbers of regions that are chronically short on water are increasing. Therefore the problems of water scarcity are mostly acute. There is an urgent need to identify and improve effective irrigation management method under the condition of water scarcity. Partial rootzone drying irrigation (PRDI) is a potential water-saving irrigation method. Using special irrigation methods which save water usually lead to soil salinity problems, when leaching is not sufficient to remove soluble salts from the rooting zone. Several factors influence the soil salinity levels of irrigated land. Some of the factors are the irrigation method and the intensive use of water combined with high evaporation rates. The main goal of this research was to investigate the effect of the partial rootzone drying irrigation (PRDI) on yields and other parameters, and to compare to the conventional irrigation (CI) when applying the same amount of water in both irrigation methods. The influence of PRDI on soil salinity movement and distribution were investigated too.

The experiments were performed in pots with volume of 225 L as well as in the open-soil of a greenhouse. The PRDI method was investigated under different irrigation water levels by splitting the root system. Moreover sodium chloride was added to the irrigation water as a tracer salts. The soil moisture distribution, tomato yield, biomass, and soil salinity were measured. Moreover, the soil salinity (soil sodium and soil chloride) was simulated under different conditions in order to compare it with results from pot and greenhouse experiments. The results showed that using the PRDI method reduced the soil salinity in the top soil layers in comparison to the CI method without affecting the yield. Also, the PRDI improved the irrigation water use efficiency (IWUE) and increased the percentage of marketable yield compared to the CI methods, especially when applying it under deficit water. Simulation of soil salinity under arid and semi-arid situations confirmed that the PRDI method has the ability to reduce salinity in the top 30 cm of soil layers and is a suitable method to reduce the risk of salinity in the top soil of agricultural fields under arid and semi-arid conditions.

Key words*:* Soil moisture, soil salinity, partial rootzone drying irrigation, water-saving

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Zusammenfassung

Global betrachtet sinkt die Verfügbarkeit von Wasser: Im vergangenen Jahrhundert stieg der der Bedarf an Wasser doppelt so stark an wie die Bevölkerung. Zudem nimmt die Anzahl der Regionen mit chronischem Wasserdefizit weiter zu. Daher sind mit der Wasserverknappung zusammenhängende Probleme derzeit aktuell. Hieraus ergibt sich die Notwendigkeit, effektive Bewässerungsstrategien für Wassermangelsituationen zu identifizieren und weiterzuentwickeln. Die Bewässerung mit partieller Trockenheit des Wurzelraums „Partial rootzone drying irrigation" (PRDI) stellt hierbei eine potentiell wassersparende Methode dar. Der Einsatz solcher wassersparender Bewässerungsstrategien kann allerdings zur Versalzung des bewässerten Bodens führen. Die Salinität des Bodens wird hierbei unter anderem durch die Bewässerungsmethode selbst, aber auch durch intensiven Wassereinsatz mit darin enthaltenen Elektrolyten und in Kombination mit hohen Evaporationsraten beeinflusst. Das Ziel dieser Arbeit war daher die Untersuchung von PRDI in Hinblick auf Erträge und andere Parameter im Vergleich zur konventionellen Bewässerung (CI) bei gleichem Wassereinsatz. Hierzu wurde zudem der Einfluss von PRDI auf die Veränderung und Verteilung der Bodensalinität untersucht.

Die Versuche wurden in 225 L Tonnen sowie im Gewächshausboden durchgeführt. PRDI verschiedener Bewässerungsstufen wurde an geteiltem Wurzelsystem („split-root Verfahren") untersucht und die Verteilung der Bodenfeuchte, Ertrag an Tomaten, Biomassezuwachs sowie Salinität des Bodens (Na, und Cl) gemessen. Letztere wurde zudem für verschiedene Wasserregime simuliert. Im Vergleich zur CI reduzierte PRDI die Salzkonzentration der oberen Bodenschichten ohne Ertragseinbußen. Hierbei führte PRDI zu einer Steigerung der Wassernutzungseffizienz (IWUE) sowie des Anteils an vermarktbaren Früchten, insbesondere unter Trockenstresssituationen. Ergebnisse der Simulation reproduzierten die Messergebnisse und zeigten, dass die Anwendung von PRDI auch in ariden und semi-ariden Gebieten zu einer Verminderung der Salzkonzentration in den oberen Bodenschichten führt.

Schlagwörte*:* Bodenfeuchte, Salinität des Bodens, Partial rootzone drying irrigation, Wassersparender

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Symbols and Abbreviations

ABA	Abscisic acid	
APRDI	Alternate partial rootzone drying irrigation	
BGT	Biosystems and Horticultural Engineering Section	
CDI	Continuous deficit irrigation	
CI	Conventional irrigation	
DI	Deficit irrigation	
DMC	Dry matter concentration	
E_{day}	Daily evaporation	[mm day^{-1}]
ET	Evapotranspiration	[mm day^{-1}]
ET_{day}	Daily Evapotranspiration	[mm day^{-1}]
ET_{max}	Maximum Evapotranspiration	[mm]
ET_{week}	Weekly Evapotranspiration	[mm $week^{-1}$]
FAO	Food and Agricultural Organization	
FC	Field capacity	[m^3 m^{-3}]
F_{cover}	Crop cover factor	[-]
F_{crop}	Crop factor	[-]
FPRDI	Fixed partial rootzone drying	
H	Hydraulic head	[mm]
ha	Hectare	
IAEA	International Atomic Energy Agency	
IWUE	Irrigation water use efficiency	[g L^{-1} $plant^{-1}$]
K	Hydraulic conductivity	[mm day^{-1}]
KCl	Potassium chloride salt	[%]
Kcp	Crop-pan coefficient	[-]
KT	Empirical coefficient	[-]
LEACHM	Leaching Estimation and Chemistry Model	
M_d	The mass of the soil after drying	[kg]
M_s	The mass of the wet sample of the soil	[kg]

M_w	Mass of the water in the soil sample before drying	[kg]
N	Nitrogen	
NM	Not measured	
NS	No significant differences	
PRDI	Partial rootzone drying irrigation	
Q	Discharge rate of emitter	[L h^{-1}]
RDI	Regulated deficit irrigation	
rH	Relative humidity	[%]
R_s	Soil radiation	[kJ m^{-2} day^{-1}]
S	Second	
SCI	Subsurface conventional irrigation	
SPRDI	Subsurface irrigation of partial rootzone drying	
SWD	Soil water deficit	
t	Time	[day]
t_a	Air temperature	[^oC]
TC	Average daily temperature	[^oC]
TD	Temperature difference (T_{max} – T_{min})	[^oC]
T_{day}	Daily transpiration	[mm day^{-1}]
t_s	Soil temperature	[^oC]
U	Sink term (water lost per unit time by transpiration)	[day^{-1}]
UNESCO	United Nations Educational, Scientific and Cultural Organization	
V	Volume	[L]
V_s	Volume of sample	[m^3]
Y	Yield per plant	[kg]
z	Depth	[mm]
θ_v	Volumetric soil moisture content	[m^3 m^{-3}]
ρ_w	Density of water	[kg m^{-3}]
Φ	Diameter	[cm]

1 Introduction

Water supplies are limited worldwide (Postel 1998; Fereres and Soriano 2007; Savić et al. 2008). Water use has been growing at more than twice the rate of population increase in the last century, and the numbers of regions that are chronically short of water are increasing. Therefore, the problems of water scarcity are mostly acute (FAO 2011). By 2025 the population growth and economic development will lead to nearly 1.8 billion people living in countries or regions with absolute water scarcity, and two-thirds of the world population could be under water stress conditions. The situation will be exacerbated (FAO 2011). Irrigation of agricultural lands accounts for over 85 % of water usage worldwide (van Schilfgaarde 1994). Even a minor reduction in irrigation water could substantially increase the water available for other purposes. There is an urgent need to identify and adopt effective irrigation management strategies under the condition of water scarcity (Fereres and Soriano 2007; Savić et al. 2008).

Partial rootzone drying irrigation (PRDI) is a potential water-saving irrigation method where, at each irrigation period, only a part of the rootzone is wetted with the other compartment left to dry to a pre-determined level. PRDI could save water by up to 50 % and yet maintain yield as shown for some grape cultivars (Loveys et al. 2000), sugar beet (Sepaskhah and Kamgar-Haghighi 1997), sugar cane (Shani-Dashtgol et al. 2006; Pandias et al. 1992), maize (Kang et al. 2000a; Kang et al. 2000b), winter wheat (Sepaskhah and Hosseini 2008), beans (Genocoglan et al. 2006), cotton (Du et al. 2006; Du et al., 2008a&b; Tang et al. 2005), potato (Liu et al. 2006; Jovanovic et al. 2010), pear (Kang et al. 2002), apple (Leib et al. 2006; Zegbe and Behboudian 2008) and tomato (Kirda et al. 2004; Zegbe et al. 2004).

Using special irrigation methods which save water usually lead to soil salinity problems. Several factors influence the soil salinity levels of irrigated land. One of the factors is the irrigation method (Le Roux et al. 2007; Lambers 2003) and the intensive use of water combined with high evaporation rates and human activity (Lambers 2003). Salinity affects nearly 70 % of all agricultural lands in over 100 countries, and sadly there is no continent free of the soil salinity problem (Szabolcs 1989). According to estimates made by the FAO and the UNESCO, more than 800 million ha of land throughout the world are salt-affected (FAO 2008), 10 million ha of irrigated land are abandoned annually as a consequence of soil salinity (IAEA 1995) and the extent of soil salinity increases continuously. Soil salinity inhibits plant growth and causes a decrease in plant biomass (Turan et al. 2009).

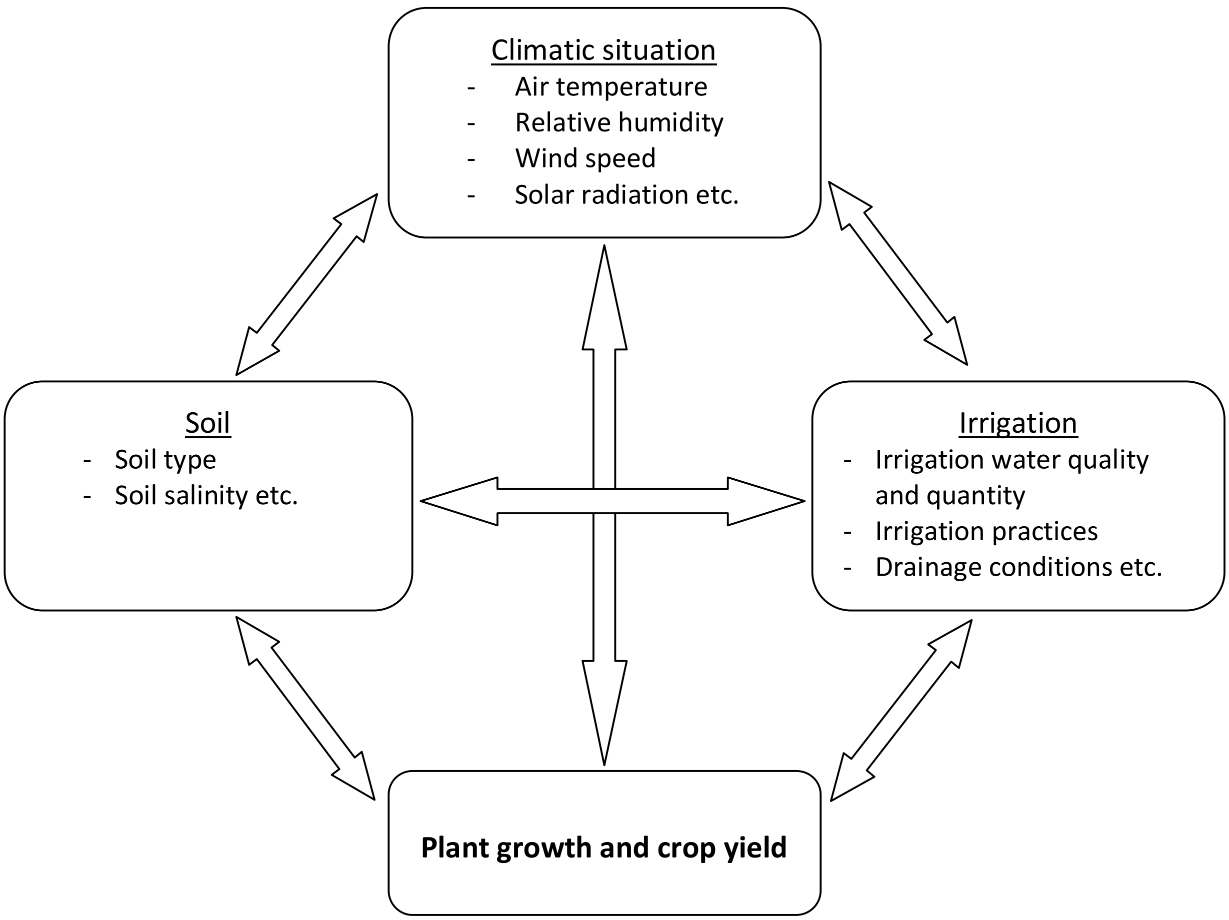


Fig. 1. 1: Schematic of interaction between growing factors related to irrigation

There are several factors affecting plant growth and crop yield; the most important factors are climatic situations (e.g. light, temperature, relative humidity), soil (e.g. soil type, soil salinity, soil nutrition, physical properties), irrigation practices and amount of irrigation water (Fig. 1. 1).

On the other hand, there are interactions between these factors. Therefore, irrigation water and irrigation practices affect both plant growth and soil (soil salinity, soil physical properties, etc). Soil salinity is influenced by irrigation practices and irrigation water. Water plays a vital role in efficient photosynthesis, respiration, transpiration, and transportation of minerals and nutrients through the plants. So using water stress practices such as deficit irrigation (DI) and partial rootzone drying irrigation (PRDI) affect the soil salinity and plant growth especially under arid and semi-arid conditions.

2 Literature Review

2.1 Water stress and deficit irrigation

Deficit irrigation (DI) is an optimization strategy in which irrigation is applied during drought-sensitive growth stages of a crop (Geerts and Raes, 2009). In a broad sense, quoting English and Raja (1996), DI consists of the deliberate and systematic under-irrigation of crops. In other words, the amount of water applied is lower than that needed to full satisfy the crop's water requirements. Generally, DI refers to fully irrigated crops from which water is withheld during certain tolerant growth stages. Regulated deficit irrigation (RDI) is a special irrigation strategy based on applying only a fraction of the plant's water requirements during certain periods of plant development (Ruiz-Sanchez et al. 2010). RDI is mainly designed to restrict water when the sensitivity of plant to water stress is minimal. RDI strategies can also be applied when the available water is insufficient to optimize maximum yields.

A lot of research was conducted on the effects of the DI on the fruits yield of vegetables, e.g. Spreer et al. (2007) found out that yields were reduced in deficit irrigation treatments when compared to the fully irrigated control. Development and post-harvest quality of fruits grown under deficit irrigation were not adversely affected when the production of mango under regulated deficit irrigation (RDI) was compared to full conventional irrigation (CI). The irrigation methods were evaluated by their effect on yield and quality of mango fruits (Spreer et al. 2007).

Shao et al. (2008) studied the effect of DI on soil water distribution, water use, growth and yield of greenhouse grown hot pepper in comparison to CI. In the CI control, irrigation water was applied to both sides of the system when soil water content was lower by 80 % of FC. Deficit irrigation (DI50, DI75) at 50 % and 75 % of the CI irrigation water was supplied to both sides of the root system. They reported that the mean soil volumetric water content of DI75 and DI50 was lower by 21.06 % and 28.32 %, respectively, than that of the CI after starting the experiment. Water consumption showed some significant effect on irrigation treatments during the growing period under drought stress application, and therefore decreased in DI75 and DI50 to a level around 75 % and 50 % of the CI method (Shao et al. 2008).

Shao et al. (2008) reported that the deficit irrigation (DI) treatments resulted in a reduction of total dry mass of 7.2 - 44.1 %, shoot biomass of 24.9 - 47.7 % when compared to conventional irrigation (CI). Although there was a recorded reduction in the DI treatments for single fruit weight and fruit volume at harvest, the total soluble solid concentration of fruit harvested under the water deficit treatments was higher than in the CI method.

For olive tree, Iniesta et al. (2009) discovered that deficit irrigation strongly reduced vegetative growth, but only slightly reduced the final fruit volume. Water stress caused a higher reduction in fresh fruit yield than oil yield due to a higher oil concentration in deficit irrigated trees, without differences between CDI and RDI. Therefore, both irrigation strategies may be used in olive to save a significant amount of irrigation with moderate reductions (about 15 %) in oil yield.

Patane and Cosentino (2010) found out in the cultivation of tomato that the greatest effect of increasing DI was the rise in fruit firmness, total solids and soluble solids. A negative trend in response to increasing DI was observed for fruit yield and size (all under Mediterranean climate conditions). An open-field experiment was carried out in two sites differing in soil and climate characteristics and irrigation management. Patane and Cosentino (2010) also stated that the variations between sites for the tomato's fruit quality response to deficit irrigation demonstrate that not only deficit irrigation (DI) but also soil and climatic characteristics influence the quality of the tomato crop such as fruit firmness, total solids and soluble solids, and fruit size.

Shao et al. (2010) reported that for hot pepper the total dry mass was reduced by 1.2 - 38.7 % in DI treatments compared to full irrigation. The highest total fresh fruit yield was obtained in the full irrigation treatment. On other hand they stated that all deficit irrigations increased the water use efficiency of hot pepper from a minimum of 1.33 % to a maximum of 54.49 % as compared to CI method. At harvest, single fruit weight and volume were reduced under the deficit irrigation treatments, but the total soluble solids concentration of fruit harvested under the DI treatments were higher compared to full conventional irrigation.

For grain Du et al. (2010) suggested that a mild water deficit at early seedling stage is beneficial for grain yield and irrigation water use efficiency (IWUE) of summer maize, and the deficit timing and severity should be modulated according to the drought tolerance of different crop varieties.

2.2 Soil salinization

The salinity of a soil refers to the amount of salts in the soil. Salinity problems are caused by the accumulation of soluble salts in the rootzone. Irrigated agriculture presently accounts for about one-third of the world's production of food. It is anticipated that it will need to produce nearly 50 percent by the year 2040 (FAO, 1988; 1999). This will likely be difficult, because extensive areas of irrigated land have been and are increasingly becoming degraded by salinization and water logging resulting from forms of poor agricultural management (FAO, 1999).

Soil salinity affects plant growth in several ways, directly and indirectly (Cardon et al. 2007; FAO, 1985). The direct soil salinity effects in plant growth are: (1) Water uptake since salt reduces the rate and amount of water that plant roots can take up from the soil. (2) Ion-specific toxicities or imbalances of some salts (sodium, chloride, boron, etc) are toxic to plants when present in high concentration in growing soil (FAO, 1985).

The indirect effects of soil salinity on plant growth are: (1) Interference with the uptake of essential nutrients. The excess of one ion limits the uptake of another ion. (2) Effect of sodium on soil structure if the concentration of sodium salts is high relative to other types of salt. A sodic soil may develop. Sodic soils are characterized by a poor soil structure. They have a low infiltration rate and are difficult to cultivate (FAO, 1985).

Sela (2011) reported that there are several factors that affect the soil salinity. These factors are:

- Quality and quantity of the irrigation water, the total amount of dissolved salts in the irrigation water and their composition.
- The type and amount of fertilizers applied to soil.
- Irrigation practices and type of irrigation system; the higher the water quantity applied, the closer soil salinity is to irrigation water salts concentration. When the soil dries, the concentration of salts in the soil solution is increased.
- The characteristics of the growing field; a poorly drained soil might reach salinity levels that are harmful to the plants and to the whole crop.

Also, climatic situations affect the soil salinity even with fresh water. Irrigation management methods project pose salinity problems in arid and semi-arid areas (FAO, 1995; Patel et al. 2001; Cardon et al. 2007). According to Cardon et al. (2007), the severity and rapidity of salinity build-up depends on a number of interacting factors such as the amount of dissolved salts in the irrigation water and especially the local climate.

Leaching requirements and salt-balance-index concepts have been used to judge the appropriateness of irrigation and drainage systems, with respect to the avoidance of salinity and water stress problems (FAO, 1999). The leaching requirement refers to the amount of leaching water needed to prevent excessive loss in crop yield caused by salinity build-up. The ‘’salt-balance index’’ is the net difference between the amount of salt added to an irrigation project and that removed in its drainage water (FAO, 1999). Soil salinity is a tracer of the net processes of infiltration, leaching, evapotranspiration, and drainage (FAO, 1999). According to Cardon et al. (2007), salts are most efficiently leached from the soil profile under higher frequency irrigation (shorter irrigation intervals). Keeping soil moisture levels higher between irrigation events effectively dilutes salt concentrations from the root zone, thereby reducing the soil salinity (Cardon et al. 2007).

According to the FAO (1999) the effective control of soil salinity and water stress requires

- knowledge of the magnitude and distribution of the rootzone soil salinity,
- knowledge of the changes and the trends of the soil salinity over time and the ability to determine the impact of management changes upon these conditions,
- ways to identify the existence of salinity problems and their causes,
- means to evaluate the appropriateness of on-going irrigation and drainage systems and practices with respect to controlling the soil salinity,
- an ability to identify the diffuse sources of irrigation and salt loading,
- knowledge of the spatial variability of soil salinity and the need to develop a site-specific management,
- a methodology for including the soil salinity in the determination of plant-available soil water and for guiding irrigation management.

2.3 Partial Rootzone Drying Irrigation (PRDI)

2.3.1 General

Partial rootzone drying irrigation (PRDI) is a new irrigation method where one half of the root system is irrigated while leaving the other half in a dried state. After a certain period of time, depending on soil and climatic conditions (Kriedemann and Goodwin, 2003), the irrigation is switched so that the wet part of the root system is allowed to dry out and the dry part is irrigated (Stoll et al. 2000). The PRDI method has either been used as a fixed partial rootzone drying (FPRDI) or as an alternate partial rootzone drying irrigation (APRDI). The FPRDI is a partial rootzone drying irrigation where the irrigation water is added to a fixed root side during the growing season while keeping the other side in a dry state. On the other hand the APRDI is a partial rootzone drying irrigation (PRDI), where the irrigated side is changed from one side to the other side; normally PRDI is applied as APRDI.

A lot of research was carried out to study the effects of the PRDI on yield and production of different crops. Generally, they show that PRDI saves irrigation water. For example, Kang et al (2002) stated for a pear orchard that the partial rootzone drying irrigation method saved water without significant reduction of fruit yield. Kirda et al. (2004) and Stikic et al. (2003) showed that the PRDI method not only saves irrigation water but also enhances fruit quality by increasing water soluble dry matter in fruits and vegetables. Stikic et al. (2003) reported that the partial rootzone drying (PRDI) is an irrigation technique which improves water use efficiency without significant yield reduction of tomato crop. According to Kang et al. (1998) and Chaffey (2001) the PRDI is an effective water-saving irrigation method and may have the potential to be used in the field. PRDI could save water by up to 50 % and maintain yield for some grape cultivars (Loveys et al. 2000). Since the plant water potential is expected to equilibrate with the wettest part of the soil (Hsiao, 1990), it is expected that plants under the PRDI will maintain as high a water potential as well watered plants.

Partial rootzone drying irrigation (PRDI) was tested and investigated for a number of crops, e.g. pear and grapevine (Dry et al. 2000; Stoll et al. 2000; dos Santos et al. 2003; De la Hera et al. 2007), pear orchard (Kang et al. 2002), hot pepper (Kang et al. 2001), maize (Kang et al. 1998; 2000), apple (Leib et al. 2004), cotton (Kaman et al. 2006), potato (Shahnazari et al. 2007; 2008), and tomato (Bertin et al. 2000; Stikic et al. 2003; Zegbe et al. 2003; Kirda et al. 2004; Zegbe et al. 2004; Kaman et al. 2006).

2.3.2 Water application levels in PRDI studies

Some publications deal with the choice of the right level of water application to manage the PRDI methods. For instance, Kang et al. (1998) showed that when both halves of the root system were alternately exposed to a drying soil and a soil with its water content maintained above 55 % or 65 % of its FC, water consumption was reduced by 34.4 % to 36.8 %, and significant increase in irrigation water use efficiency (IWUE) was recorded.

In the cultivation of green bean, Gençoğlan et al. (2006) discovered that irrigation scheduling based on a 0.8 crop-pan coefficient is recommended for conventional irrigation whereas 1.0 is recommended for the partial rootzone drying method by green bean producers experiencing water shortage. That means the PRDI method should be used under crop-pan coefficients Kcp = 1.0. These results were confirmed for two drip irrigation techniques and four irrigation water levels.

When growing maize, Wang et al. (2008) found out that a maximum biomass accumulation was obtained under well-watered conditions, and severe water deficit led to a 50 % reduction of biomass when compared to the CI treatment. In their experiments, they tested three irrigation methods: conventional irrigation (CI), alternate partial rootzone drying irrigation (APRDI), and fixed partial rootzone drying irrigation (FPRDI) under three different watering levels: (1) well-watered, (2) mild water deficit and (3) severe water deficit.

Almond fruits growth was not affected by PRDI treatment according to Egea et al. (2009). Whereas the PRDI had a negative impact on the final kernel dry weight for the most stressed treatments.

Intrigliolo and Castel (2009) studied the effects of irrigation water amount and partial rootzone drying (PRDI) on water relations, growth, yield, and quality of vine. The PRDI applied at two levels (100 % and 50 % of the estimated crop evapotranspiration) were compared to conventional drip irrigation. They found out that the effects of irrigation water amount on yield and vine quality differed between the years. With low yield values for instance, irrigation neither affected grape production nor vine quality. In the following year, with a much higher general yield, the high irrigation increased the must total soluble solids and vine alcohol content. However, they suggested that under their experimental conditions, it was the irrigation amount rather than the system of application that affected vine performance.

2.3.3 Soil moisture content and irrigation water use efficiency (IWUE)

Much research focused on the effect of PRDI on soil moisture content and irrigation water use efficiency. Kang et al. (1998) studied the effect of the PRDI methods on growing maize and effect of this irrigation method on irrigation water use efficiency. In their experiments, the maize plants were grown in pots with their roots divided and established into two or three separated containers. The results showed that a better IWUE, root development and distribution as well as shoot biomass production were achieved by the alternate drying and rewetting.

In following publications, Kang et al. (2000a; 2000b) reported that the alternate partial rootzone drying irrigation maintained a high grain yield of maize with up to 40 % - 41.6 % reduction of irrigation water in comparison to conventional irrigation.

Further research on maize (Kang and Zhang, 2004) showed that under PRDI the irrigation water consumption was reduced by 35 % with a total biomass reduction of 6 - 11 % when compared to fully irrigated plants. Another study with hot pepper under drip irrigation demonstrated that PRDI reduced irrigation water consumption by approximately 40 % while maintaining a similar yield as in fully irrigated plants (Kang et al. 2001). The PRDI was furthermore tested for peach and apple by using a drip irrigation system (Gong et al. 2001), and in a pear orchard by using a flood irrigation system (Kang et al. 2002). The results showed water savings of 52 % in peach and 23 % in pear (Kang and Zhang, 2004). For potato growing, water use when compared to fully irrigated treatment was decreased and irrigation water use efficiency (IWUE) was increased essentially by PRDI as reported by Shahnazari et al. (2006).

Zegbe et al. (2004) investigated the effects of PRDI on processing tomatoes. They showed that the PRDI could save water by 50 %, and thereby increase the irrigation water use efficiency by 92 % or 64 % (furrow and drip irrigation, respectively) in comparison to fully irrigated plants. Drip irrigated PRDI not only increased the irrigation water use efficiency but also kept the photosynthetic rate and leaf water potential similar to fully drip-irrigated plants.

In the semi-arid region of Washington State, Leib et al. (2004) discovered that on a deep and high water holding capacity soil, deficit irrigation (DI) and partial rootzone drying irrigation (PRDI) of apples conserved 35 % to 45 % of the irrigation water with only minimal reduction in apple yield and size when compared to a control treatment (CI). The PRDI treatment also conserved more soil moisture than the DI even though the DI received slightly more irrigation than the PRDI method.

For green bean, Gençoğlan et al. (2006) stated that under subsurface drip irrigation the PRDI method saved 50 % of irrigation water when considering irrigation water applied after the treatment programs began. Likewise irrigation water saving and water-use reduction were found to be 16 % and 13 %, respectively, without yield or dry biomass reduction.

Shahnazari et al. (2006) also studied two subsurface irrigation treatments. For potato, the PRDI treatment saved 30 % of irrigation water while maintaining potato tuber yield. This led to a 61 % increase of the irrigation water use efficiency (IWUE).

In their 2008 publication for hot pepper, Shao et al. (2008) reported that the mean soil volumetric water content of the PRDI method were lower by 24.4 % to 34.7 % than in the CI method. Water consumption decreased in the PRDI to a level around 50 % to 75 % when compared to the CI method. However, the PRDI treatment had 52 % higher irrigation water use efficiency (IWUE) than the CI treatment.

Surface evaporation constitutes a large fraction of the irrigation water loss in the cropped field (more than 20 %) according to Tang et al. (2010). Under both PRDI (APRDI and FPRDI) treatments nearly 40 % of the evaporative water loss is saved. Transpiration accounted for 48 %, 58 %, and 57 % of the total amount of irrigation respectively for the CI, APRDI and FPRDI treatments.

In field potato and tomato experiments the water-saving irrigation strategies DI and PRDI were able to save about 20 - 30 % of the water used in fully irrigated plants, as reported by Jensen et al. (2010).

Li et al. (2010) showed for maize that the partial rootzone drying irrigation reduced water consumption by 10.6 to 12.9 % and 31.7 to 32.4 % (FPRDI and APRDI, respectively) in comparison to the CI method. Partial rootzone drying irrigation did not reduce the total dry mass accumulation significantly, thus increasing IWUE by 10.4 to 13.6 % and 41.2 to 41.8 %, (FPRDI and APRDI, respectively). FPRDI reduced the total dry mass significantly even though it also improved canopy IWUE.

According to Du et al. (2010) APRDI could be a useful-water saving irrigation method for wide spaced cereals in arid regions, and a mild water deficit in earlier stage might be a practical irrigation strategy for planting cereals. Application of such temporal and spatial deficit irrigation in field grown crops has a greater potential for saving water, maintaining economic yield and improving IWUE. In the cultivation of potato, the PRDI treatment saved 33 % - 42 % of irrigation water while maintaining similar yield as the CI method. This resulted in 38 % and 61 % increase in IWUE (Jovanovic et al. 2010).

Only one publication dealt with the PRDI method, using the same amount of water as the CI method. De la Hera et al. (2007) concluded that the PRDI had both higher yield (43 % compared to CI) and irrigation water use efficiency (40 % compared to CI) when they studied the effects of the PRDI method on irrigation water use efficiency of grapevines irrigated by the same amount of water as conventional irrigation.

According to these literatures, the PRDI is a useful water-saving irrigation method since it saved the irrigation water while maintaining similar yield as in the CI method. Therefore the PRDI increased the irrigation water use efficiency (IWUE).

2.3.4 Crop yield and biomass

Many experiments were performed to investigate the effects of the PRDI method on vegetable crops. Stikic et al., (2003) for instance investigated the cultivation of tomato crop plants with the root system divided equally between two plastic pots under partial rootzone drying irrigation. As a consequence of PRDI treatment the growth of whole plants was reduced, the crop water use efficiency increased and sugar content increased too.

Zegbe et al. (2004) reported that PRDI could maintain the fresh and dry mass of tomato fruits in comparison to fully irrigated plants. Fruit maturity was more advanced in drip irrigated PRDI in terms of redness of fruit with an increase in total soluble solids concentration and dry mass concentration of the fruit. Either of both PRDI treatments have a great potential to be adopted as a water saving methods especially for environments with limited water. Again for tomato, Savić et al. (2008) discovered that the PRDI reduced the fresh weight while having no significant effect on the fruit diameter. These results were obtained when investigating tomato fruit growth and cell wall peroxidase activity in tomato growth under chamber conditions.

For potato cultures, Shahnazari et al. (2006) showed that no significant differences were found between the CI and PRDI treatments in the leaf area index, top dry mass and tuber yield. Moreover, the important marketable class of tuber size was significantly higher (20 %) under PRDI than in the CI treatment with two subsurface irrigation treatments. Jensen et al. (2010) found that the PRDI increased the marketable yield in potatoes significantly by 15 % due to an improved potato tuber size distribution. It was stated that PRDI increased the antioxidant content significantly by approximately 10 %.

The APRDI treatment significantly reduced the hot pepper yield by about 24.0 % compared to CI according to Shao et al. (2008). However, the APRDI treatment had 17.2 % and 24.5 % additional yield over the DI and FPRDI treatments, respectively. At harvest, single fruit weight and volume were reduced under DI and PRDI treatments, but the total soluble solids concentration under DI were higher than CI treatment.

When using conventional subsurface drip irrigation (SCI) and alternating subsurface drip irrigation of partial rootzone drying irrigation (SPRDI), the harvested yields of green bean were similar (Gençoğlan et al. 2006). However, dry plant weight for SCI was a little higher than that of SPRDI. In both irrigation methods, green bean yield decreased with increasing water deficit.

For maize, several studies are available. Kang et al. (1998) reported that the total biomass production was reduced by only 6 % ± 11 % compared to the well irrigated plants. Root to shoot ratio and stomatal resistance for water diffusion were observed as a result of such treatment. Leaf transpiration was reduced substantially while the rate of photosynthesis and leaf water content was not significantly altered. Wang et al. (2008) found that a smaller reduction of the maize yield was obtained under the APRDI therefore the irrigation water use efficiency (IWUE) was increased. It was suggested that the APRDI resulted in the best aeration and moisture conditions in the soil and enhanced the activities of soil microorganisms, which might also have benefited the plant growth. According to Hua et al. (2010), APRDI showed the same biomass production, achieving significantly higher irrigation water use efficiency under mild water deficit. The results suggested that plants under APRI experienced less oxidative stress or damage induced by water deficit. Tang et al. (2010) reported that APRDI reduced the average final yield of cotton by only 4.4 %. The FPRDI resulted in a significant reduction in yield of 12.0 % in comparison to conventional irrigation. Moreover, the PRDI brings in earlier flowering and a higher economical return due to early harvested cotton. This indicates that the final economical output could compensate for the loss of cotton yield due to water saving.

Also, PRDI was tested for fruit trees. Kang et al. (2002) reported that the APRDI and FPRDI did not affect pear fruit numbers, yield per tree, and the total yield in unit area in comparison to conventional irrigation (CI). Leib et al. (2004) compared partial rootzone drying and deficit irrigation to conventional irrigation for apple trees. CI and PRDI produced equal weight of apples per tree but DI produced 10 % less apple weight when compared to the CI. CI produced the largest apples while the size of PRDI apples was reduced by 4 % and DI apples by 9 %. The deficit irrigated apples also tended to be slightly firmer and higher in soluble solids but no differences in starch levels were found.

It was suggested for apple fruits by Zegbe and Pérez (2011) that PRDI did not damage fruit quality at harvest or after storage at room temperature. They recommended PRDI for commercial use in semi arid regions and to growers interested in either long term storage or distant markets. After 3 years of evaluation, apple fruit quality at harvest, flesh firmness, and total soluble solids concentration was similar between CI and PRDI. Dry matter concentration (DMC) was higher under PRDI than under CI. The fruit quality after 18 days storage was similar between CI and PRDI methods. Spreer et al. (2007) stated that mango fruit size of the PRDI method was increased and fruits had a higher fraction of edible parts when compared to fully irrigated treatment.

Different experiments were carried out to study the effects of the PRDI method on vine. De la Hera et al. (2007) showed that when PRDI was applied earlier, the yield under PRDI was 43 % higher than under CI, mainly due to an increase in cluster weight since the cluster number per vine was similar. Berry number per cluster and cluster weight were also significantly increased in the PRDI vines. The must and vine quality was not significantly altered and there was also a positive effect on vegetative and reproductive growth. Chaves et al. (2007) reported that the PRDI treatment resulted in an improvement in berry quality without any significant yield reduction compared to DI and CI. However, compared to the CI method the better microclimate observed in the PRDI vines was a consequence of a reduction in vine growth, where lower values of leaf area, canopy wideness, water shoots and shoot weight were recorded. Moreover, a tendency for a deeper root system in the PRDI vines was observed, while the DI and CI showed more homogeneous root distribution throughout the different soil layers. According to Poni et al. (2009) the stressed vines achieved no variation in yield level and components, and had an improved grape composition concerning soluble solids and total anthocyanin. This optimal behavior is likely due to earlier shoot growth cessation, enhanced maturity and a buffering leaf-to-fruit ratio that mitigated the effects of post veraison stress.

2.3.5 Soil salinity

Literature on the effects of the PRDI on the intensity and spatial distribution of soil salinity is limited. Only one publication and a single internet communication are available and the comparison between CI and PRDI is based on different amounts of irrigation water. Kaman et al. (2006) studied the effects of the PRDI irrigation methods on salt accumulation in the soil under cotton and tomato crops using 50 % of irrigation water for the PRDI method. It was stated that the differences in salt accumulation were limited to only the surface soil layers of 30 and 20 cm depth for cotton and tomato, respectively. The soil salinity at harvest under the PRDI was 35 % higher when compared to full conventional irrigation. However, it was concluded that the PRDI and DI methods at the specific site conditions do not require additional salt leaching when compared to full conventional irrigation. The PRDI method should be valued equally with DI for increasing crop irrigation water use efficiency with the smallest salinization risk. To interpret the results one has to consider that PRDI and DI methods apply 50 % less water than full conventional irrigation (Kaman et al. 2006).

2.3.6 Overview about state of the art

Table 2.1 summarizes the literature about the PRDI investigations. One can see that the boundary conditions of the experiments limit the comparability of the results because a different (smaller) amount of irrigation water was used in the PRDI investigation. The only publication using the same amount of water in PRDI and CI was De la Hera et al. (2007). In the other publications, 50 % of the conventional irrigation water was used in the PRDI method and the results were evaluated for irrigation water use efficiency and plant production. At present, the effects of the PRDI method when using the same water amount in comparison to conventional irrigation on soil salinity are unknown. Therefore, the effects of the PRDI method on soil salinity, yield and soil moisture using the same water amount as in conventional irrigation were determined in this study.

Table 2. 1: Literature overview PRDI

Author & year	Crop	*Root splitting	Applied water (PRDI/CI) [%]	Results of the PRDI compared to the CI			
				IWUE [%]	total biomass [%]	fruit yield [%]	soil salinity [%]
Kang et al. (1998; 2000)	Maize	Yes	50	+	- (6 to 11)	NS	NM
Kang et al. (2002)	Pear orchard	No	48 - 77	+ (12 to 28)	NS	NS	NM
Stikic et al. (2003)	Tomato	Yes	50	+	- (22 to 26)	- 30	NM
dos Santos et al. (2003)	Grapevines	No	50	-----	NS	NS	NM
Zegbe et al. (2003)	Tomato	No	50	-----	NS	NS	NM
Kang and Zhang (2004)	Maize	Yes	50	+	NS	NS	NM
Kang et al. (2004)	Tomato	Yes	50	+	- (6 to 11)	NS	NM
Leib et al. (2004)	Apple	No	50	+	NS	NS	NM
Kirda et al. (2004)	Tomato	No	30 and 50	+ 56	- (17 to 28)	+ (10 to 27) marketable yield	NM
Zegbe et al. (2004)	Tomato	No	50	+ 70	NS	NS	NM
Dorji et al. (2005)	Hot pepper	No	50	+	- 19	- (20 fruit numbers)	NM
Gençoğlan et al. (2006)	Green bean	No	50	+	NS	NS	NM
Kaman et al. (2006)	Cotton	No	50	+ (88 to 95)	-----	+ (3 to 6.4)	+35
Kaman et al. (2006)	Tomato	No	50	+ (88 to 95)	-----	-----	+30

Author & year	Crop	*Root splitting	Applied water (PRDI/CI) [%]	Results of the PRDI compared to the CI			
				IWUE [%]	total biomass [%]	fruit yield [%]	soil salinity [%]
Shahnazari et al. (2007)	Potato	No	50	+ 61	NS	+ 20 marketable yield	NM
Spreer et al. (2007)	Mango	No	50	+	NS	+ fruit size + marketable yield	NM
De la Hera et al. (2007)	Grapevines	No	100	+ 40	+	+ 43 yield + (27 to 38 fruit set)	NM
Shao et al. (2008, 2010)	Hot pepper	No	50	+ 52.1	- (7.3 to 44.1)	- (23.98)	NM
Poni et al. (2009)	Grapevines	No	50	+ 54.5	NS	NS	NM
Ahmadi et al. (2010)	Potato	No	65	+	NS	NS	NM
Tang et al. (2010)	Cotton	No	70	+	NS	NS (4.44)	NM
Li et al. (2010)	Maize	No	50	+ (13.6 to 41.8)	-	NS	NM
Jovanovic et al. (2010)	Potato	No	50	+ (38 to 61)	NS	NS	NM
Hua et al. (2010)	Maize	No	50	+	NS	NS	NM
Zegbe and Pérez (2011)	Apple	No	50	+	NS	+ fruit quality	NM

(*) Root splitting means that the roots of the plants in the experimental were split into separated containers

(+) the PRDI method increases this factor

(-) the PRDI method decreases this factor

(NS) no significant differences

(NM) not measured

3 Objectives

The main goal of this research is to investigate the partial rootzone drying irrigation (PRDI) as an irrigation method where the same amount of water is applied, compared to conventional irrigation (CI). In many cases water saving methods lead to soil salinity problems especially in arid and semi-arid regions. Therefore soluble salt movement and relocation under applying PRDI should be determined in detail. Out of this reason the specific objectives of this study are:

- Qualifying the PRDI using the same amount of water as in the CI method.
- Comparing the effects of PRDI and CI on soil moisture content under different water application levels.
- Comparing the effects of PRDI and CI on crop yield and biomass.
- Studying the effects of PRDI and CI on movement and relocation of soluble salts in the soil.
- Transferring the results from pot and greenhouse experiments to an arid location on field scale.

The investigation was evaluated with the most planted crop tomato and for the drip irrigation mode.

4 Materials and methods

4.1 General

This chapter describes general setups, materials and methods mostly used in the preliminary studies and main experiments. Fig. 4.1 presents the flow chart of the main experiments.

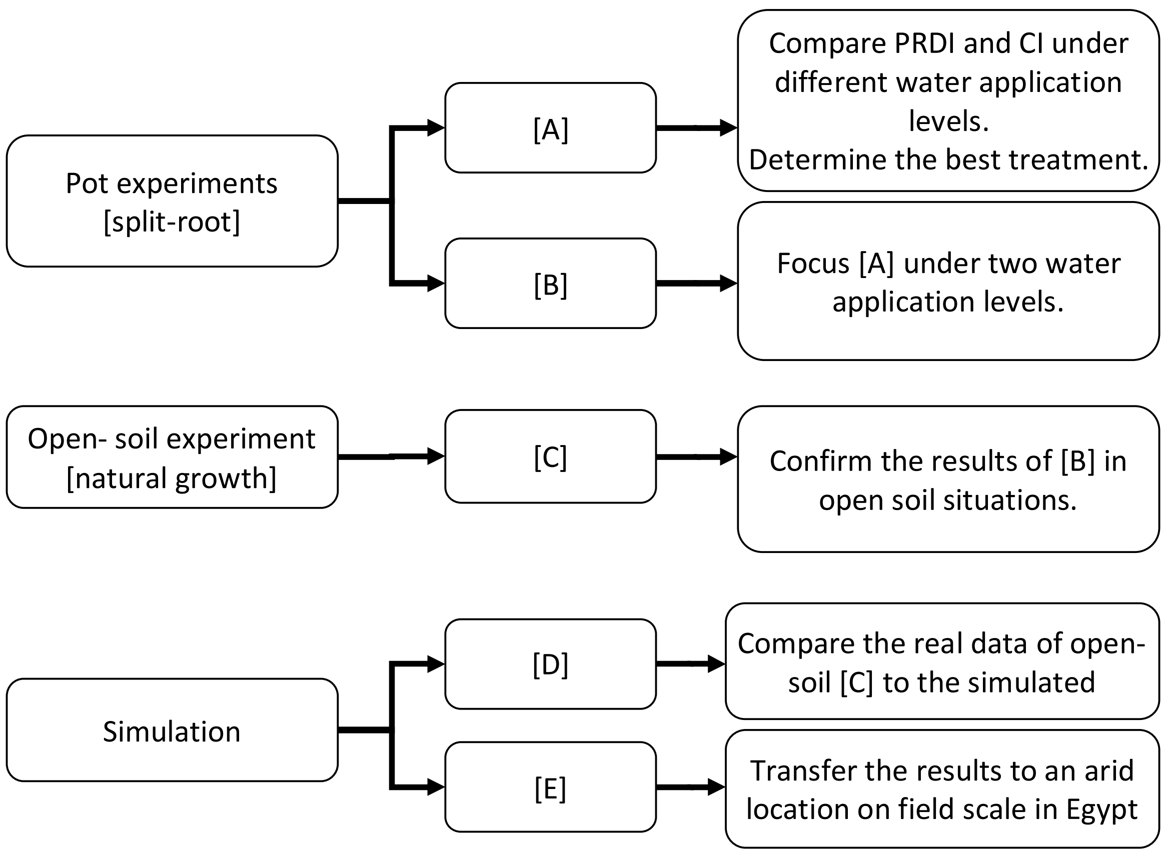


Fig. 4. 1: Flow chart of the main experiments

The first part of this work was performed to study and evaluate the PRDI on tomato crop yield and soil salinity relocation. It was distributed into three experiments. The first experiment took place in 2007, which was carried out in a glass greenhouse using big pots under different levels of water application (preliminary studies A). The second experiment was performed in 2008 and focused on two water application rates under PRDI compared to conventional irrigation (experiment B). In 2009, the third experiment was conducted. This experiment was carried out in open-soil inside a plastic covered greenhouse to exclude precipitation (experiment C). It was carried out to confirm the results of the previous experiments and to compare findings on PRDI with CI in open-soil and natural growth situations. To simulate the soil salinity in open-soil situations, experiment D was designed. Experiment E was conducted to transfer the results to field scale in arid and semi-arid situations.

4.2 Plant material, plant nutrition and tracer salts

Tomato (*Lycopersicon esculentum cv. Panovi*) was used as a model plant in this study. Seeds of tomato were germinated in commercial compost. Plants were grown in plastic pots (225 L) for the preliminary and the pot experiments and in a greenhouse soil (sandy soil with very low clay content) during the open-soil experiment.

The fertilizer requirements were calculated in a basic of soil nutrition analysis. Soil nutrition analysis was performed in the Vegetable Systems Modeling Section, Institute of Biological Production Systems, Leibniz Universität Hannover. The fertilizer (slowly release Osomocote Tomaten- Duenger with 15-8-16 of N-P-K; release time 6 months) was mixed with the soil before the experiments to reach the set point of 270 kg N ha^{-1}.

In order to compare the salt movement during the different irrigation methods, sodium chloride (NaCl) was added as a salt tracer to the irrigation water. NaCl was chosen as a salt tracer since Na and Cl ions are both affected by the amount of irrigation water and irrigation management. Moreover, the movement of Cl is affected more by irrigation water than the movement of Na according to White and Broadley (2001). Sodium chloride (NaCl – 58.44 g/mol) was added to the irrigation water to maintain the salinity at 50 mmol L^{-1} (≈ 5.2 mS/cm). The total amount of NaCl was equal for all treatments in every experiment, because the total amount of water in PRDI and CI treatments was the same under the same water application.

4.3 Drippers and irrigation

In the open-soil experiment, the irrigation was carried out using the **Aqua-Traxx** irrigation drip tape (Boswell, 2000; Toro-Ag, 2011). The irrigation drip tapes had 16 mm (5/8'') tape diameter and 30 cm (12'') emitter spacing within the irrigation tape (see Fig. 4.2).

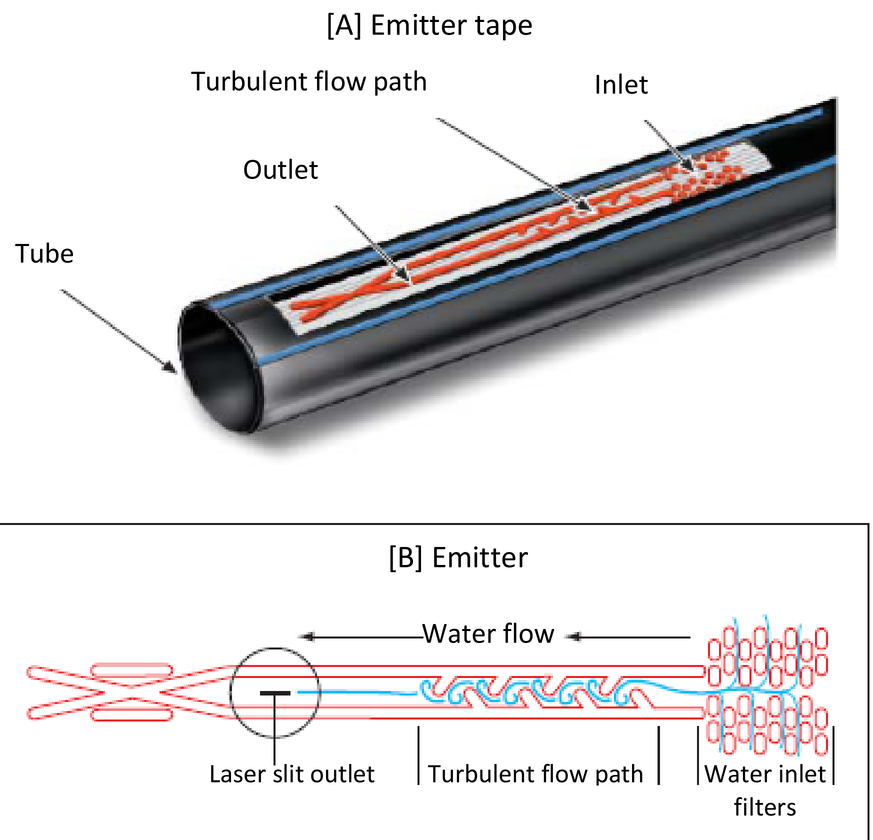


Fig. 4. 2: Aqua-Traxx irrigation drip tape and emitter (Boswell, 2000; Toro-Ag, 2011)

The technical properties of the emitter tape are summarized in Table 4.1.

Table 4. 1: Technical properties of the emitter tape (Toro-Ag, 2011).

Outlet spacing	Individual emitter flow rate (L h^{-1}) at		Flow rate per 30.5 m tape length (L h^{-1}) at	
	0.55 bar	0.70 bar	0.55 bar	0.70 bar
30 cm	1.3	1.4	127.3	141.0

4.4 Data acquisition

4.4.1 Climatic data

During the preliminary experiments, the air temperature (***t_a***) and relative humidity (***rH***) inside the greenhouse were measured using aspirated psychrometers developed at the Biosystems and Horticultural Engineering Section (BGT), Institute of Biological Production Systems, Leibniz Universität Hannover. The psychrometers consisted of thin sheathed type (NiCr-Ni) thermocouples (ϕ = 0.5 mm) enclosed in a radiation shield open on one end and fitted with a small fan on the other (accuracy ± 0.3 K). Inside the greenhouse, five psychrometers were positioned at a height of 1.5 m above the ground surface of the greenhouse. One sensor was installed in the middle of the greenhouse whereas others sensors were placed between the experimental plants.

In order to measure the solar radiation (***S***), seven solarimeters type CM 6 (Kipp and Zonen 1998) were positioned at different places in the greenhouse. One sensor was placed at the middle of the experiment and the other sensors at the corners of the experimental setup. The sensors were placed 1.5 m above the ground surface of the greenhouse.

The soil temperature (***t_s***) in the pots was determined using the same thermocouples as mentioned above at a depth of 0.1 m below the soil surface. Twenty-four thermocouples were placed in the pots. One sensor was installed on each side of the plant rootzone.

Data of these climatic parameters were recorded every 15 minutes by a datalogger (Biosystems and Horticultural Engineering section (BGT), Leibniz Universität Hannover, Germany) during the preliminary experiments and using a LabJack U3-HV during the open-soil experiment.

4.4.2 Soil moisture and field capacity

General

Field capacity (FC) of the soil and its relationship to the volumetric water content (θ_v) was determined before setting up the experiment. The FC of the soil was measured according to Veihmeyer and Hendrickson (1931). The soil was irrigated until saturation. Then, it was covered using a plastic foil for a period of three days. Then soil samples were collected using special cylinders (volume of 380 cm^3) to avoid the destroying of the soil structure and bulk density, after that the soil samples were weighed and oven-dried at 105 ^oC for three days.

The soil moisture contents of the collected samples were measured gravimetrically on a volumetric basis using the following equation:

$$\theta_v = \frac{M_w}{\rho_w \cdot V_s} \qquad (4.\ 1)$$

M_w was given by:

$$M_w = M_s - M_d \qquad (4.\ 2)$$

Where:

θ_v: volumetric water content	[$m^3\ m^{-3}$]
M_w: mass of water in the soil sample	[kg]
M_s: the mass of the wet sample of the soil	[kg]
M_d: the mass of the soil after drying	[kg]
ρ_w: density of the water	[$kg\ m^{-3}$]
V_s: volume of the sample before drying	[m^3]

Measurement of the soil moisture during the experiments

The soil moisture was determined using the ML2x ThetaProbe (Delta-T Devices Ltd., Fig. 4.3) and the PR2 Profile Probe sensors (Delta-T Devices Ltd., Fig. 4.4). The sensors are based on dielectric measurements. The ML2x ThetaProbe sensors were used to measure the soil moisture at different locations, whereas the PR2 Profile Probe sensor was used to detect soil moisture at different soil depths. The data of the ML2x sensors were recorded every 15 minutes by a datalogger (Biosystems and Horticultural Engineering section (BGT), Leibniz Universität Hannover, Germany) during the preliminary experiments and by a LabJack U3-HV during the pot experiments and the open-soil experiment. The data of the PR2 sensors were recorded every other day using a HH2 Moisture Meter (Delta-T Devices Ltd.) during the pot experiments and the open-soil experiment. The specific technical data of the ML2x Theta Probe and the PR2 Profile Probe are presented in Table 4.2.

Soil-specific calibration of the ML2x ThetaProbe

Soil-specific calibrations significantly improved the accuracy of the ML2x ThetaProbe (Foley and Harris 2007). Therefore, the ML2x ThetaProbe sensors were calibrated by taking samples from the soil and measuring the ML2x ThetaProbe output voltage. The soil samples were then oven-dried and the soil moisture contents were calculated gravimetrically. These measurements were repeated four times with different soil moisture contents. Thus the data were used to plot the relationship between volumetric soil moisture contents and the readings of the ML2x ThetaProbe sensor (see data of sensor calibration in chapter 5.1.1.2).

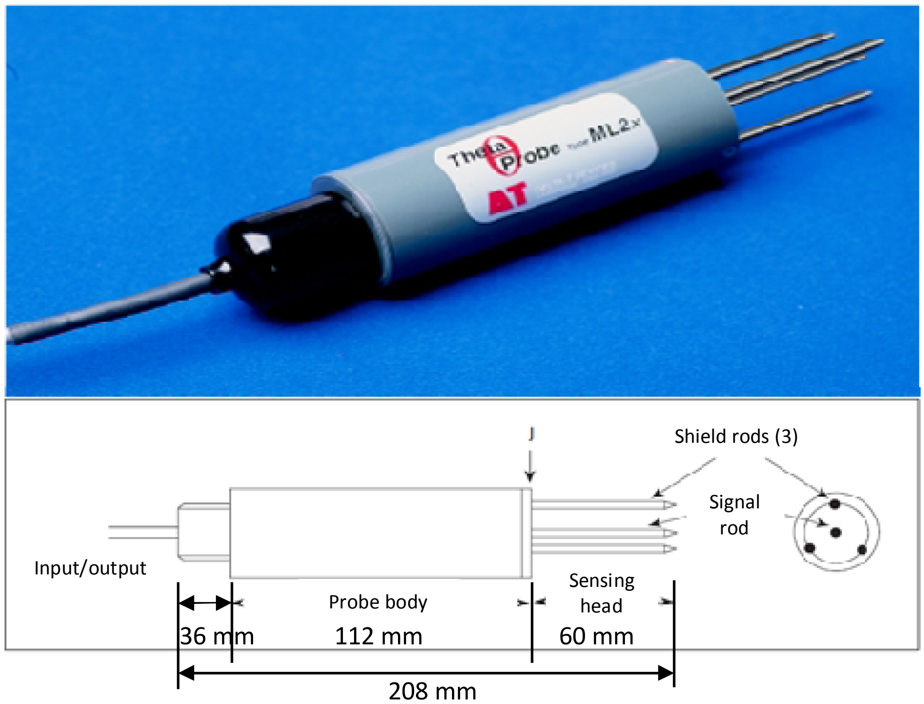


Fig. 4. 3: ML2x ThetaProbe (Delta-T Devices, 1999)

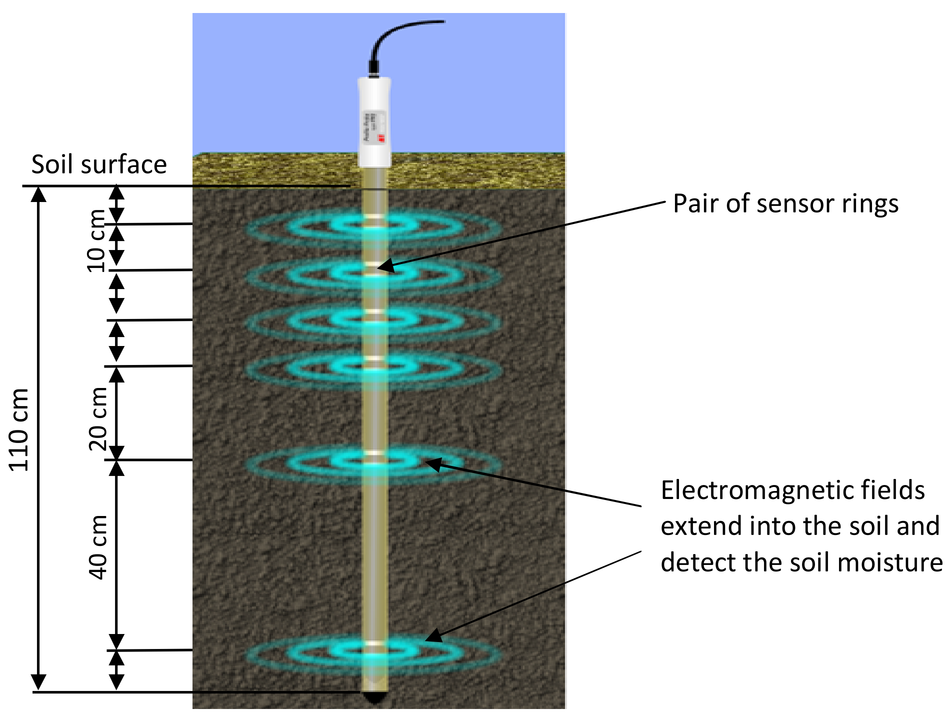


Fig. 4. 4: PR2 Profile Probe (Delta-T Devices, 2008)

Table 4. 2: Technical data of the ML2x ThetaProbe and the PR2 Profile Probe (Delta-T Devices, 1999 and 2008).

Sensor	Working principle	Measurement volume	Measurement range	Advantages	Disadvantages
ML2x Theta Probe	**Electro magnetic**	**Cylinder [3 cm]**	**From 0 to saturation**	• Accurate (± 1 %) and ± 5 % without calibrating • Allows measurements in saline conditions up to 20 dS m^{-1} • Minimal soil disturbance • Can be connected to data loggers • Inexpensive due to standard circuitry • Not affected by temperature	• Soil-specific calibration recommended • Measurement affected by air gaps, stones or channeling water directly onto the probe rods • Small sensing volume [4.43 cm^3]
PR2 Profile Probe	**Electro magnetic**	**Sphere [10 cm]**	**From 0 to saturation**	• Accurate (± 4 %) and ± 5 % without calibrating • Allows measurements in saline conditions up to 5 - 40 dS m^{-1} • Can be connected to data loggers • Not affected by temperature • Measurement in different depths • Big sensing volume 5 cm vertically and 10 cm horizontally	• Soil-specific calibration recommended • Measurement affected by air gaps, stones or channeling water directly onto the probe rods • No minimal soil disturbance

4.4.3 Plant biomass and fruit yield

Tomato plants were grown in a two stem way. Other side stems with old leaves were cut every second week. The remaining parts of the plants were collected, weighed, and oven-dried at 70 °C to a constant mass to calculate the plant biomass according to Zegbe et al. (2004).

Fruits from each plant were collected and weighed to calculate the total fruit yield. Then, the fruits were cut into halves and oven-dried at 85 °C to a constant mass to determine the total dry mass and fruit biomass according to Zegbe et al. (2004).

4.4.4 Irrigation water use efficiency (IWUE)

Irrigation water use efficiency (IWUE) was calculated using the following equation (Kirda et al. 2004):

$$IWUE = \frac{Y}{I} \tag{4. 3}$$

Where:

IWUE: irrigation water use efficiency [kg L^{-1}]

Y: yield per plant [kg]

I: irrigation water applied per plant [L]

4.4.5 Sodium chloride measurements

The concentrations of Na and Cl before and at the end of the experiments were determined at a soil depth of 0, 10, 20, 30, 40, 50, and 60 cm. The soil samples were collected 10 cm away from the plant's stem for each side (left and right sides), and from different places for each replication, then the soil was mixed together for each sample. Na in soil was analyzed using the CAT solution (160 ml of CAT solution / 20 g open-air dried soil) with a flame emission photometer (Eppendorf ELEX 6361) at the Institute of Plant Nutrition, Leibniz Universität Hannover. Cl in soil was measured using a chloride-electrode (type of 15 213 3000 chloride electrode, type of 373-90-WTE-ISE-S7 reference electrode) at the Institute of Plant Nutrition, Leibniz Universität Hannover, Germany.

4.5 Calibration and sensor sensitivity

4.5.1 Moisture sensors calibration and sensitivity

Equipments

Due to the importance of soil moisture sensors in irrigation control and management practices it has become necessary to determine how moisture sensors behave under various conditions. Soil moisture sensors such as ML2x ThetaProbe, PR2 Profile Probe, and many others sensors were used extensively in irrigation programs and in the present investigations. Therefore, calibration and sensitivity investigations are necessary for measuring soil moisture in a three dimensional way. One has to determine which factors influence the measurements and readings of these sensors, and which would be the best position to install and place the sensors under field situations. These calibrations were conducted in plastic boxes. Water was added to the pots in different levels and locations by using syringes.

<u>Plastic pots and boxes</u>

For measuring the sensor sensitivity, plastic pots of 19.3 cm height, 21 cm diameter and 139.10 g weight were used with the ML2x ThetaProbe, rods facing downwards, as shown in Fig. 4.6. In the sensitivities experiments of the ML2x ThetaProbe facing upwards, plastic pots of 22.7 cm height, 26 cm diameter and 219.87 g weight were used (Fig. 4.7). Within the ML2x ThetaProbe test, the sensor was placed horizontally in a box with the dimensions 115 cm x 25 cm x 25 cm (Fig. 4.8). For the testing of the PR2 Profile Probe, plastic boxes with the dimension 30 cm x 30 cm x 20 cm were used (Fig. 4.9).

<u>Water application and soil</u>

Syringes with volumes of 20 ml and 100 ml provided with needles of different lengths (5, 7 and 9 cm) were used to apply deionized water to specific points in order to test the 3D sensitivity of the ML2x ThetaProbe. Deionized water was applied to prevent the effect of salinity on the results.

For the calibration of ML2x ThetaProbe and PR2 Probe beach sand (Bauhaus GmBH & Co.KG) of medium sand size was used. The beach sand soil was oven dried at 105 °C for 24-72 h after every treatment.

<u>Data acquisition</u>

The data were logged with the LabJack U3 (Meilhaus Electronic GmBH, Germany) data logger which was connected to a computer using the software Profilab Expert 4.0. The HH2 Moisture

Meter (Delta-T Devices Ltd, Cambridge, UK) was used together with the PR2 Profile Probe for reading and collecting the results (Fig. 4.5).

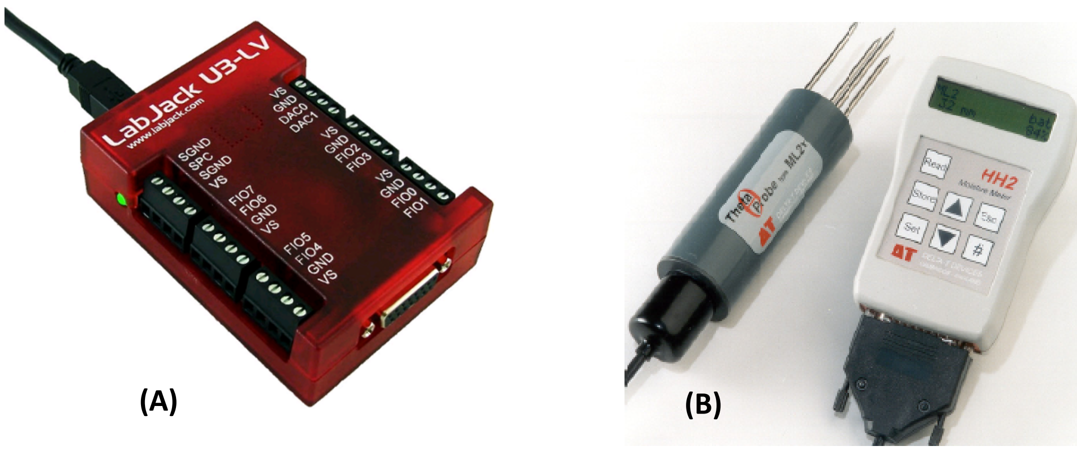


Fig. 4. 5: Data measurement and collection (A) LabJack U3 (Labjack, 2010) and (B) ML2x ThetaProbe and HH2 moisture meter (Delta-T Devices, 2005).

<u>Calibration and sensitivity of the ML2x ThetaProbe sensor facing downwards</u>

Plastic pots were filled with beach sand soil to a total weight of 7 kg. Sensors were placed at depths of 0, 3 and 5 cm below the soil surface as shown in Fig. 4.6. 200 ml of deionized water was applied at different positions, 3, 4, and 6 cm away from the central rod of the sensor and at depths of 1, 3, and 5 cm below the soil surface as shown in Fig. 4.6. Sensor readings were recorded every 15 s for a period of 5 minutes, every treatment was repeated 5 times (n = 5).

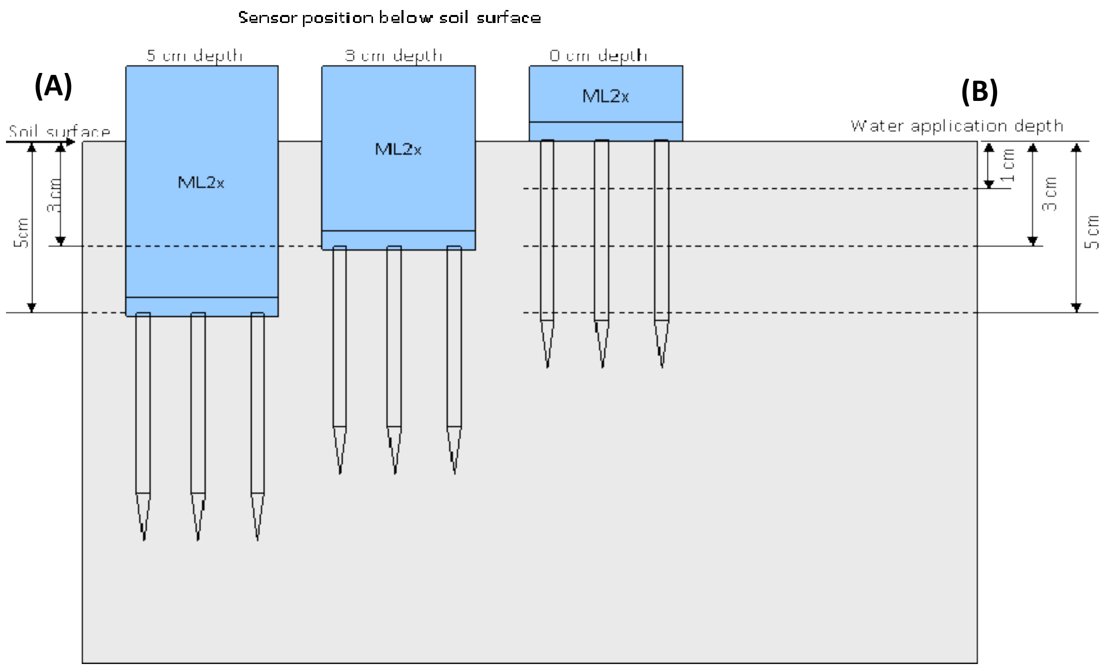
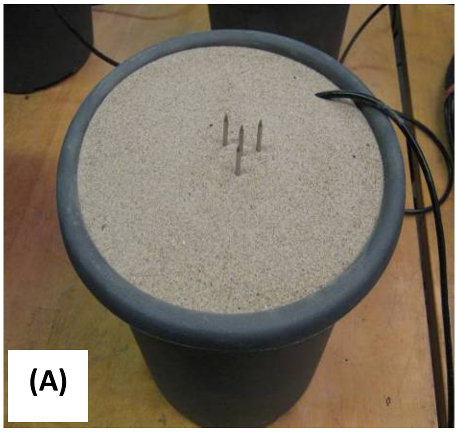


Fig. 4. 6: ML2x sensor facing downwards setup: (A) depth of sensor placement and (B) depth of water application

Calibration and sensitivity of the ML2x sensor facing upwards

The experiment was conducted to determine the sensitivity of the ML2x ThetaProbe facing upwards (Fig. 4.7A). The water was applied within the rods as shown in Fig. 4.7B. The pots were filled with sandy soil up to a total weight of 8.5 kg. Water was applied at the points of 1, 2, 3, 4, 5, and 6 (see Fig. 4.7). The treatments were replicated 3 times with 6 sensors and were carried out using 20 ml of water. In order to compare the application of water within and outside of the sensor, four sensors were placed in plastic boxes and 100 ml water was added at 1, 2, 3, and 4 cm away from the centre rod. Water was applied at depths 1, 3, and 5 cm below the soil surface. These investigations were performed four times with three replications for each depth. Readings for all tests were taken every 15 s for 5 minutes.



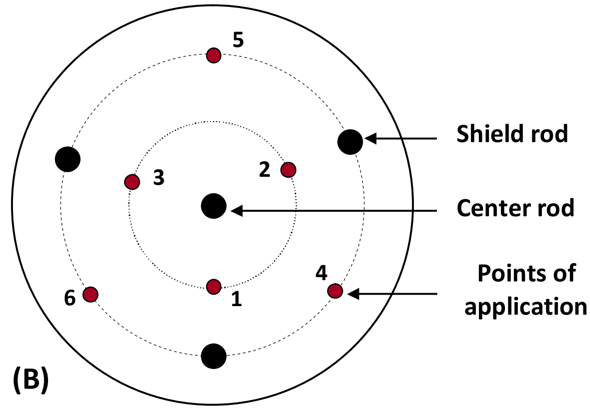


Fig. 4. 7: ML2x sensor facing upwards setup: (A) placement of sensor with rods facing upwards and (B) points of water application within the sensors rods (Eyahanyo, 2010)

Calibration and sensitivity of the PR2 Profile Probe sensor

Five boxes of 30 cm length, 30 cm width and 20 cm height as shown in Fig. 4.8 were used for this test. They were structured up to a tower and were filled with sand. The last box on top of the four boxes was filled with various moisture contents around the access tube. Four cylinders with a diameter of 6.8, 10.8, 14.8, and 18.8 cm were used in the experiment as shown in Fig. 4.8. The cylinders were placed in the top box. Different uniformly beach sand soil with moisture contents of 10, 20 and 30 % (weight basis) were used in this investigation. In order to investigate the first moisture content, sandy soil with a moisture content of 10 % was placed in the first cylinder of 6.8 diameter (2 cm around the access tube) while a dry sand was applied around it. The cylinder was then removed and readings were quickly recorded along the various depths of the sensor at 10, 20, 30, 40, 60 and 100 cm depths. Dry sand soil was then placed in the cylinder of 6.8 diameter (2 cm cylinder around the access tube) and soil with 10 % moisture content (weight basis) was placed in the cylinder of 10.8 diameter (4 cm cylinder away from the access tube). Dry sand was then applied around the 6.8 and 10.8 cm cylinders as well. The cylinders were then removed and readings were taken quickly. This was also done for the cylinders with 14.8 cm and 18.8 cm by putting soil with moisture content of 10 % away from the access tube in these cylinders. The same treatments were repeated for soil with moisture contents of 20 and 30 % (weight basis). The treatments were repeated three times.

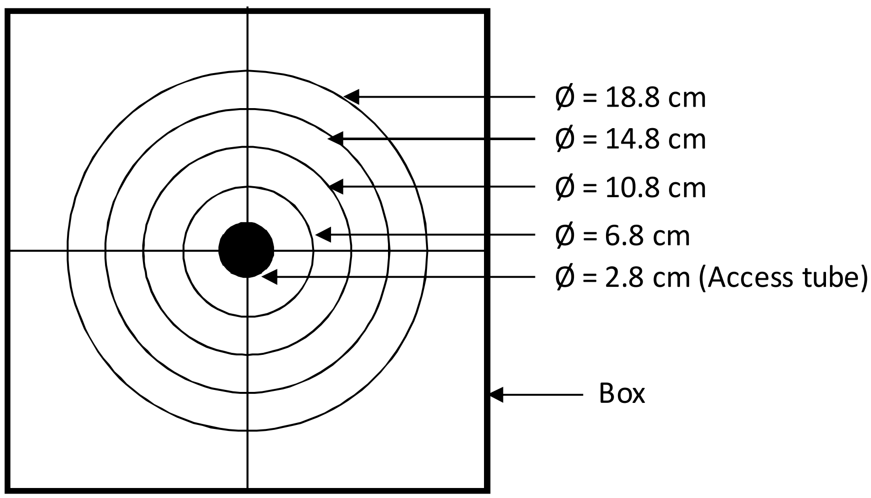


Fig. 4. 8: Placement of cylinders around the access tube, where Ø is the diameter of the cylinder

4.5.2 Dripper calibration

In the open-soil experiment, a drip irrigation system was used to irrigate the plants. The drip emitters were calibrated before transplanting the plants. The calibration was performed by measuring the discharge of the emitters. Therefore, the discharged water from the emitters was collected and the volume was measured using glass bottles while recording the discharge time using a stop watch. The discharge rate was calculated according to the equation 4.4.

$$\mathbf{Q} = \frac{\mathbf{V}}{\mathbf{t}} \qquad (4.\ 4)$$

Where:

Q: discharge rate of the emitter	[L h^{-1}]
V: volume of the discharged water	[L]
t: time	[h]

The calibration was conducted for every tube within the PRDI treatment (shown in Fig. 4.9A); the two tubes of the CI treatment were calibrated together (shown in Fig. 4.9B).

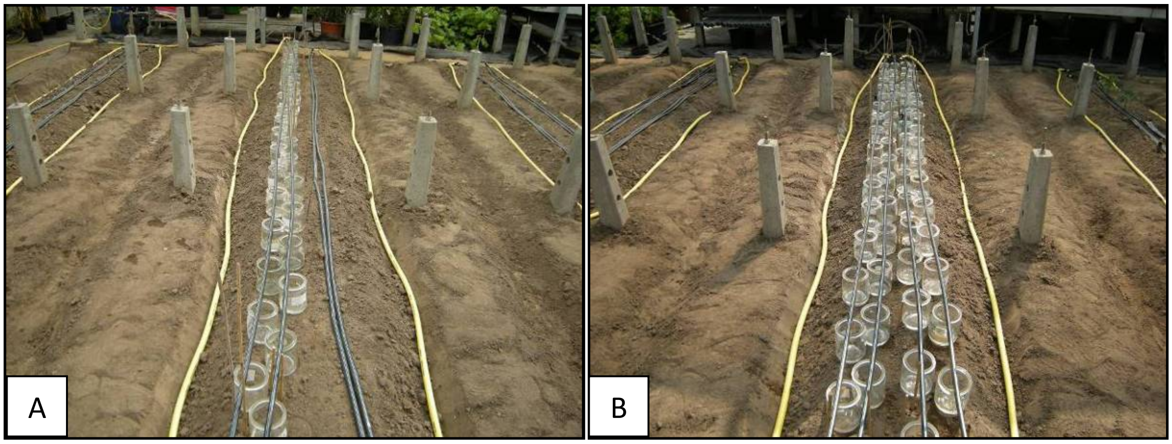


Fig. 4. 9: Calibration of the emitters of the drip irrigation system: (A) tubes of PRDI treatment (B) tubes of CI treatment

4.6 Data analysis

Statistical evaluations of the experiments were conducted using the SPSS-Statistical Package (SPSS 18). A linear mixed model at a 5 % significance level was used for the results. With Microsoft Office Excel the results were plotted into diagrams. Sigma Plot 11.0 and Gnuplot software were used for creating the charts.

4.7 Experimental set-up

4.7.1 Pot experiments (split-root)

4.7.1.1 Root and pot splitting methods

Tomatoes were planted in plastic pots of 55 cm diameter and 95 cm height (volume of 225 L). Each pot was split into two compartments by two plastic bags as shown in Fig. 4.10 and Fig. 4.11. The plastic bags were used to prevent any movement of irrigation water and plant roots from one pot compartment to the other as demonstrated in Fig. 4.10 and Fig. 4.11A. The root system of each plant was split by a sharp blade into two parts (Fig. 4.11B). Each part was placed in one half of the pot (Fig. 4.11C). Some holes were drilled into the bottom of each pot to allow the water to drain after irrigation. To avoid the effects of high temperature on soil and fertilizer, the pots were covered with aluminum foil as shown in Fig. 4.11D.

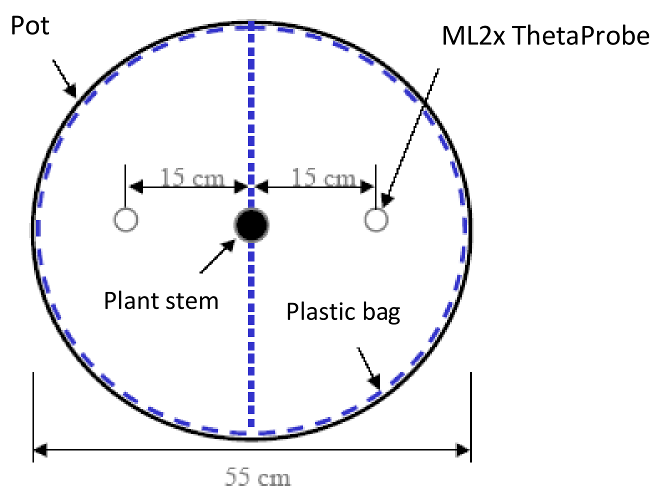


Fig. 4. 10: The pot setup

4.7.1.2 Location and soil type

The experiments were carried out in a greenhouse at the Biosystems Engineering Section (BGT), Institute of Biological Production Systems, Leibniz Universität Hannover. The preliminary experiment A was started in May and lasted till September 2007; the pot experiment B was conducted from May till October 2008.

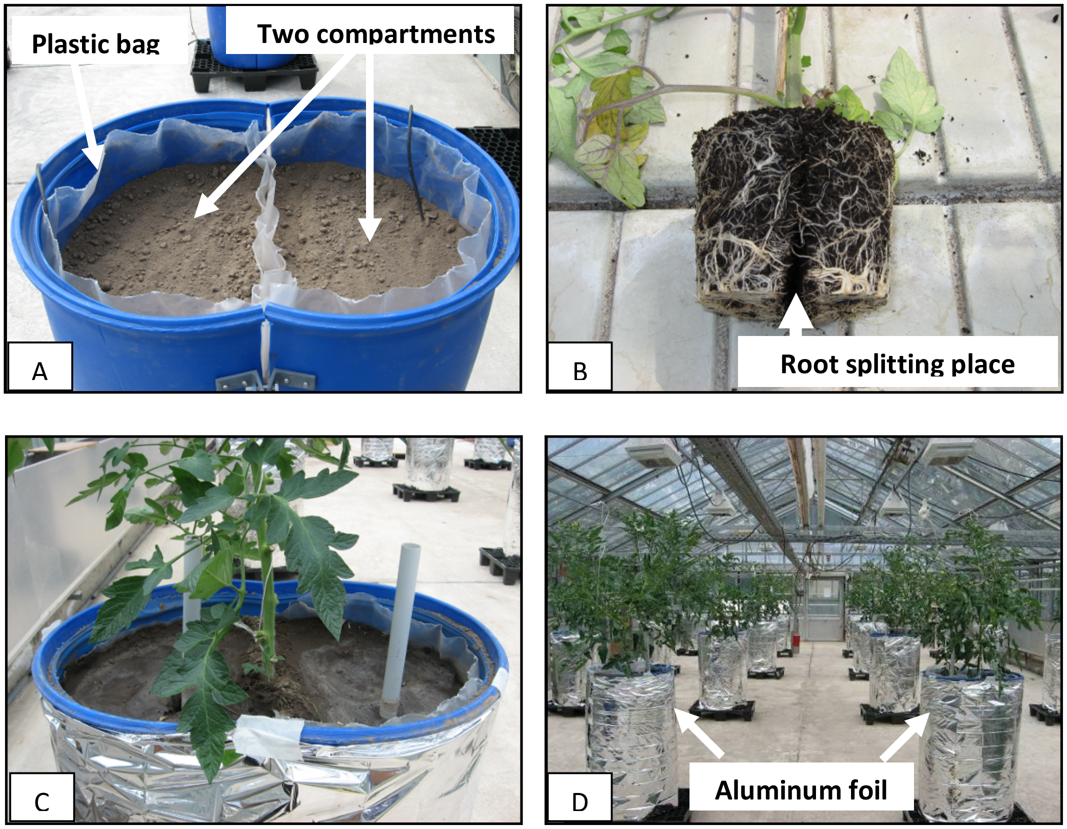


Fig. 4. 11: The root and pot splitting methods

The pots were filled with the same volume of air dried sandy loam soil collected from 0 - 30 cm top soil layers of an open field soil (Herrenhausen, Hannover, Germany 52 23` N and 9 42` E). Physical properties of the soil are shown in Table 4.3. The needed fertilizer was mixed with the soil, and then the pots were filled with the soil.

Table 4. 3: Grain size distribution of the soil in the pot experiments

Grain size distribution [%, based on weight basis]			texture
Clay	Silt	Sand	
7.2	21.2	71.6	sandy loam

The grain size distribution of the soil was analyzed in the LUFA Nord-West (Jägerstrasse 23-27, 26121 Oldenburg)

4.7.1.3 Treatments

Two irrigation methods (CI and PRDI) were tested and the irrigation was carried out by hand. The amount of water applied was calculated by measuring the volumetric soil moisture content (θ_v) for every pot before irrigation.

Table 4. 4: Treatments during the preliminary and the pot experiments A and B

Treatment denomination	Irrigation method		Water application level % of FC					No. of replication	Experiment No.	
	CI	PRDI	70 - 80	55 - 80	40 - 80	65 - 80	50 - 80		A	B
CI-70	**X**		**X**					**2**	**X**	
PRDI-70		**X**	**X**					**2**	**X**	
CI-55	**X**			**X**				**2**	**X**	
PRDI-55		**X**		**X**				**2**	**X**	
CI-40	**X**				**X**			**2**	**X**	
PRDI-40		**X**			**X**			**2**	**X**	
CI-65	**X**					**X**		**4**		**X**
PRDI-65		**X**				**X**		**4**		**X**
CI-50	**X**						**X**	**4**		**X**
PRDI-50		**X**					**X**	**4**		**X**

Preliminary experiment [A] = 12 Pots Pot experiment [B] = 16 pots

In the preliminary experiment A, six treatments were conducted (2 irrigation methods X 3 water application levels), which were CI-70, PRDI-70, CI-55, PRDI-55, CI-40, and PRDI-40 as presented in Table 4.4 and Fig. 4.12. In order to control irrigation, 80 % of FC was considered as maximum irrigation for all treatments, and 70 % of FC was considered as minimum rate to CI-70 and PRDI-70 treatments, however 55 % of FC was set as minimum rate to CI-55 and PRDI-55 treatments, and 40 % of FC as minimum rate to CI-40 and PRDI-40 treatments (Fig. 4.12).

In the CI-70 and the PRDI-70 treatments, when the soil moisture content on the irrigated side of the PRDI-70 treatment was reduced to 70 % of FC, the PRDI-70 treatment was watered up to 80 % of FC (only one side). The same amount of water was added to the CI-70 treatment (both sides). The same technique was used in different treatments: 55 % of FC for CI-55 and PRDI-55 treatments, and 40 % of FC for CI-40 and PRDI-40 treatments. When the dry side of the PRDI treatment reached 30 % of FC, it was considered the point to alternate the irrigated side. The treatments were replicated twice and randomly arranged inside the greenhouse as depicted in Fig. 4.13.

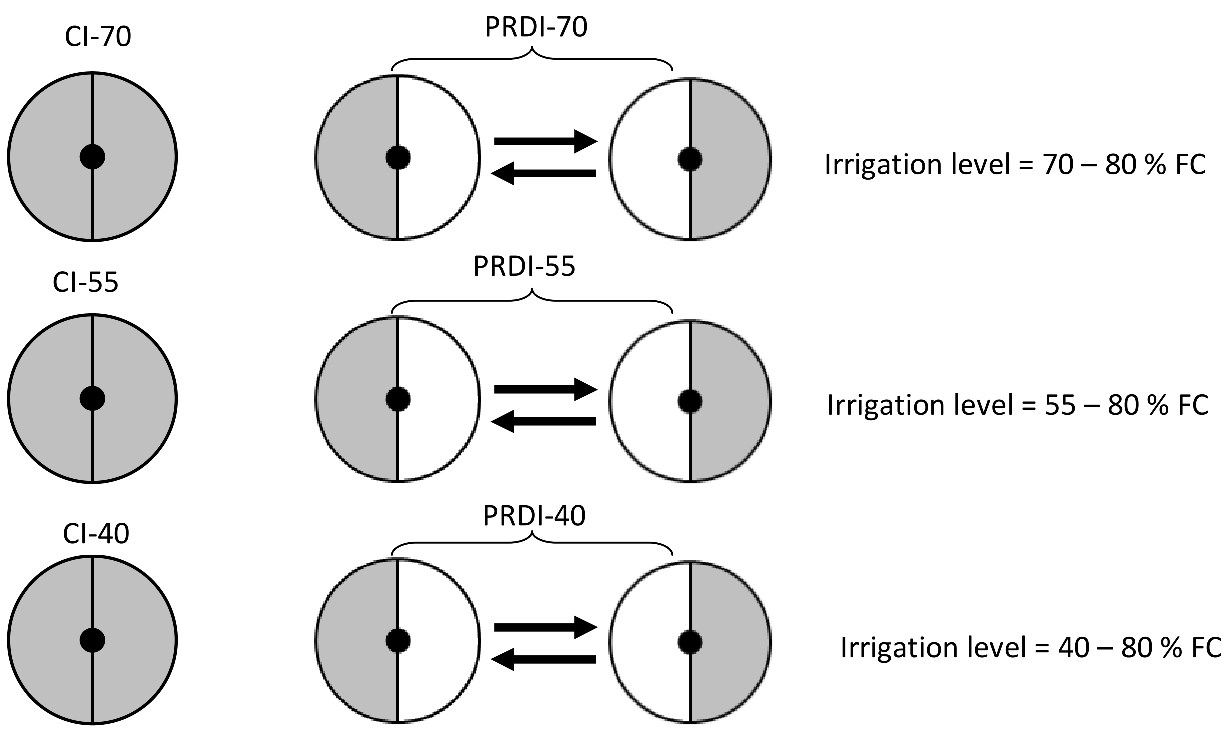


Fig. 4. 12: Treatments during the preliminary experiment A

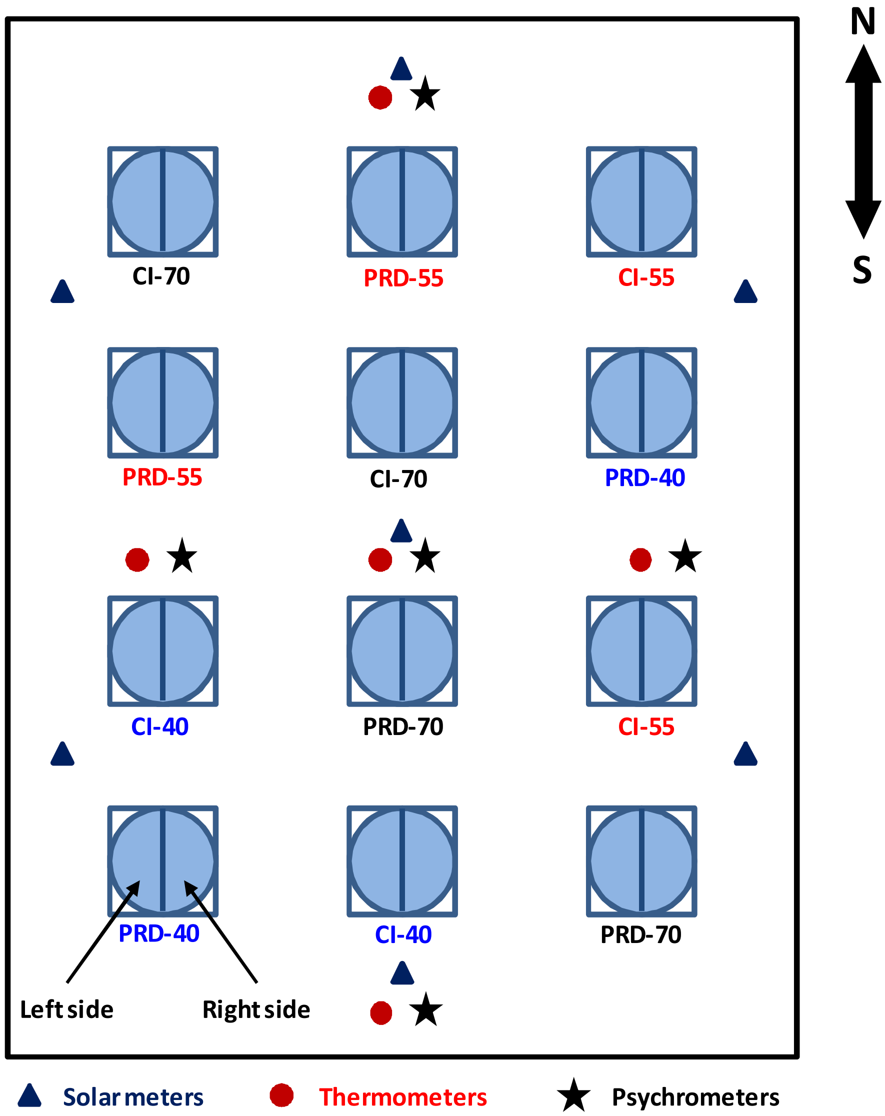


Fig. 4. 13: Replication arrangement inside the greenhouse during the preliminary experiment A

Four treatments were chosen for the pot experiment B (2 irrigation methods X 2 water applications), which were CI-65, PRDI-65, CI-50, and PRDI-50 treatments, as presented in Table 4.4 and Fig. 4.14. To control irrigation in this experiment, 80 % and 65 % of the FC were considered as maximum and minimum irrigation for the CI-65 and PRDI-65 treatments and 65 % and 50 % of the FC were considered as max and min for the CI-50 and PRDI-50 treatments. The irrigation shifting was done after a fixed period of time. So within the PRDI treatment three weeks of irrigation time was used to alternating the irrigated and the dry part of the soil from left side to right side (shown in Fig. 4.14 and Table 4.5). The treatments were replicated four times and were arranged randomly inside the greenhouse as shown in Fig. 4.15.

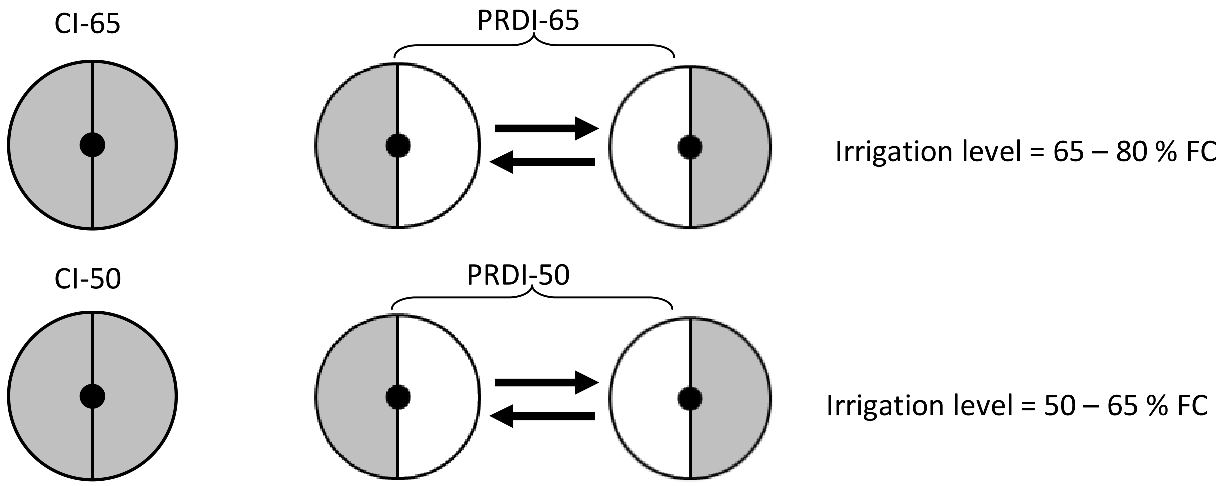


Fig. 4. 14: Treatments during the pot experiment B

Table 4. 5: Irrigation management during the pot experiment B

Treatment denomination	Θ_v of CI treatment		Irrigation by CI		Irrigation by PRDI		Irrigation shifting
	left side	right Side	left side	right Side	left side	right Side	
CI-65 & PRDI-65	= 65 %	*	X	X	X		Starting in left side of PRDI
	= 65 %		X	X	X		
	= 65 %		X	X	X		
	*	= 65 %	X	X		X	Shifting to right side of PRDI
		= 65 %	X	X		X	
		= 65 %	X	X		X	
	= 65 %	*	X	X	X		Shifting to left side of PRDI
	= 65 %		X	X	X		
	= 65 %		X	X	X		
CI-50 & PRDI-50	= 50 %	*	X	X	X		Starting in left side of PRDI
	= 50 %		X	X	X		
	= 50 %		X	X	X		
	*	= 50 %	X	X		X	Shifting to right side of PRDI
		= 50 %	X	X		X	
		= 50 %	X	X		X	
	= 50 %	*	X	X	X		Shifting to left side of PRDI
	= 50 %		X	X	X		
	= 50 %		X	X	X		

* Duration time of 3 weeks

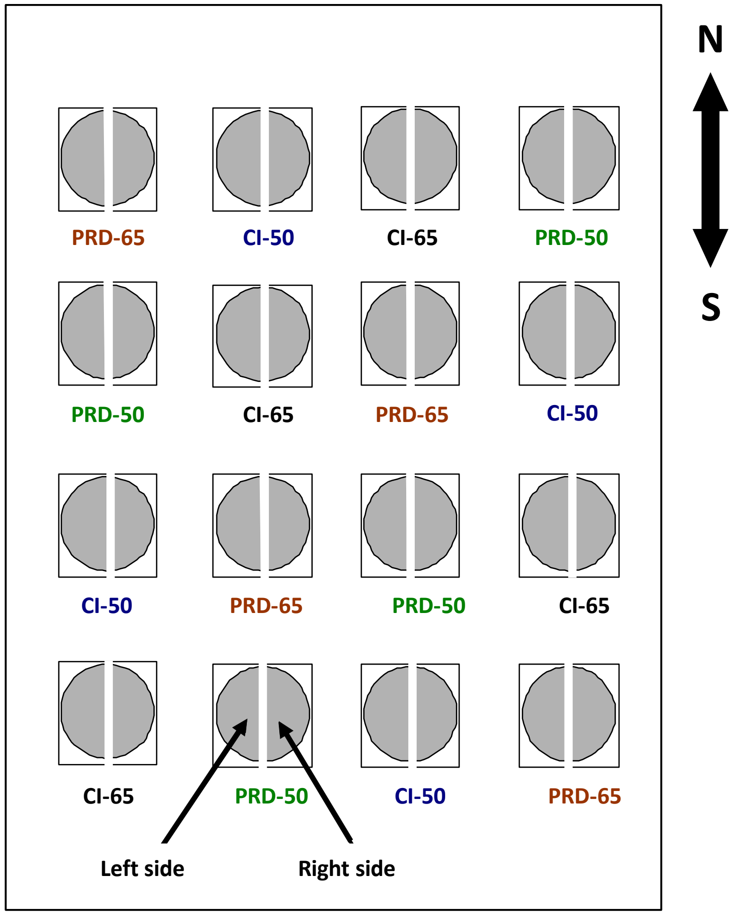


Fig. 4. 15: Replication set-up inside the greenhouse during the pot experiment B

4.7.2 Open-soil experiment (natural growth)

4.7.2.1 Location and arrangement of the experiment

The experiment was conducted on the loamy sand soil of a plastic greenhouse of the Biosystems engineering section (BGT), during the months of May until October 2009. Plants were grown in rows of 60 cm width and 45 cm within the row as presented in Fig. 4.16 and Fig. 4.17. One soil moisture sensor (ML2x ThetaProbe) was installed at every side of the row to measure at 20 cm below soil surface. Also, one access tube of the PR2 profile probe was fixed on every side to measure the soil moisture content at different depths of the plant row as shown in Fig. 4.16A.

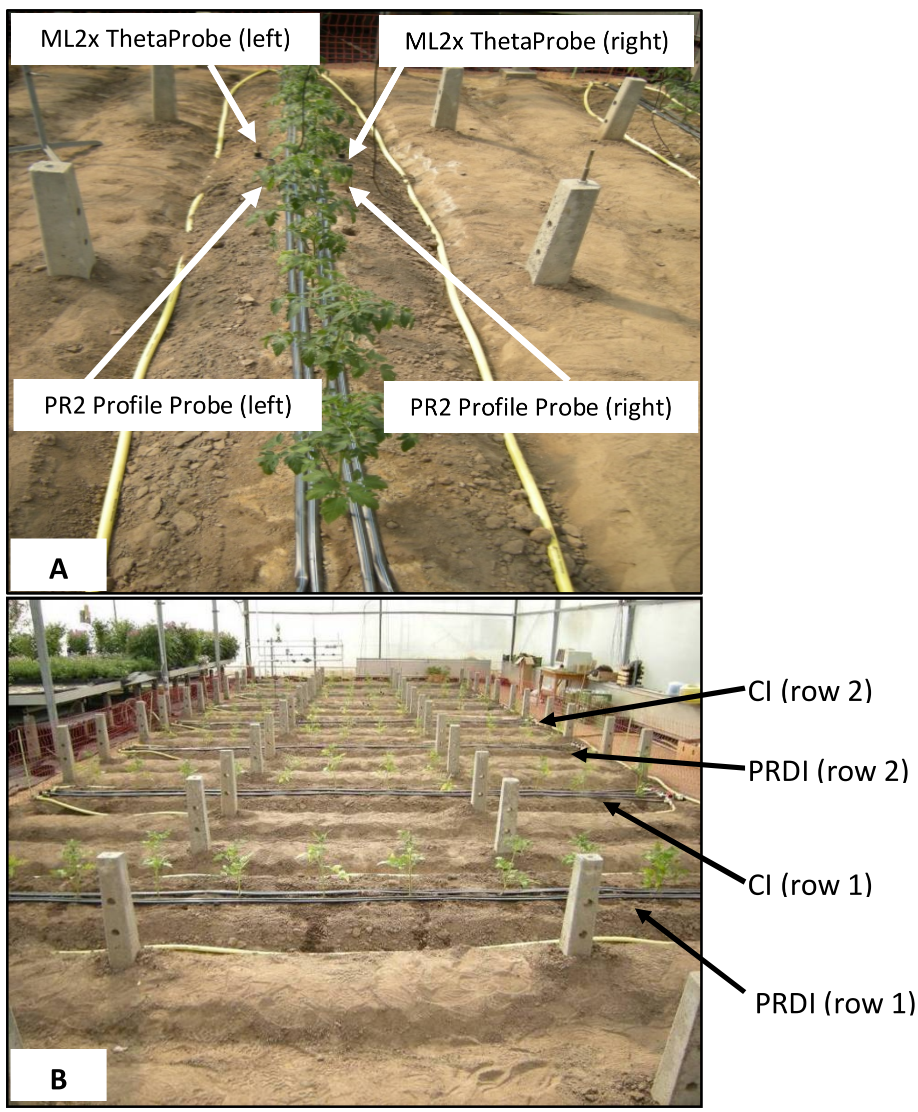


Fig. 4. 16: Open-soil experimental set up: (A) one row and (B) the whole experiment

4.7.2.2 Treatments

Two irrigation methods (CI and PRDI) with four replications were tested in this experiment. The irrigation was carried out by a drip irrigation system (see chapter 4.3). The amount of water applied was calculated according to the volumetric soil moisture content (θ_v) in every treatment before irrigation. Irrigation was applied to every row over four parallel irrigation tubes, two lines on each side of a row of plants (Fig. 4.17A). A water valve was used to control the irrigation at each side. The water was measured by a weight system and water pump in order to control the amount of irrigation water (see Fig. 4.17B). The irrigation was switched on and off by hand.

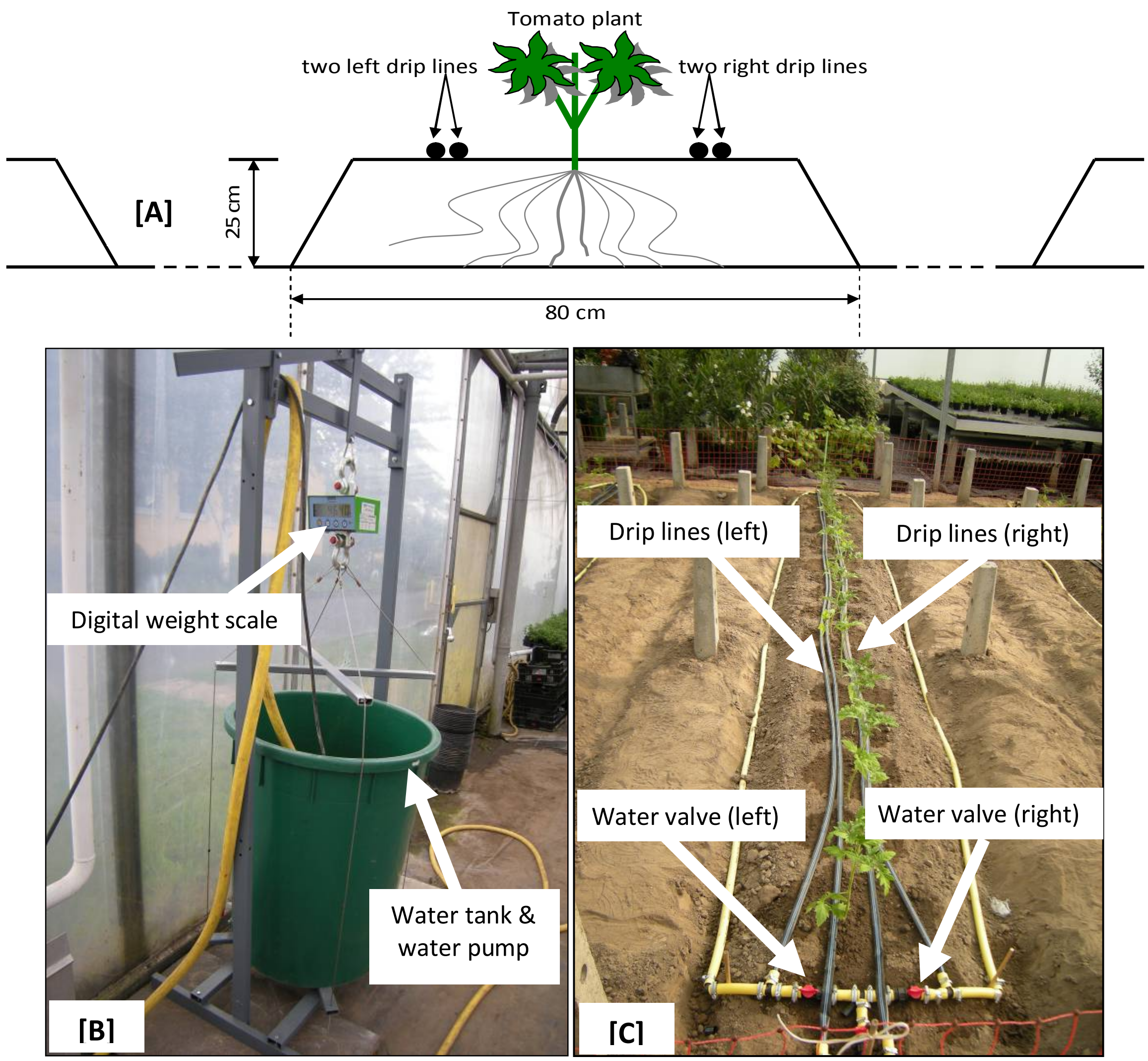


Fig. 4. 17: Water management: (A) schematic front view of the crop row, (B) control of the water applied and (C) irrigation control of the left and right side.

To control irrigation, 80 % and 65 % of the FC were set as maximum and minimum moisture contents, respectively. When soil moisture content in the CI treatment was reduced to 65 % of FC, the CI treatment was irrigated up to 80 % of FC (see Table 4.6). The same amount of water was then added to one side of the PRDI treatment. In the PRDI treatment, three weeks of irrigation time was chosen for shifting the irrigation from wet side to dry side (shown in Fig. 4.18). The treatments were repeated four times and arranged randomly in the greenhouse (Fig. 4.16).

Table 4. 6: Irrigation management during the open-soil experiment

Treatment denomination	Θ_v of CI treatment		Irrigation by CI		Irrigation by PRDI		Irrigation shifting
	left side	right Side	left side	right Side	left side	right Side	
CI & PRDI	= 65 %	*	X	X	X		Starting on left side of PRDI
	= 65 %		X	X	X		
	= 65 %		X	X	X		
	*	= 65 %	X	X		X	Shifting to right side of PRDI
		= 65 %	X	X		X	
		= 65 %	X	X		X	
	= 65 %	*	X	X	X		Shifting to left side of PRDI
	= 65 %		X	X	X		
	= 65 %		X	X	X		

* Duration time of 3 weeks

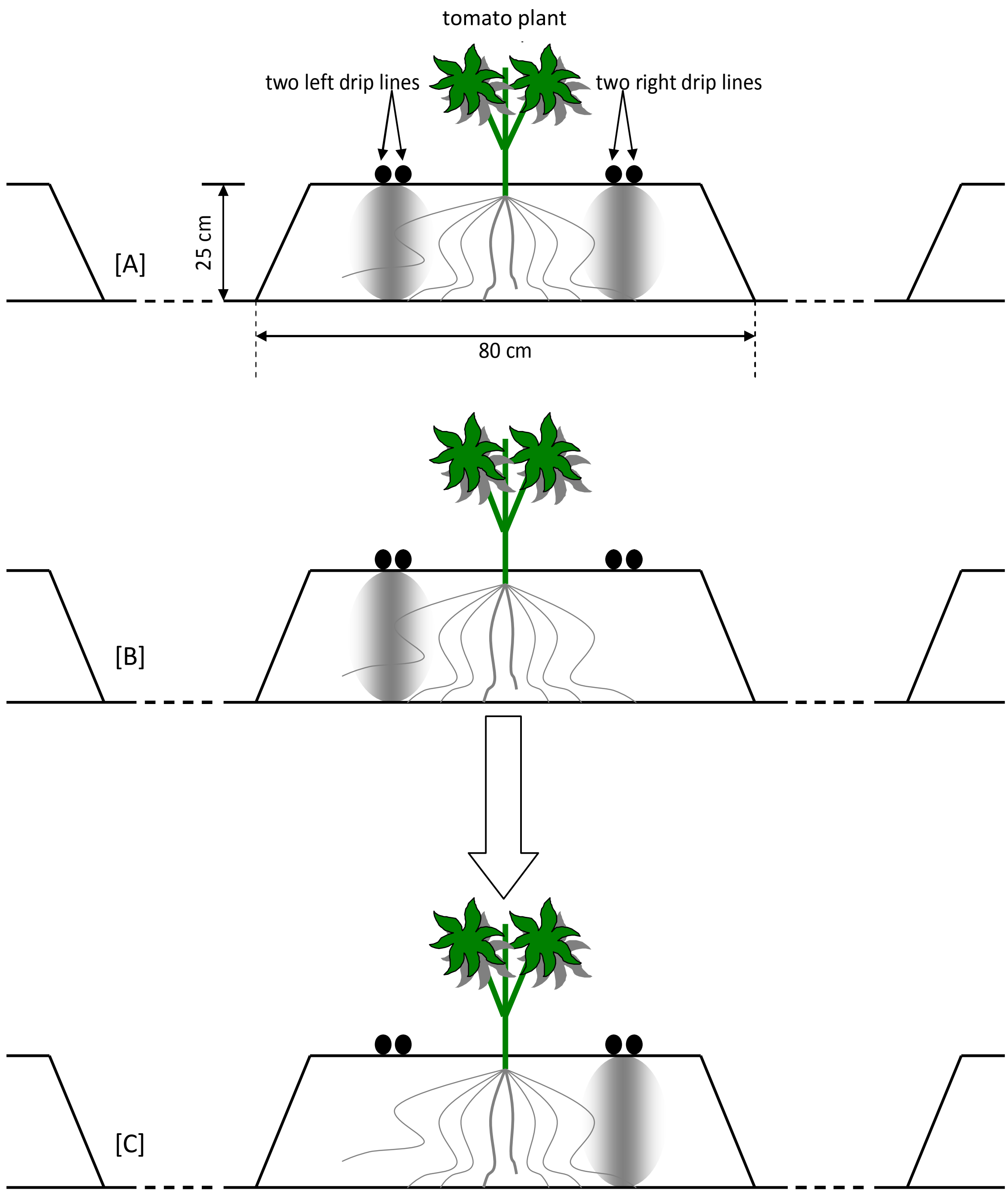


Fig. 4. 18: Irrigation management: (A) both sides of CI treatment were irrigated, (B) left side of PRDI treatment was irrigated, and (C) right side of PRDI treatment was irrigated.

4.7.3 Simulation (natural growth)

4.7.3.1 Software and calculation

A simulation was performed by the software system LEACHC (Hutson, 2003). LEACHC is one of five different versions of the LEACHM model (an acronym for a **L**eaching **E**stimation **A**nd **CH**emistry **M**odel). It is one of several versions of a simulation model which describes the water regime as well as the chemistry and transport of solutes in unsaturated or partially saturated soils up to a depth of about two meters (Wagenet and Hutson, 1987, 1989; Hutson and Wagenet, 1992). The versions utilize similar numerical solution schemes to simulate water and chemical movement. Most of the input data required for LEACHC is format free and can be provided in tables created by editing an already existing file. LEACHC requires the chemical composition of the irrigation water (and underground water, if a water table boundary condition is selected) and the chemical compositions of the soil profile.

LEACHM uses a finite-difference form of Richard's equation as a means of predicting water contents, fluxes, and potentials in the soil (Hutson, 2003). Richards' equation (the soil water flow equation for transient vertical flow derived from Darcy's law and the equation of continuity) is shown as following:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial H}{\partial z}\right] - U(z,t) \qquad (4.\ 5)$$

Where:

Θ: volumetric water content of the soil	[m^3 m^{-3}]
H: hydraulic head of the water	[mm]
K: hydraulic conductivity of the soil	[mm day^{-1}]
t: time	[day]
z: depth, positive downwards	[mm]
U: sink term representing the water loss per unit time by transpiration	[day^{-1}]

Richards’ equation assumes that the soil is rigid, incompressible, non-hysteretic, and isothermal. Water flow is via the soil matrix only in a 2 dimensional way, and not via macro pores and larger preferred pathways. It also assumes that the soil is homogeneous and isotropic, so that the hydraulic conductivity is uniform and does not depend on the direction of water movement.

The evapotranspiration subroutines are based upon the methods of Childs and Hanks (1975). In the LEACHC program, the potential ET is calculated at the start of each day. By using a weekly total potential evapotranspiration (ET_{week}) and a crop factor (F_{crop}), the daily potential evapotranspiration (ET_{day}) was calculated by:

$$ET_{day} = \left(F_{crop} * ET_{week}\right)/a \quad (4.\ 6)$$

$$T_{day} = ET_{day} * F_{cover} \quad (4.\ 7)$$

$$E_{day} = ET_{day} - T_{day} \quad (4.\ 8)$$

Where:

ET_{day}: daily evapotranspiration	[mm day^{-1}]
ET_{week}: weekly evapotranspiration	[mm $week^{-1}$]
T_{day}: daily transpiration	[mm day^{-1}]
E_{day}: daily evaporation	[mm day^{-1}]
F_{crop}: crop factor	[-]
F_{cover}: crop cover fraction	[-]
a = 7	[days / week]

The potential evapotranspiration (ET) for a time step was calculated with the following equation.

$$ET_p = ET_{max} * \sin[2\pi(t - 0.3)] \quad (4.\ 9)$$

Where:

ET_p: evapotranspiration for a time step	[mm]
t: time, varying between 0.3 day and 0.8 day	[-]
ET_{max}: f (ET_{day}, max (sin [2π (t-0.3)])	[mm]

0.3 day equals 7 h 12 min, 0.55 day equals 13 h 12 min and 0.85 day equals 19 h 12 min.

According to Hutson (2003), the chemical processes of salts included in the LEACHC program are summarized in Fig. 4.19. The chemical processes are based on the differences between input salts sources and leaching salts with water. The input sources contain the salts added by irrigation and rain water, fertilizers and amendments, and the accumulated salts from the atmosphere.

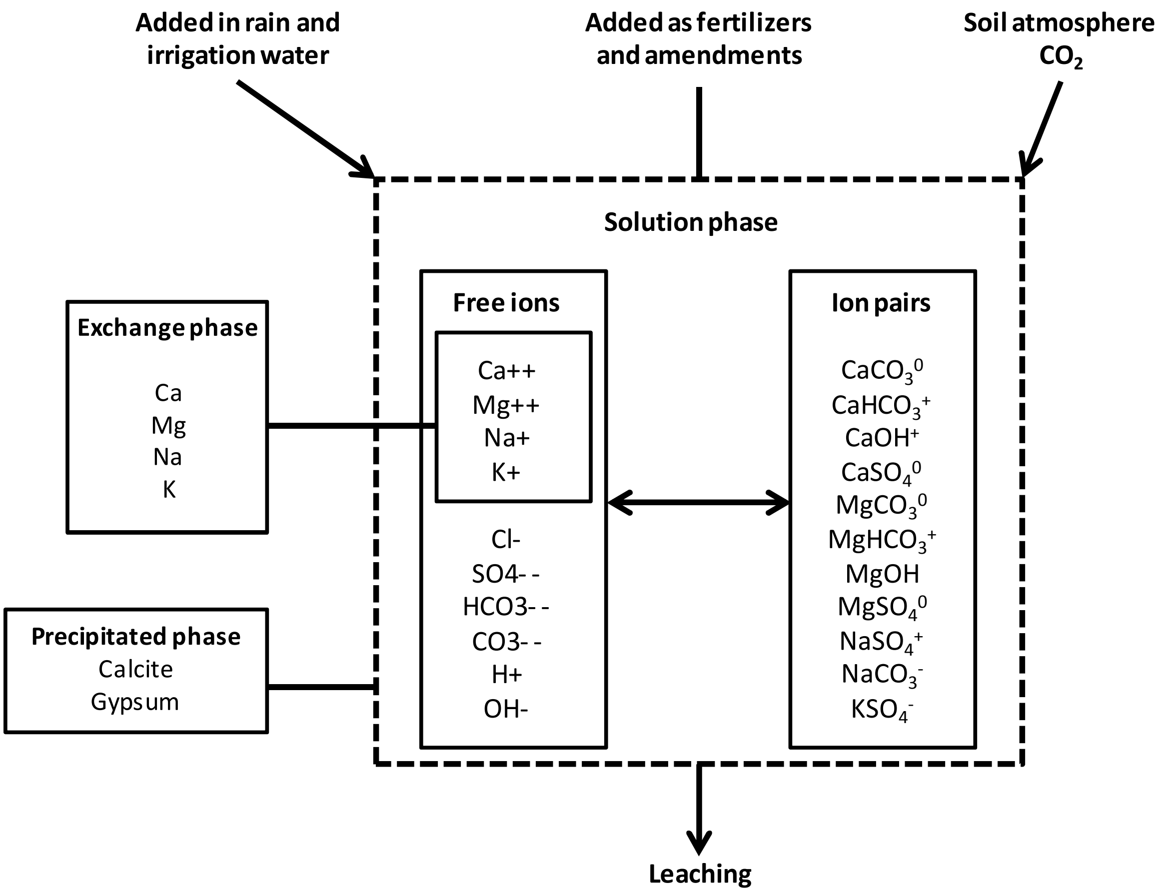


Fig. 4. 19: Chemical processes of salts included in the LEACHC program (Hutson, 2003)

4.7.3.2 Parameters

LEACHC has different lower boundary conditions: (1) fixed depth water table, (2) free drainage, (3) zero flux, and (4) lysimeter. The free drainage lower boundary (2) was chosen in the present simulation.

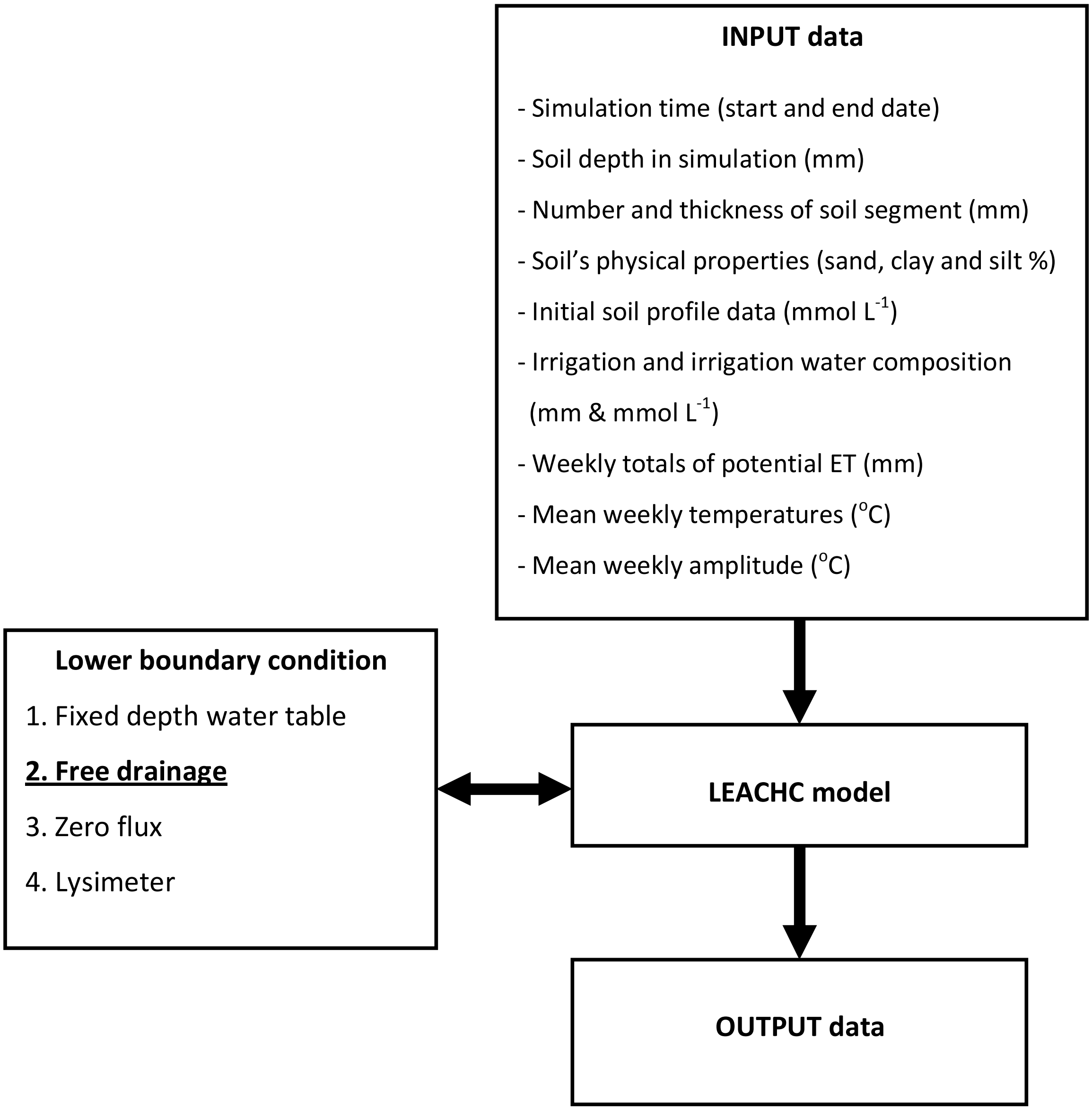


Fig. 4. 20: Illustration of the model inputs and boundary condition (Hutson, 2003**)**

4.7.3.3 Runs

4.7.3.3.1 Open-soil simulation (natural growth)

In the present work, LEACHC was used to simulate the influence of the irrigation methods PRDI and CI on the accumulation and relocation of salts in the soil profile. Basic data were coming from the open-soil experiment C (see Chapter 4). For the simulation, the irrigation applications were calculated according to the soil moisture content and to the soil properties during the experiments. Since the irrigation was shifted from one side to the other in the PRDI method, while it was similar in both sides of the CI method. Therefore the soil salinity was simulated for each side of the PRDI method and only for one side of the CI method.

The following input factors were chose for the simulation:

Simulation time: from 06/05/2009 to 05/10/2009 (the growing period of the open-soil experiment).

Irrigation method: drip irrigation

Crop cover fraction (tomato): 0.85

Soil depth of simulation: up to 60 cm

Number and thickness of soil segments: the soil depth was classified into 6 soil segments; each segment was 10 cm thick.

Soil physical properties: 4 soil samples per row were collected in the experiment [C] and analyzed for the soil's physical properties for each soil layer. Table 4.7 presents the soil texture analysis that served as input for the LEACHC model.

Table 4. 7: The soil texture analysis for the input into the LEACHC program (open-soil and nature growth simulation based on weight basis)

	Sample No.								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Average**
Clay [%]	8.2	7.6	7.3	4.7	9.0	9.4	5.2	6.0	**7.2**
Silt [%]	18.9	17.0	16	22.5	21.1	23.1	26.7	24.6	**21.2**
Sand [%]	72.9	75.4	76.7	72.8	69.9	67.5	68.1	69.4	**71.6**

NB: The texture analysis of the soil was analyzed in the LUFA Nord-West (Jägerstrasse 23-27, 26121 Oldenburg)

Initial soil profile data: The initial soil data was based on the measurements in the open-soil experiment C. The soil samples were collected and analyzed for soluble cations and anions in each soil layer of the soil profile (n = 4). Table 4.8 presents the results of the initial soil profile data.

Table 4. 8: Soluble cations and anions of initial profile data input for the LEACHC program

simulation depth [cm]	Ion concentration [mmol L^{-1}]					
	Ca	Mg	Na	K	Cl	SO_4
0-10	1.57	5.67	4.51	4.60	5.41	15.99
10-20	1.57	5.67	4.51	4.60	5.41	15.99
20-30	1.57	5.67	4.51	4.60	5.41	15.99
30-40	1.57	5.67	4.51	4.60	5.41	15.85
40-50	1.57	5.67	4.51	4.60	5.41	15.85
50-60	1.57	5.67	4.51	4.60	5.41	15.85

NB: The initial profile data of the soil were analyzed in the LUFA Nord-West (Jägerstrasse 23-27, 26121 Oldenburg)

Evapotranspiration (ET): The evapotranspiration was calculated according to Hargreaves and Samani (1982; 1985); Samani, (2000) using equation 4.10 to calculate the daily evapotranspiration. Then the weekly evapotranspiration was determined using the daily amounts. The calculated amounts of weekly evapotranspiration by equation 4.10 were used for input data of simulation program.

$$ET \approx 0.0135 * R_s * (TC + 17.8) \qquad (4.\ 10)$$

Where:

ET: evapotranspiration	[mm day^{-1}]
TC: average daily temperature	[^oC]
R_s: solar radiation	[MJ m^{-2} day^{-1}]

Climatic data: The climatic data was generated by using the original climatic data of the experiment C. The necessary inputs are: total weekly potential evapotranspiration, mean weekly temperature, and mean weekly temperature amplitude.

Irrigation water [mm] was calculated by dividing the amount of irrigation water of the experiment by the irrigated area. The irrigated area in the CI treatment equaled the whole planted area. In the PRDI treatment, it was only half of the planted area. The number of irrigations and the irrigation water composition are listed in Table A.1 of appendix.

Lower boundary condition: Free drainage was chosen as the low boundary condition.

4.7.3.3.2 Egypt situation simulation (natural growth)

In order to study the effects of PRDI method on soil salinity relocation under arid and semi-arid situations, the LEACHC program was used to simulate soil sodium and chloride movement in Egypt (Shebin EL-Kom, Egypt 30 54` N and 31 00` E). The climate at Shebin EL-Kom is characterized by a very low rainfall during a four month winter season. Summer is characterized by warm and sunny days with minimum night temperature between 17 °C and 22 °C and maximum daytime temperatures ranging between 30 °C and 35 °C. These days are sometimes interrupted by heat waves with maximum temperatures of up to 40 °C and relative humidity dropping to 15 %. Maximum global radiation reaches about 1100 Wm^{-2} in summer and 600 Wm^{-2} in winter (Taha, 2003). The required data for the simulation was collected from a publication by Malash et al. (2008a) and internet sources NOAA (2010) and Weather (2010).

http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.html (01/11/1010)

http://www.weather.com/weather/climatology/daily/EGXX0004? (01/11/2010)

Simulation time: From 01/05/2009 to 31/10/2009

Irrigation method: Drip irrigation

Soil depth of simulation: 150 cm

Number and thickness of soil layers: The soil depth was divided into 15 segments; each layer corresponded to 10 cm.

Soil physical properties: The physical properties of each soil layer in the soil profile were derived from published data of Malash et al. (2008a) (see Table 4.9).

Initial profile data: The initial soil profile data for each soil layer also based on Malash et al. (2008a) (see Table 4.10).

Table 4. 9: Soil physical properties input for the LEACHC program for the Egypt simulation (Malash et al. 2008a)

	Soil content [%]					
	Soil depth [cm]					
	0-30	**30-60**	**60-90**	**90-120**	**120-150**	**150-180**
Clay	30.9	38.9	38.9	36.4	33.9	39.1
Silt	71.3	31.1	33.7	33.8	39.1	28.7
Sand	27.78	30.06	27.40	29.89	27.03	32.30

Table 4. 10: Soluble cations and anions of initial soil profile data input for the LEACHC program under Egypt conditions (Malash et al. 2008a).

Simulation depth [cm]	Ion concentration [mmol L^{-1}]					
	Ca	Mg	Na	K	Cl	SO4
0 - 10	6.6	3.6	15.9	3.5	12.5	7.1
10 - 20	6.6	3.6	15.9	3.5	12.5	7.1
20 - 30	6.6	3.6	15.9	3.5	12.5	7.1
30 - 40	4.5	3.0	18.0	2.1	10.5	7.1
40 - 50	4.5	3.0	18.0	2.1	10.5	7.1
50 - 60	4.5	3.0	18.0	2.1	10.5	7.1
60 - 70	3.2	4.0	22.1	1.7	8.5	8.0
70 - 80	3.2	4.0	22.1	1.7	8.5	8.0
80 - 90	3.2	4.0	22.1	1.7	8.5	8.0
90 - 100	2.0	4.0	23.0	0.1	5.0	4.1
100 - 110	2.0	4.0	23.0	0.1	5.0	4.1
110 - 120	2.0	4.0	23.0	0.1	5.0	4.1
120 - 130	2.0	3.2	23.0	0.1	6.8	0.6
130 - 140	2.0	3.2	23.0	0.1	6.8	0.6
140 - 150	2.0	3.2	23.0	0.1	6.8	0.6

Irrigation water [mm] was considered according to Malash et al. (2008a). The shifting of the irrigated side in the PRDI method was conducted at three different times: each 5 days, each 15 days and each 30 days. The number of irrigation and irrigation water composition are listed in Table A.2 (Appendix).

Climate data: The climate data was generated by using the original climate data of the Egypt situation. The inputs were the total weekly potential evapotranspiration, mean weekly temperature, and mean weekly temperature amplitude, see Table A.3. The climate data was collected from NOAA (2010) and Weather (2010).

http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.html (01/11/1010)

http://www.weather.com/weather/climatology/daily/EGXX0004? (01/11/2010)

Lower boundary condition: For the low boundary condition, free drainage was chosen.

5 Results

5.1 Sensors and drippers

5.1.1 ML2x sensor sensitivity and calibration

5.1.1.1 Sensor sensitivity for soil moisture

In order to determine the sensor's sensitivity to the water distribution as well as the depth of water application, an experiment was conducted in which the sensor faced downwards. In this investigation, the water was applied at 3 cm, 4 cm and 6 cm away from the center rod, as well as at 1 cm, 3 cm and 5 cm below soil surface. It was thereby shown that the distance affected the sensitivity of the ML2x ThetaProbe sensor. A statistical analysis of the results at 0, 3, and 5 cm sensor positions showed no significant differences at a distance of 3 cm from the center rod. The results are presented in Table 5.1.1 and Fig. 5.1.1. Therefore, the sensor has a very small sensitivity area around the rods and the level of installation plays no role.

Table 5.1. 1: Measurement of the sensor sensitivity for soil moisture at the soil surface.

Rod position length [cm]	Sensor voltage measurement [V]		
	Distance from the center rod		
	3 cm	4 cm	6 cm
1	$0.71^{A, a}$	$0.53^{B, a}$	$0.25^{D, b}$
3	$0.69^{A, c}$	$0.34^{C, d}$	$0.12^{D, d}$
5	$0.43^{A, e}$	$0.20^{C, e}$	$0.12^{D, e}$

NB: The capital letters are the comparison between the depths and the small letters are the comparison across the distances ($p \leq 0.05$).

Fig. 5.1.1 shows that the sensor sensitivity depends on the special distribution of the water at the soil surface. At a distance of 6 cm from the center rod no readings were generated.

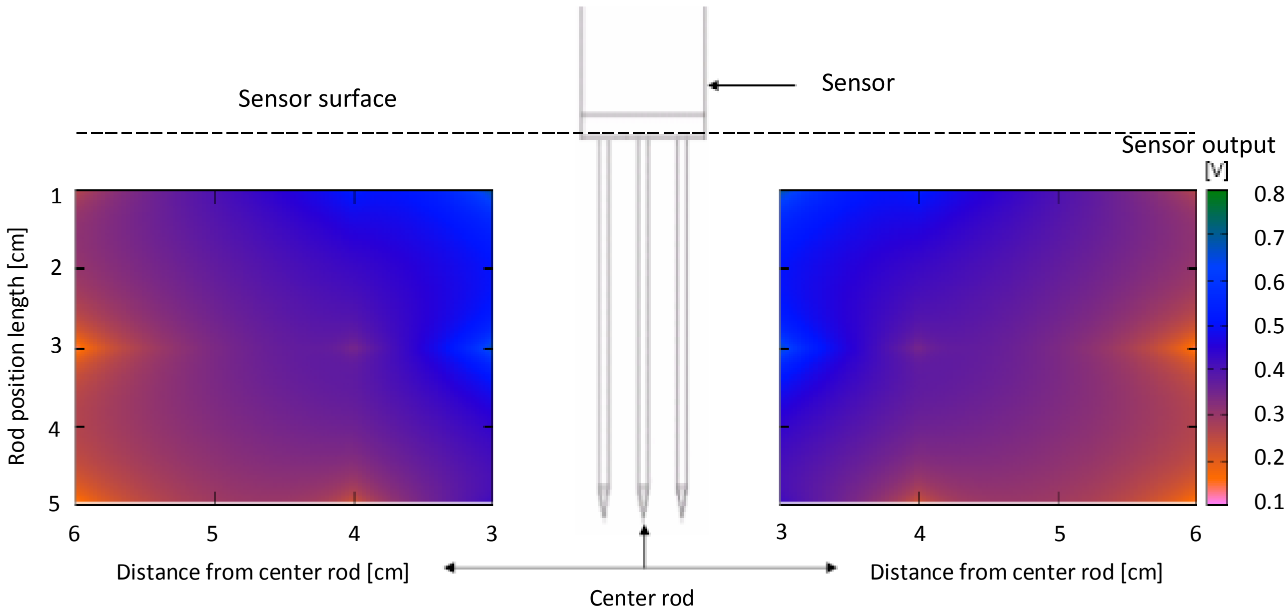


Fig. 5.1. 1: 3D sensitivity chart of sensor at the soil surface.

A second experiment was carried out to determine the effect of time on the sensitivity of the sensor with the rods facing upwards (Fig. 5.1.2). Generally, 15 s was sufficient to generate the highest readings under all application depths. Moreover, the highest readings were generated closest to the top of the soil surface (≈ 1 cm), and these results depended on the movement of the water in the top soil layers as found in Fig. 5.1.1.

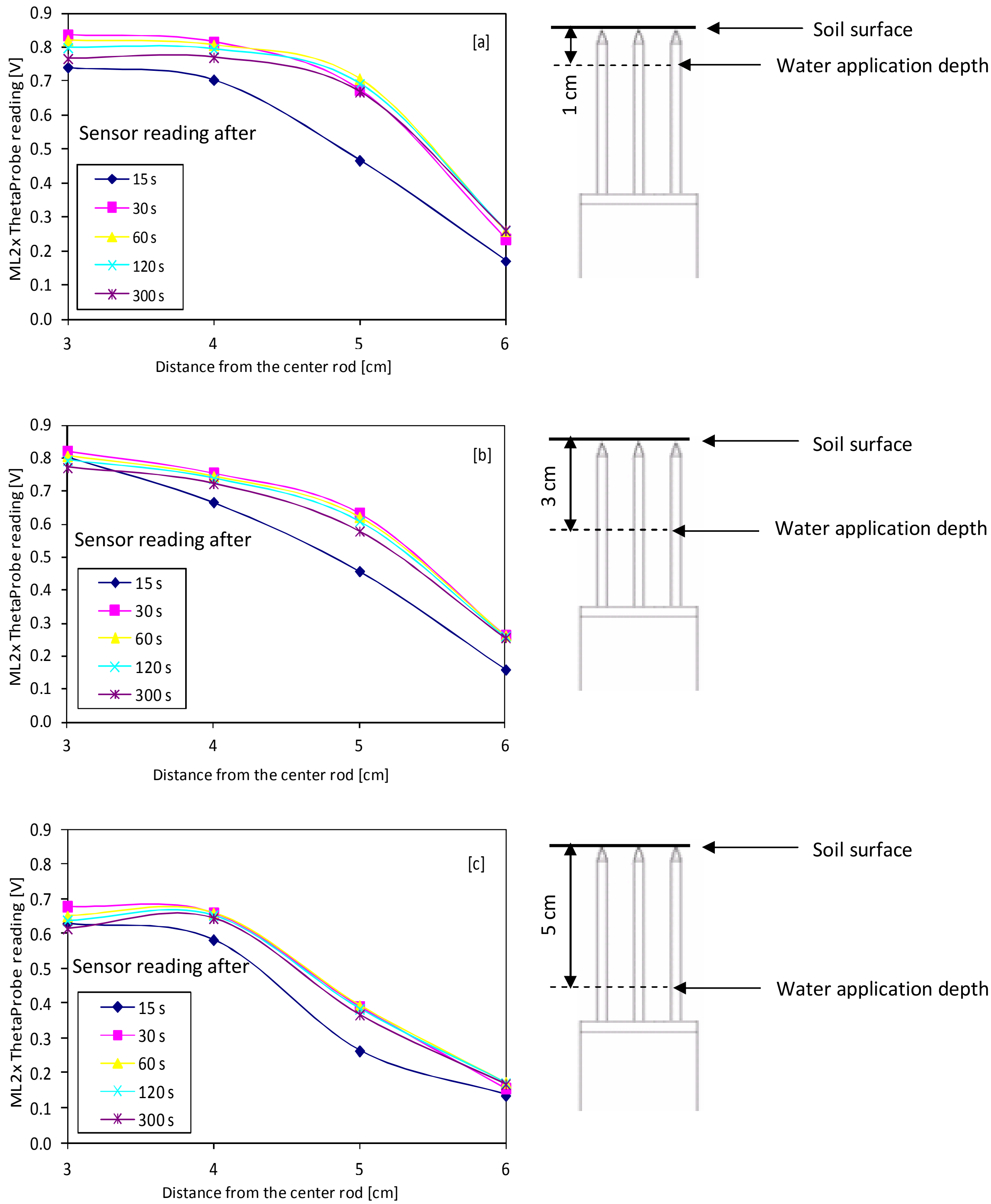


Fig. 5.1. 2: Sensitivity of the ML2x Theta Probe at 1 cm, 3 cm, and 5 cm depth.

After determining the sensitivity of the ML2x ThetaProbe in different positions (rods facing downwards or rods facing upwards), it became evident that there were effects of salinity on the sensitivity of the sensor. Therefore different NaCl solutions in the concentration range from 0 - 250 mmol/L were injected at 3 cm depth between the rods (sensor upwards). Fig. 5.1.3 shows that the sensitivity of the ML2x ThetaProbe sensor increased with a rising salinity in the application water, but there were only little differences between the 0 and 50 mM water salinity in the sensor readings. These results confirm that the applied irrigation water with NaCl concentration of 50 mM during the main experiments did not affect the reading of ML2x ThetaProbe sensor for soil moisture content.

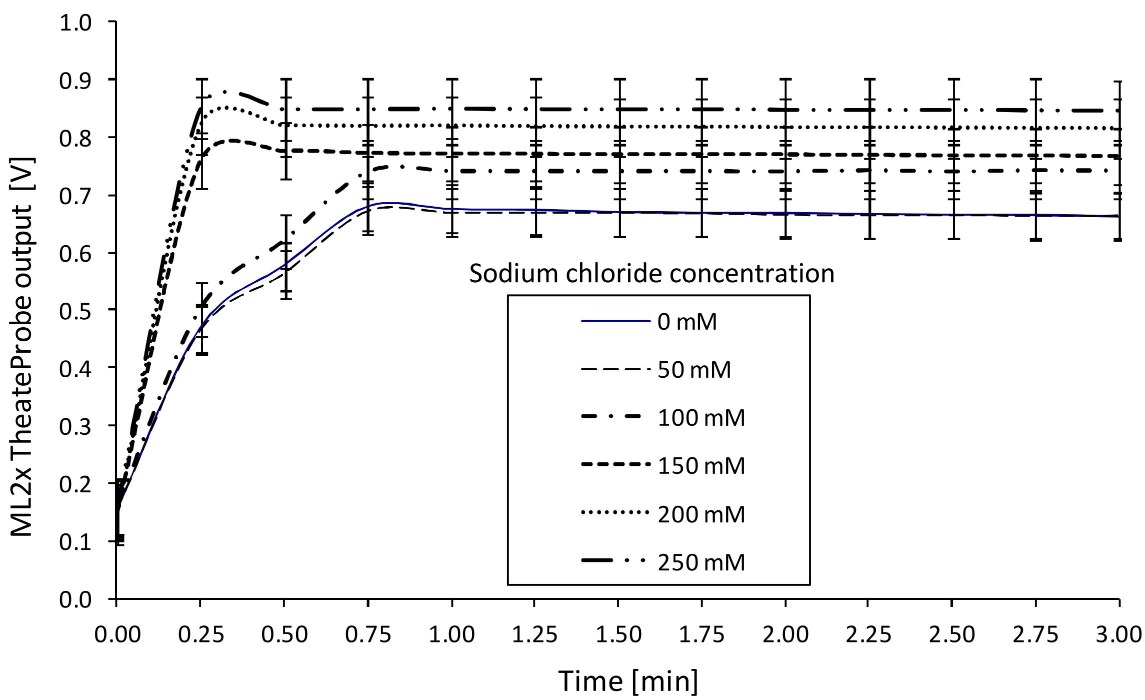


Fig. 5.1. 3: The effect of water salinity on the sensitivity of the ML2x Theta Probe (n = 5)

5.1.1.2 Sensor calibration

The relationship and equation for the volumetric soil moisture content and the output voltage of ML2x ThetaProbe sensor was linear as shown in Fig. 5.1.4:

$$\theta_v \approx 0.46203\, V - 0.03149 \qquad (R^2 = 0.9963)$$

Where:

θ_v: soil moisture content [$m^3\,m^{-3}$]

V: output of ML2x ThetaProbe sensor [V]

This equation was always used to calculate the volumetric soil moisture content by converting the reading of the ML2x ThetaProbe sensor.

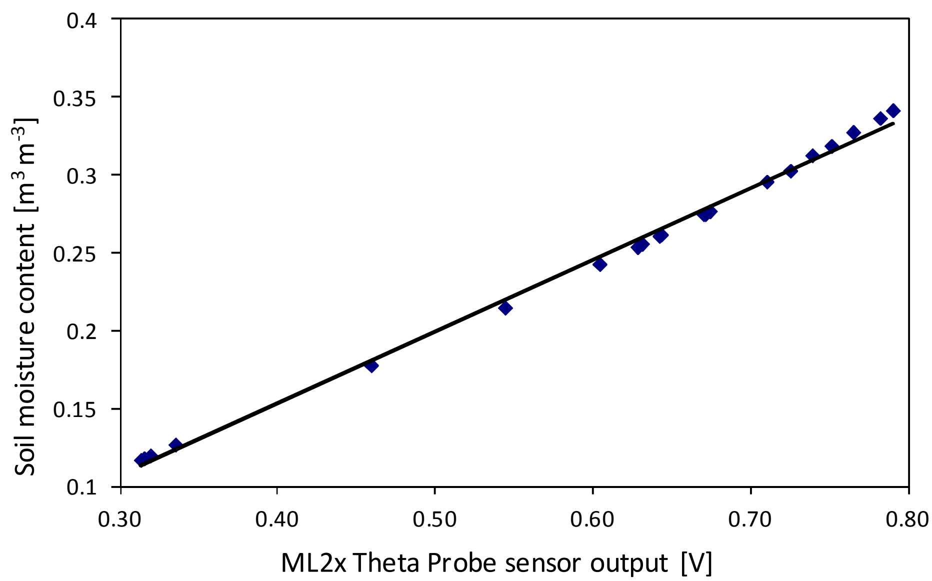


Fig. 5.1. 4: ML2x ThetaProbe calibration curve for the used soil.

5.1.2 PR2 sensor sensitivity and calibration

5.1.2.1 Sensor sensitivity

Fig 5.1.5 shows the sensor sensitivity under different soil moisture contents. As the moisture application distance from the access tube increased, the sensitivity of the PR2 Profile Probe decreased with no readings being generated at a distance of 6 cm. The highest readings were generated at a distance closest to the access tube of the PR2 Profile Probe sensor. Also, there is a strong vertical sensitivity effect. This means that in deeper soil layers, the sensitivity was not like in soil layers close to the soil surface.

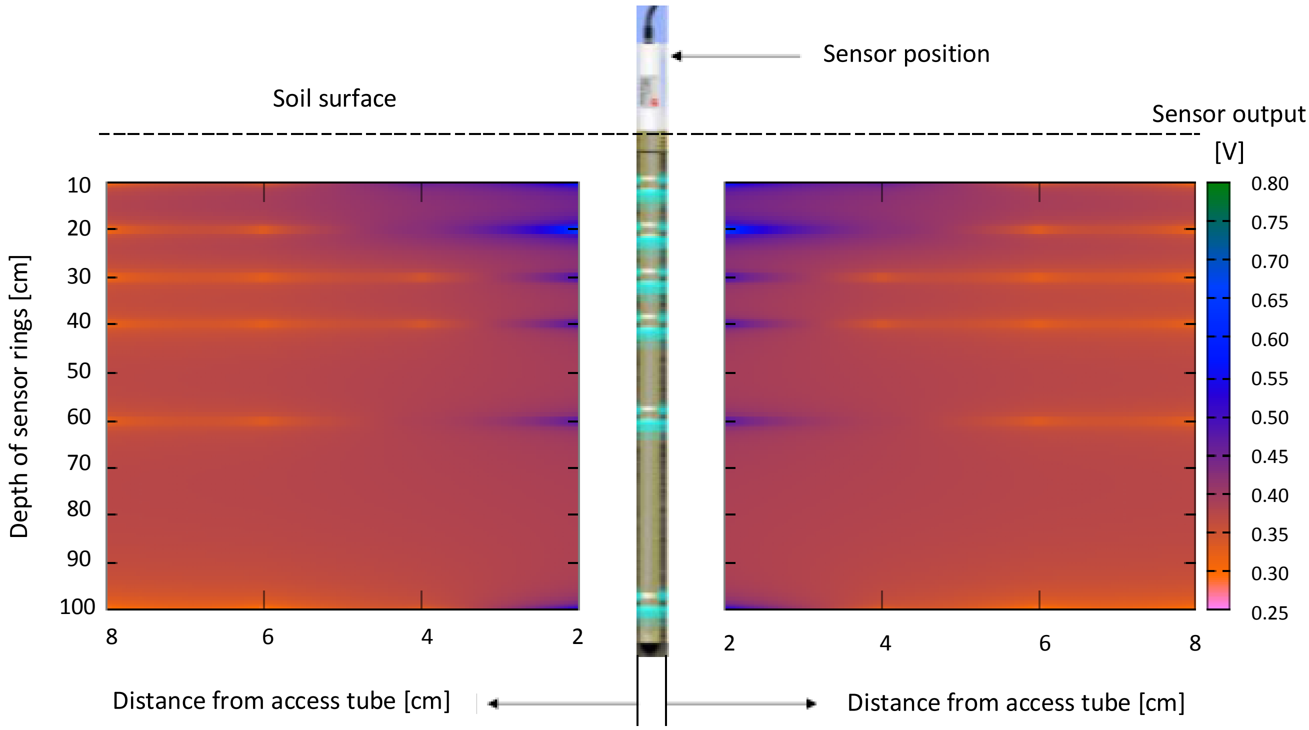


Fig. 5.1. 5: Sensitivity charts of the sensor using 30 % moisture content (weight basis)

In Fig. 5.1.6 the results for different soil moisture contents are depicted. There were no significant differences between various vertical measurement points with 10 % soil moisture content. However, increasing the soil moisture content generate higher differences between vertical measurement points. Also, the sensitivity of the sensor decreased with an increasing distance of application away from the access tube. In every case the sensitivity of the PR2 Profile Probe decreased with no readings being generated at a distance of 6 cm from the access tube.

5.1.2.2 Soil-specific calibration of PR2 Profile Probe

According to the PR2 manual, the soil-specific sensor calibration to different soils is based on the ML2x ThetaProbe sensor. Therefore, the calibration curve of the ML2x ThetaProbe sensor was also used to convert the sensor measurements to the volumetric soil moisture (see Chapter 5.1.1.2).

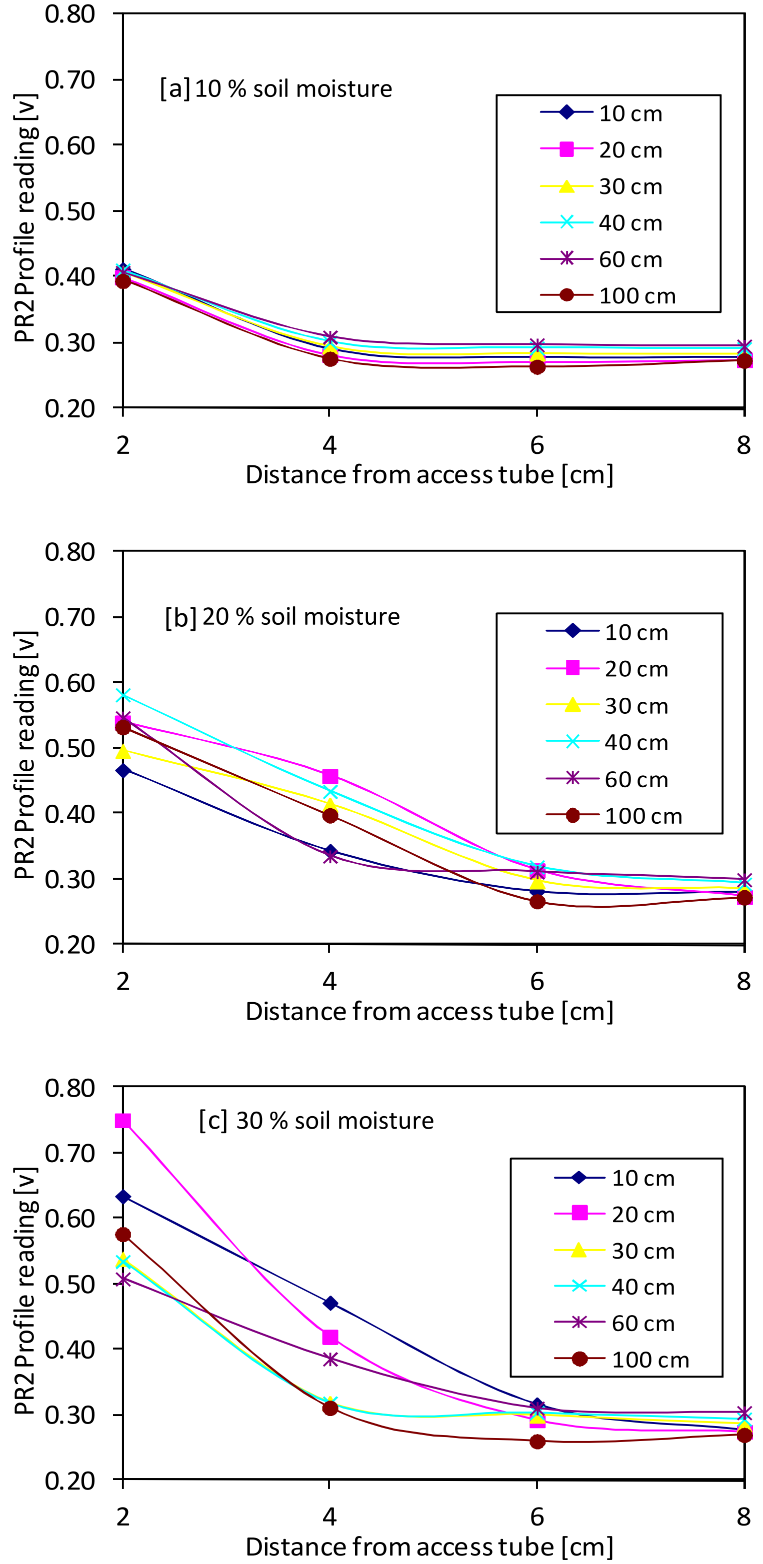


Fig. 5.1. 6: PR2 Profile Probe reading against horizontal and vertical distances: (a) 10 %, (b) 20 % and (c) 30 % of soil moisture content (weight basis).

5.1.3 Usage and accuracy of the irrigation drippers

Fig. 5.1.7 shows the discharge of the drippers before the start of the open-soil experiment C for both irrigation methods (CI and PRDI) at either side of the plant rows. The discharge in each line was similar and homogenous except the first and last points of the irrigation tube line. This result was confirmed for all irrigation tubes lines.

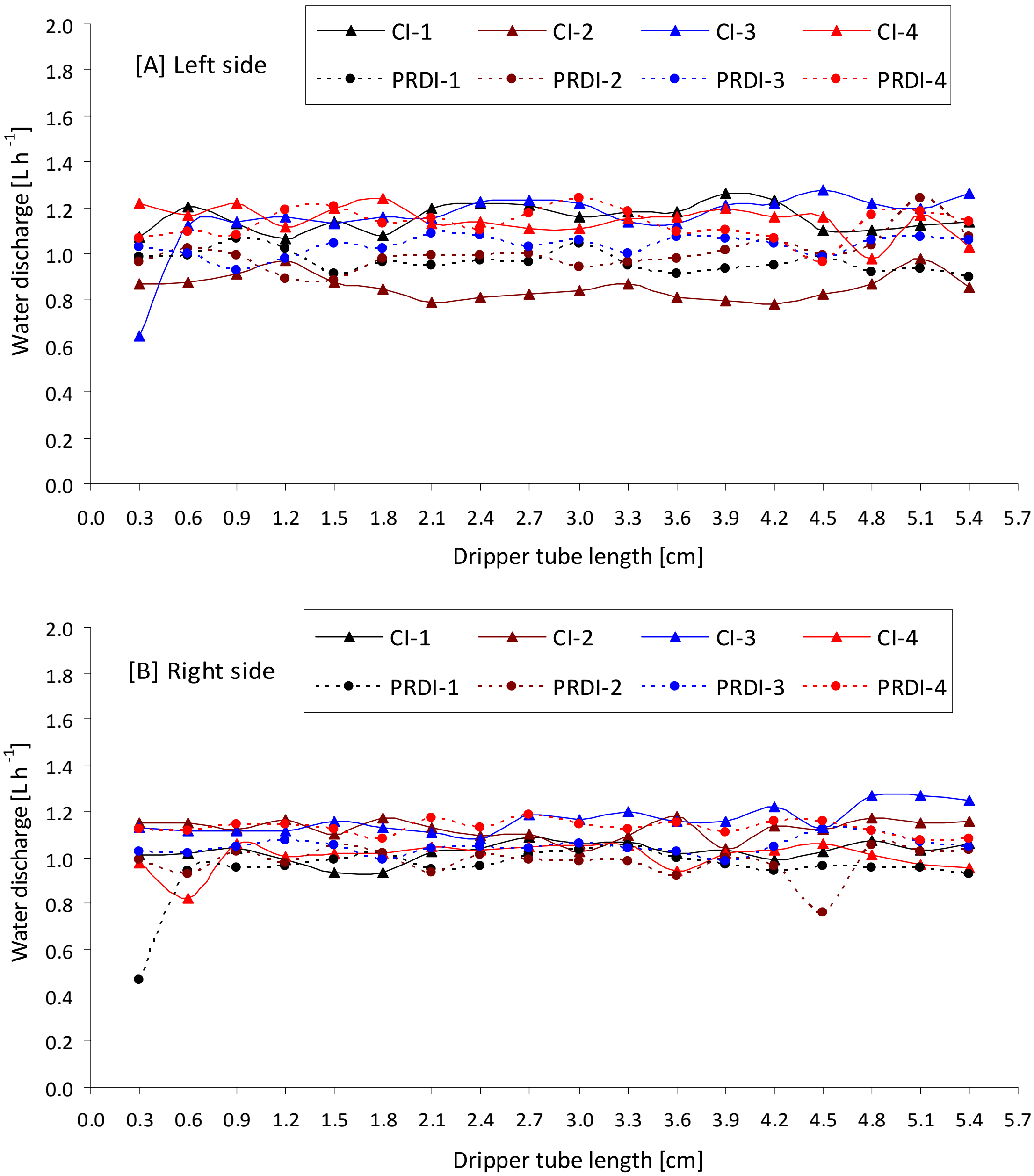


Fig. 5.1. 7: Accuracy of the irrigation drippers before starting the experiment where CI-1 is the first replicate of the CI treatment and PRDI-1 is the first replicate of the PRDI treatment, etc.

In Fig. 5.1.8, the discharge of the drippers at the end of the experiment is shown. The discharge accuracy within the irrigation tube line was similar to the starting condition. Generally the discharge levels were reduced by approximately 10 % and a little inhomogeneous as a result of dripper blocking.

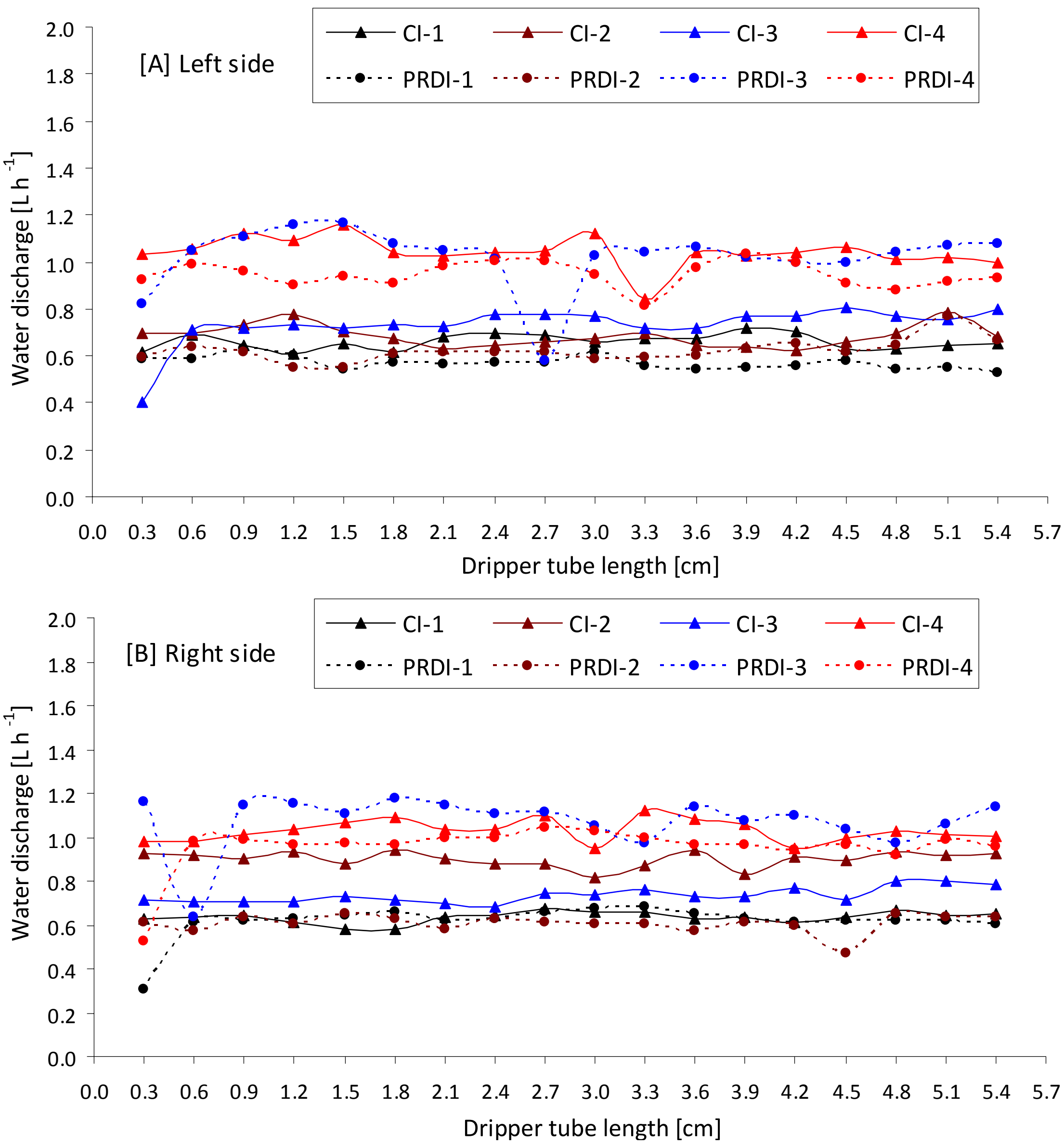


Fig. 5.1. 8: Accuracy of the irrigation drippers at the end of the experiment (after 23 weeks) where CI-1 is the first replicate of the CI treatment and PRDI-1 is the first replicate of the PRDI treatment, etc.

5.2 Preliminary studies

5.2.1 Soil chemical properties

Table 5.2.1 presents the soil nutrition analysis in the top 30 cm before the preliminary experiments. The results indicate that the soil within the different pots was homogeneous for the most of the nutrient analysis in the soil except the content of K_2O is little different.

Table 5.2. 1: Nutrient content of the soils samples before the preliminary experiments

Sample No.	Depth [cm]	N_{min} [kg/ha]	P_2O_5 [mg/100g]	K_2O [mg/100g]	MgO [mg/100g]	pH [--]	EC [mS/m]	KCl [%]
1	30	58.9	35	12	7	6.4	53	0.028
2	30	60.3	35	10	7	6.4	56	0.030
3	30	67.4	38	12	7	6.4	59	0.031
4	30	65.0	35	11	7	6.4	54	0.028
5	30	69.1	34	14	8	6.5	57	0.030
6	30	69.1	37	15	7	6.5	61	0.032
7	30	72.4	36	15	8	6.5	58	0.031
8	30	45.7	31	8	9	6.3	65	0.034
9	30	54.4	28	6	7	6.5	50	0.027
10	30	38.7	30	6	7	6.4	54	0.029
11	30	42.2	31	7	8	6.4	57	0.030
12	30	74.6	26	7	7	6.3	56	0.030

NB: The nutrition analysis of the soil samples was analyzed at the Institute of Biological Production Systems, Vegetable Systems Modeling Section, Leibniz Universität Hannover.

5.2.2 Greenhouse climatic situation

Greenhouse air temperature and relative humidity

Fig. 5.2.1A shows the mean and standard deviation of the greenhouse air temperature at five different places at a height of 1.5 m above the soil surface inside the greenhouse. The maximum air temperature was 24.0 ^{o}C and the minimum air temperature was 23.4 ^{o}C during the experiment. The differences between air temperatures at different places were neglectable. This meant that the air temperature was almost the same in the greenhouse. Therefore, were to be expected, no effects of the greenhouse air temperature on the results of the treatments.

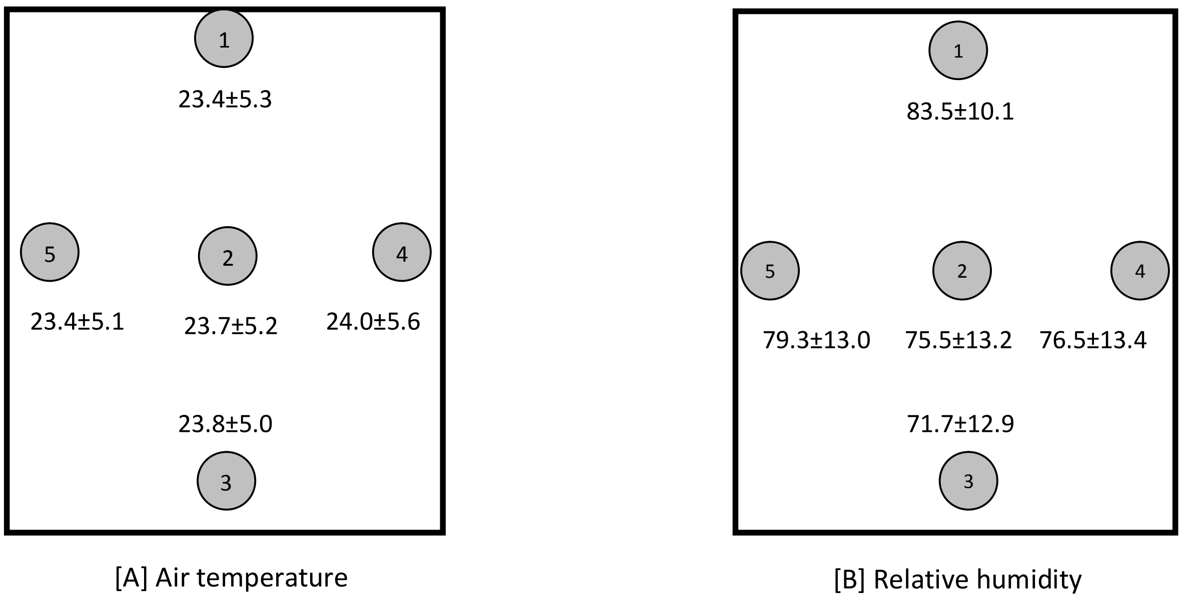


Fig. 5.2. 1: Mean and standard deviation (mean ± SD) of air temperature (^oC) and relative humidity inside the greenhouse of the preliminary experiment

In Fig. 5.2.1B the mean and standard deviation of the greenhouse relative humidity (%) at five different places inside the greenhouse are shown. The maximum air relative humidity was 83.5 % at the northern side of the greenhouse and the minimum air relative humidity was 71.7 % at the southern part of the greenhouse during the experimental time (20 weeks). The difference between the maximum and minimum of relative humidity was 16.46 %.

<u>Solar radiation inside the greenhouse</u>

The comparison between the mean values of the solar radiation at different points inside the greenhouse is shown in Fig. 5.2.2. The minimum value of the solar radiation was 110.7 Wm^{-2} at the south-west corner of the greenhouse. However, the maximum value of the solar radiation was 24.84 % higher at the southern part of the greenhouse.

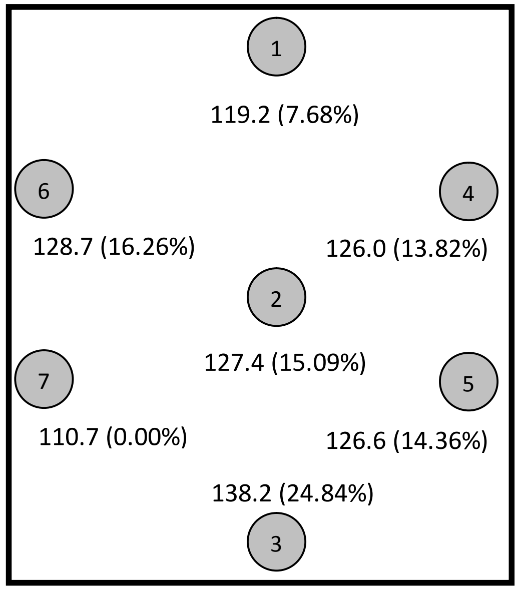


Fig. 5.2. 2: Mean and difference of the solar radiation (W m^{-2}) inside the greenhouse of the preliminary experiment (point 7 = reference)

Soil temperature

In order to avoid the effect of high temperature on the soil, the experimental pots were covered by aluminum foil. The effects of the covering on the soil temperature (10 cm below the soil surface) are shown in Fig. 5.2.3. The soil temperature was reduced by 6.0 ^{o}C and thereby the side effects of high temperature on plant nutrition and evapotranspiration were limited.

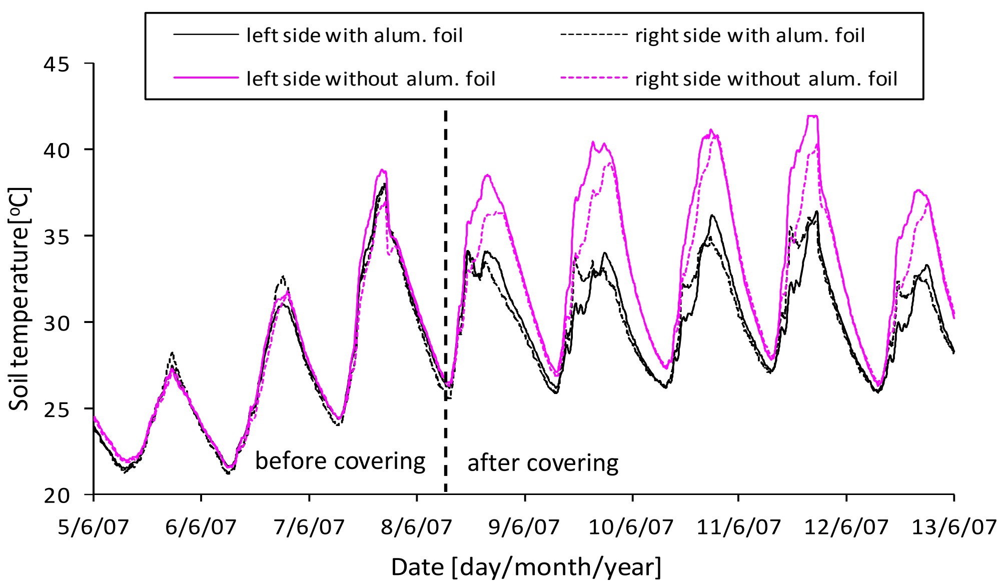


Fig. 5.2. 3: Effects of covering the pots with aluminum foil on soil temperature during the preliminary experiment

The comparison between the mean and standard deviation of the soil temperature is summarized in Table 5.2.2. The mean temperatures of the soil on both sides of the CI treatments were almost the same. The temperature in the non-irrigated side of PRDI however was higher than in the irrigated side of the PRDI treatments. The soil temperature of the irrigated side under PRDI was the same as that of the CI treatment. The results showed that by irrigation, there is some tendency for a reduction of soil temperature.

Table 5.2. 2: Mean and standard deviation of the soil temperature (°C) of the left and the right side of the experimental pot during the preliminary experiment

Treatment	Total		1st sequence of PRDI*		2nd sequence of PRDI**	
	left side	right side	left side (irrigated)	right side (non irrigated)	left side (non irrigated)	right side (irrigated)
PRDI-70	24.9±4.0	24.8±4.2	24.9±4.6	25.8±5.1	24.6±3.0	23.6±2.9
CI-70	24.5±4.1	24.3±4.2	24.9±4.8	24.7±4.8	23.6±2.9	23.4±2.8
PRDI-55	24.9±4.2	24.8±4.2	25.1±5.0	25.7±5.0	24.3±2.9	23.8±2.8
CI-55	24.5±4.4	24.5±4.2	25.0±5.1	25.1±5.0	23.6±3.0	23.7±2.9
PRDI-40	25.1±4.2	25.0±4.2	25.3±5.0	25.9±5.0	24.7±3.1	24.2±3.1
CI-40	24.9±4.3	25.0±4.2	25.4±5.0	25.5±5.0	24.1±3.1	24.2±3.1

* 1st sequence of PRDI: irrigation of the left side of the PRDI treatment

** 2nd sequence of PRDI: irrigation of the right side of the PRDI treatment

5.2.3 Soil moisture

Fig. 5.2.4 shows the effect of the PRDI and CI methods on the distribution of the volumetric soil moisture ($m^3\ m^{-3}$) during the preliminary experiments. In all cases the soil moisture content was the same at the beginning of the irrigation treatments. The soil moisture content of the irrigated side of the PRDI-70 treatment was higher than the non-irrigated side or both sides of the CI-70 (Fig. 5.2.4A).

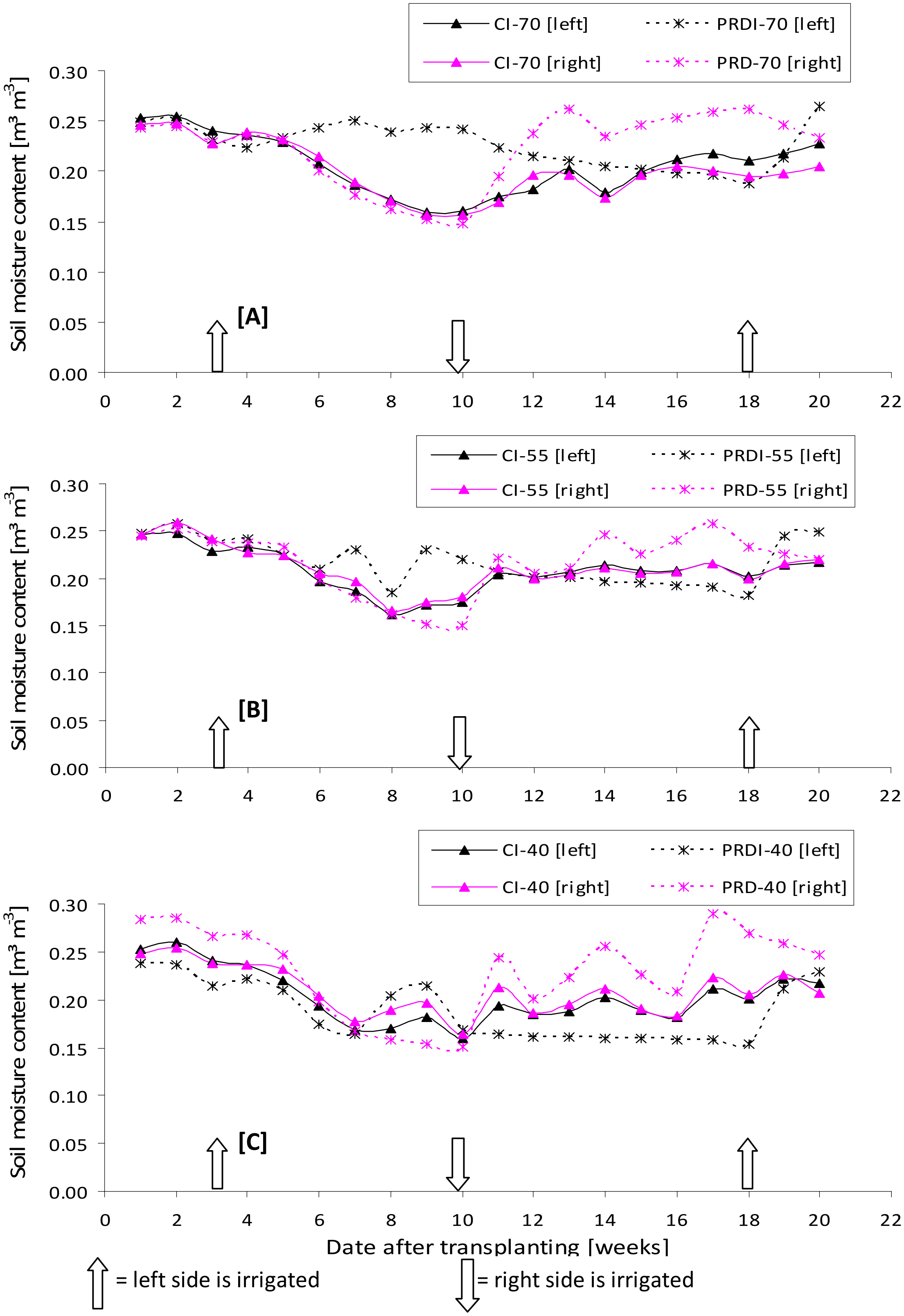


Fig. 5.2. 4: Variation of the volumetric soil moisture content (Θ_V) at 20 cm soil depth in the preliminary experiment: (A) 70 -80 %, (B) 55 -80 %, and (C) 40 - 80 % of FC (n = 2).

This effect was reduced if the irrigation limit were set lower. So the soil moisture content in the irrigated side of the PRDI-55 treatment was only little higher than in the CI-55 treatment. Depending on the irrigation time, it sometimes reached high values and sometimes dropped to low values (see Fig. 5.2.4B). The tendency was also similar for the PRDI-40 treatment, which is shown in Fig. 5.2.4C.

From the preliminary experimental results, it could be concluded that the irrigation methods (PRDI and CI) were usable where the soil moisture content was changed according to the irrigation method; but the irrigation treatments should be set to higher values to avoid the strong fluctuation of the soil moisture. Pot and root splitting methods are possible and can control the partial rootzone drying irrigation. Pot covering with aluminum foil is necessary to avoid mischievous effects of higher temperature on soil evaporation and fertilizers. The greenhouse climatic parameters are more or less homogeneous and it could be used for the experiments if the pots are placed randomly.

5.3 Main experiments

5.3.1 Pot experiment (split-root)

5.3.1.1 Effect of PRDI on soil moisture

Fig. 5.3.1 shows the distribution of the volumetric soil moisture content ($m^3\ m^{-3}$) in the PRDI and CI treatments of the pot experiment.

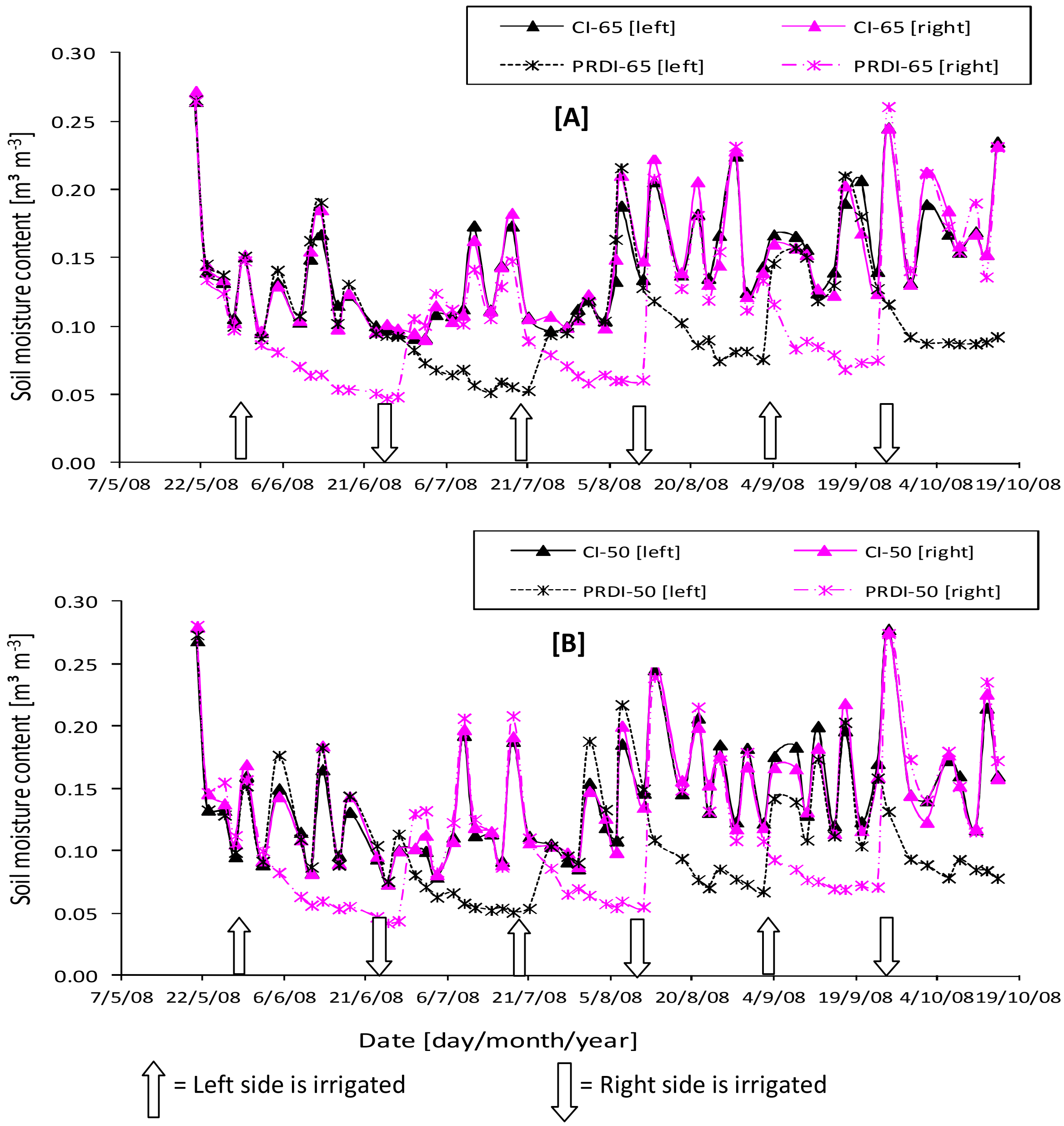


Fig. 5.3. 1: Variation of the volumetric soil moisture content (Θ_V) at 20 cm soil depth in the pot experiment: (A) 65 – 80 %, and (B) 50 - 65 % of FC (n = 4).

The soil moisture content on each side of the PRDI treatment depended on whether the side of PRDI was irrigated or not. From Fig. 5.3.1 it could be seen that the PRDI method was working well; moreover, the irrigation was shifted 6 times during the growing season. This means that the soil water application levels were chosen in the right way.

A comparison between averages, maximum and minimum values of the volumetric soil moisture content in the left and right side of the pot experiment are shown in Table 5.3.1. The mean results of soil moisture content in either side of the CI treatment did not differ (as was to be expected), however the average soil moisture content of either side of the PRDI treatment showed a drying effect (the average value of the soil moisture content of the PRDI-65 was reduced by 24.5 % and 21.1 % for left and right side, respectively, in comparison to the CI-65).

Table 5.3. 1: Average, maximum and minimum of the soil moisture content of the different water application levels during the pot experiment (n = 4).

Soil depth [cm]		Volumetric soil moisture content [m^3 m^{-3}]							
		CI-65		PRDI-65		CI-50		PRDI-50	
		left side	right side	left side	right side	left side	right side	left side	right side
20	Average	0.147	0.147	0.111	0.116	0.143	0.144	0.108	0.118
	Max	0.246	0.245	0.216	0.261	0.278	0.276	0.217	0.275
	Min	0.091	0.091	0.052	0.047	0.074	0.074	0.051	0.042
40	Average	0.284	0.272	0.260	0.279	0.253	0.258	0.224	0.257
	Max	0.365	0.375	0.392	0.367	0.379	0.377	0.354	0.362
	Min	0.194	0.184	0.165	0.217	0.167	0.180	0.136	0.148
80	Average	0.374	0.376	0.400	0.362	0.372	0.371	0.379	0.381
	Max	0.465	0.472	0.481	0.473	0.472	0.473	0.461	0.469
	Min	0.332	0.336	0.360	0.303	0.328	0.305	0.301	0.288

Astonishingly, the differences between the different water application levels in the soil moisture content within the CI treatments were very small (about 2.05 % for both sides). The soil moisture of the PRDI with an application level of the 65 % – 80 of FC was higher than under the 50 % – 65 % of FC in both sides of the treatments. Similar to the CI treatment, the differences between the two application levels were very small (2.7 and 1.7 % for the left and the right side, respectively, as shown in Table 5.3.1).

5.3.1.2 Tomato yield, biomass and root growth

Table 5.3.2 compares the results of the tomato fresh weight, fruit weight, dry matter content, and the water applied under all four irrigation treatments during the pot experiment. Total water applied in both irrigation treatments were similar, but 75 % of irrigation water was used in stress treatment. In one case a significant difference was found between PRDI and CI. Only between the different water application levels a significant difference were given for fresh weight, fruit yield, and total biomass.

Table 5.3. 2: Average results of tomato plants biomass and fruit yield during the pot experiment (n = 4).

Treatment	**plant**		**fruit yield**		**total biomass/ plant [kg]**	**total applied water [L]**
	fresh weight [kg]	**dry matter [%]**	**fresh weight/plant [kg]**	**dry matter [%]**		
CI-65	4.154[a]	14.7[c]	1.517[e]	12.7[g]	5.670[h]	102.5
PRDI-65	3.967[a]	15.1[c,d]	1.529[e]	13.3[g]	5.496[h]	102.5
CI-50	3.374[b]	15.3[c,d]	0.906[f]	14.3[g]	4.280[i]	75.0
PRDI-50	3.188[b]	15.6[d]	1.297[e]	13.1[g]	4.485[i]	75.0

NB: Treatments labeled with the same letter do not differ significantly at $p \leq 0.05$.

In Fig. 5.3.2 the accumulated fruit yield of the different treatments is shown. The results indicated that the CI-65 and PRDI-65 were similar during the experiment, but there was a difference between the CI-50 and PRDI-50 treatments in so far as the PRDI treatment increased the yield (kg per plant) from 0.9 kg to 1.2 kg with a statistical significance. This leads to the assumption that under water stress, PRDI can produce a higher yield than the CI method.

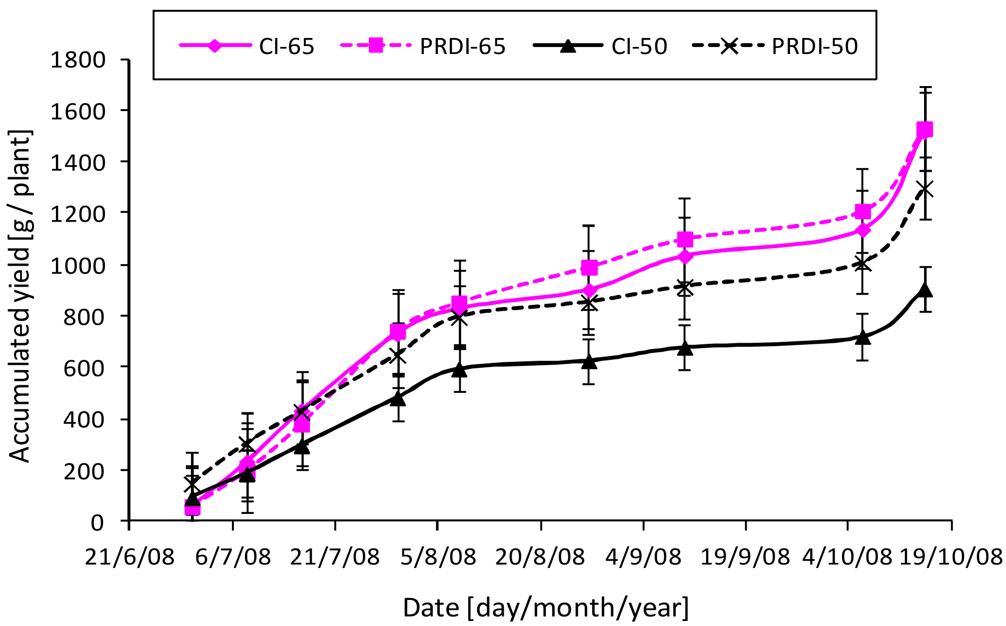


Fig. 5.3. 2: Accumulated yield of tomato fruit in the pot experiment (n = 4)

Fig. 5.3.3 presents the irrigation water use efficiency (IWUE). The highest values were recorded under the PRDI-50 treatment and the differences between the PRDI-50 treatment and the other treatments (CI-65, PRDI-65 and CI-50) proved to be significant. This result confirmed that the PRDI improved IWUE under deficit water treatment.

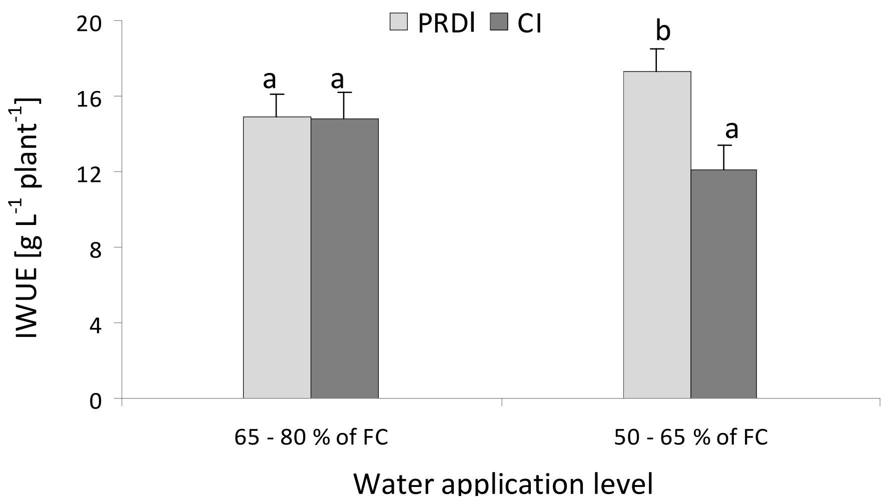


Fig. 5.3. 3: Average results of irrigation water use efficiency (IWUE) during the pot experiment ($n = 4$ and $p \leq 0.05$)

The analyses of the root systems of the plants showed that the root growth of the PRDI treatment was different than the CI treatment. Roots under PRDI were prolonged and hard whereas the root system under CI was intensive and shortly, as shown in Fig. 5.3.4. These results indicate that the roots of the plants under the PRDI treatment were grown more and prolonged during the drying state in order to find the sufficient soil moisture for plants.

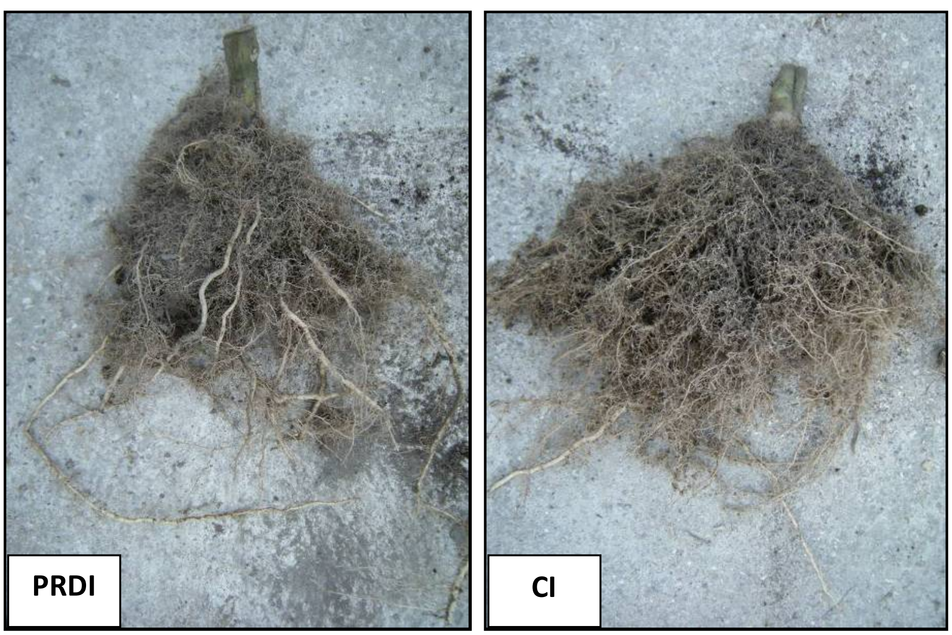


Fig. 5.3. 4: Root growing of the tomato plants at the end of the pot experiment

5.3.1.3 Effect of PRDI on soil salinity

Sodium concentration in the soil

Fig. 5.3.5 demonstrated the distribution of sodium [mg /100 g open-air dry soil sample] in the soil under two water application levels during the pot experiment.

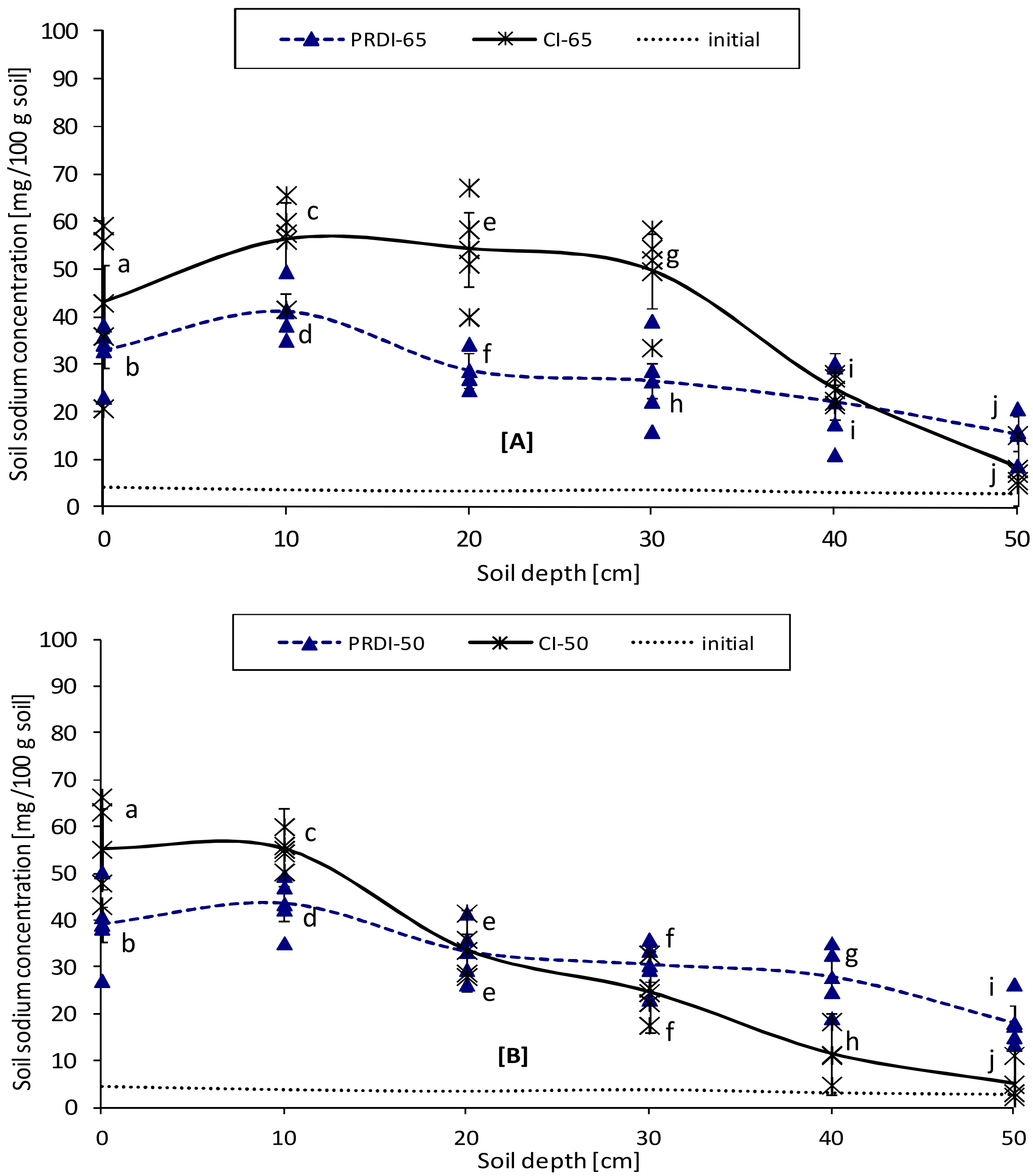


Fig. 5.3. 5: Sodium accumulation in the rootzone at the end of irrigation of the pot experiment: (A) 65-80 and (B) 50 - 65 % of FC (n = 4). Treatments labeled with the same letter at each depth do not differ significantly at $p \leq 0.05$

The soil salinity profiles indicated that the salt accumulation under PRDI-65 treatment was lower in the top surface soil layers (40 cm of depth) as compared to the CI-65 treatment (Fig. 5.3.5A). The difference between sodium concentrations in these treatments was very high as well. However, there was only a small difference to be found between them in the soil layers below 40 cm of depth. The statistical analysis showed that the differences between the two irrigation methods at depths of 0, 10, 20, and 30 cm were significant.

Concerning the water application 50 % - 65 % of FC, the soil salinity profile confirmed that soil sodium accumulation under PRDI-50 treatment was also proportionally lower in top surface soil layers (within a depth of 20 cm) than in the CI-50 treatment (Fig. 5.3.5B). The statistical analysis showed that the differences between the two irrigation methods were significant at depths 0, 10, 40, and 50 cm.

Chloride concentration in the soil

Fig. 5.3.6 depicts the distribution of the chloride in the soil under two water application rates during the pot experiment. The soil salinity profiles indicated that the soil chloride concentration under the PRDI-65 treatment was slightly lower in the top surface soil layers (40 cm of depth) in comparison to the CI-65. But the salinity of PRDI-65 was higher within the soil layers below 40 cm depth, (significant differences between the two irrigation methods at 50 cm of the soil profile, see Fig. 5.3.6A).

The salinity profile of the water application level of 50 - 65 % of FC confirmed that the chloride concentration in the soil under the PRDI-50 treatment was proportionally lower in the top surface soil layers of 25 cm depth compared with the CI-50 treatment. The salinity of the CI-50 treatment was lower in the bottom soil layers below 25 cm depth. The chloride distribution was similar to the sodium distribution under the same water application level; significant differences were found between the PRDI and CI methods at of 0, 10, and 50 cm of soil depths, see Fig. 5.3.6B.

Fig. 5.3.5 and Fig. 5.3.6 shows that in all treatments the PRDI method lead to a lower salt concentration in the top 40 cm and 25 cm soil layers for 65 - 80 % and 50 - 65 % of FC, respectively. In comparison with the sodium concentration, the influence was lower. Also between the PRDI-65 and CI-65 treatments, the difference effect was very clear.

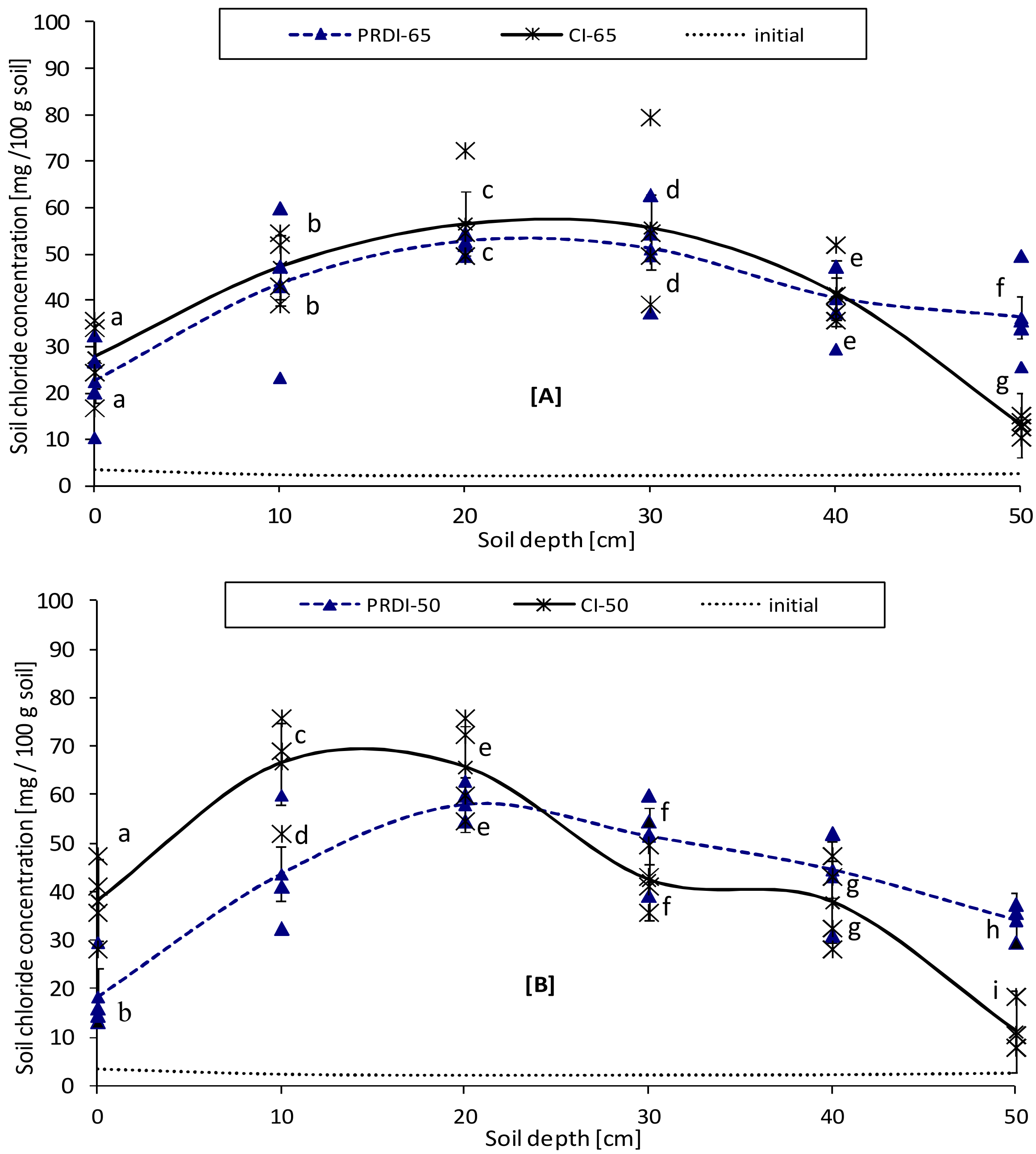


Fig. 5.3. 6: Chloride accumulation in the rootzone at the end of the irrigation of the pot experiment: (A) 65- 80 and (B) 50 - 65 % of FC (n = 4). Treatments labeled with the same letter at each depth do not differ significantly at $p \leq 0.05$

5.3.1.4 Effect of water deficit on soil salinity

In Fig. 5.3.7, the distribution of either sodium (A) or chloride (B) under different water application levels for the CI method are compared. The salinity profile of the sodium accumulation and concentration show that the sodium level under the CI-65 treatment was proportionally lower than in the CI-50 treatment within the first 10 cm soil layer depth, whereas it was higher in the layers below 10 cm (significant differences were found between the two water application levels at of 20, 30, and 40 cm of soil depths, see Fig. 5.2.7A).

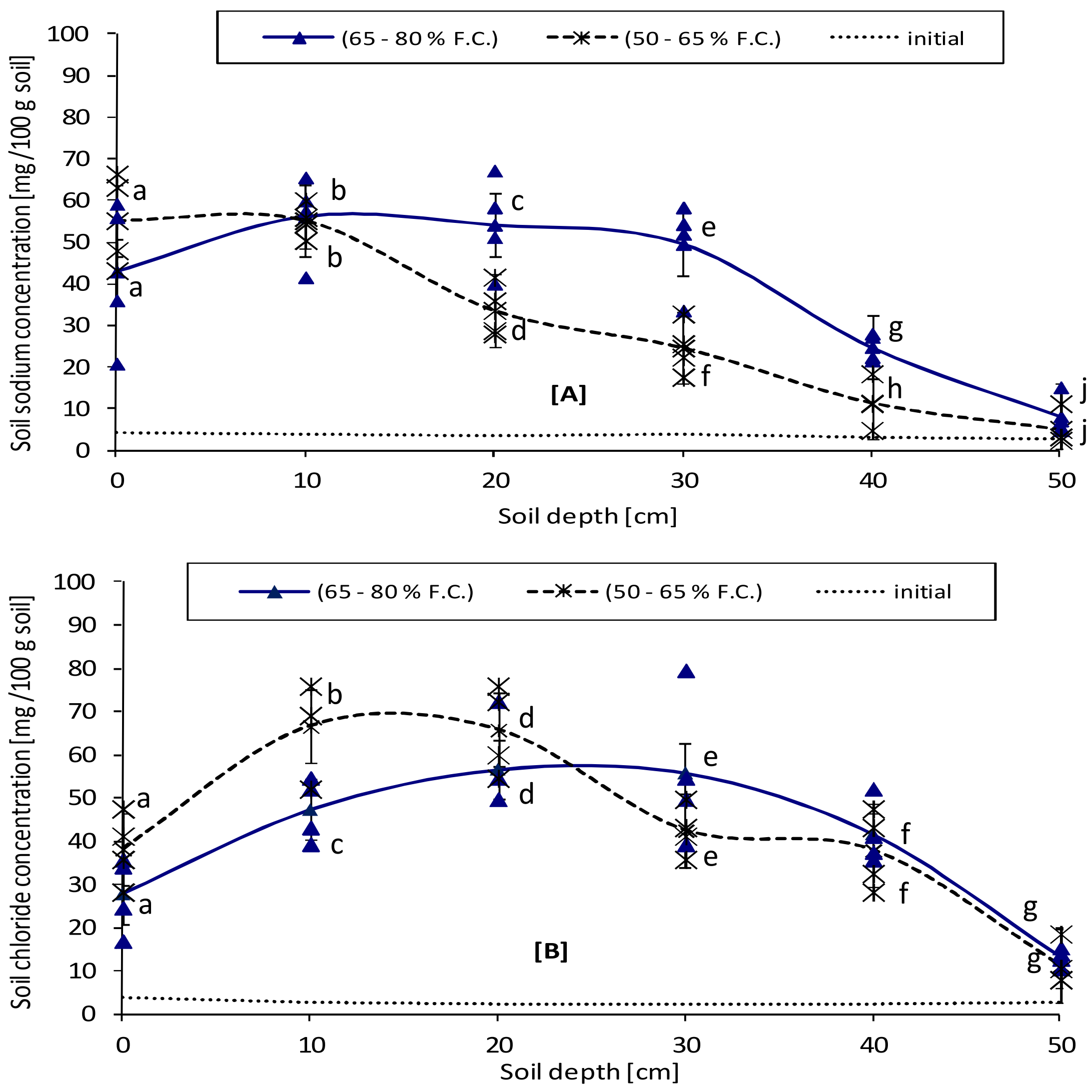


Fig. 5.3. 7: Salt accumulation at the soil at the end of the irrigation of the pot experiment under the CI method: (A) sodium concentration and (B) chloride concentration (n = 4). Treatments labeled with the same letter at each depth do not differ significantly at $p \leq 0.05$

Salinity results were also obtained for chloride (see Fig. 5.3.7B). The salinity profile of the soil chloride accumulation and concentration confirmed that the soil chloride accumulation under CI-65 was lower in the top soil layers within 25 cm depth than under CI-50, but with no significant differences below 40 cm (Fig. 5.3.7B). Fig. 5.3.8 compares the distribution of the soil salinity under different water application levels for the PRDI method. The salinity profile indicated that the salt movement was occurred at low water application levels, but without any statistical significant effect.

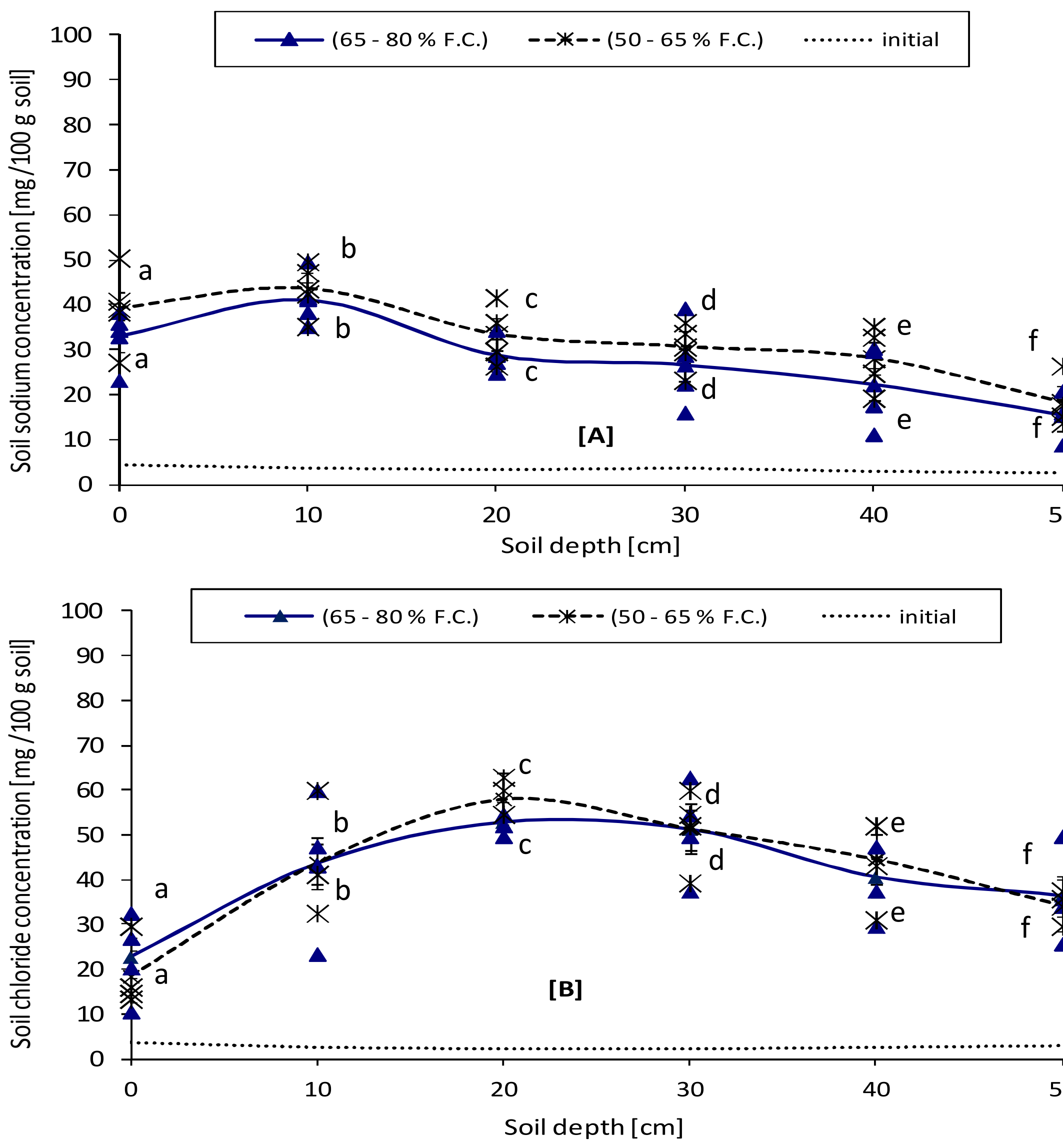


Fig. 5.3. 8: Salt accumulation at the soil at the end of the irrigation of the pot experiment under the PRDI method: (A) sodium concentration and (B) chloride concentration (n = 4). Treatments labeled with the same letter at each depth do not differ significantly at $p \leq 0.05$

5.3.2 Open-soil experiment (natural growth)

5.3.2.1 Climatic data

Fig. 5.3.9 presents the average weekly evapotranspiration, air temperature, maximum temperature, and minimum temperature inside the greenhouse during the open-soil experiment. The highest values of the average (24.0 ^{o}C) and maximum air temperature (34.0 ^{o}C) were measured in the second week of July, and the lowest temperature (13.2 ^{o}C) was obtained in the first week of October. The weekly evapotranspiration differed from one week to the other, depending on many factors such as temperature, solar radiation, relative humidity, and wind speed. The highest evapotranspiration (37.4 mm week^{-1}) was found in the second week of July (Fig. 5.3.9). The results show that the climatic parameters inside the greenhouse were changed from one week to the other. Also, the evapotranspiration changed accordingly. This means that the irrigation methods were applied under different climatic conditions.

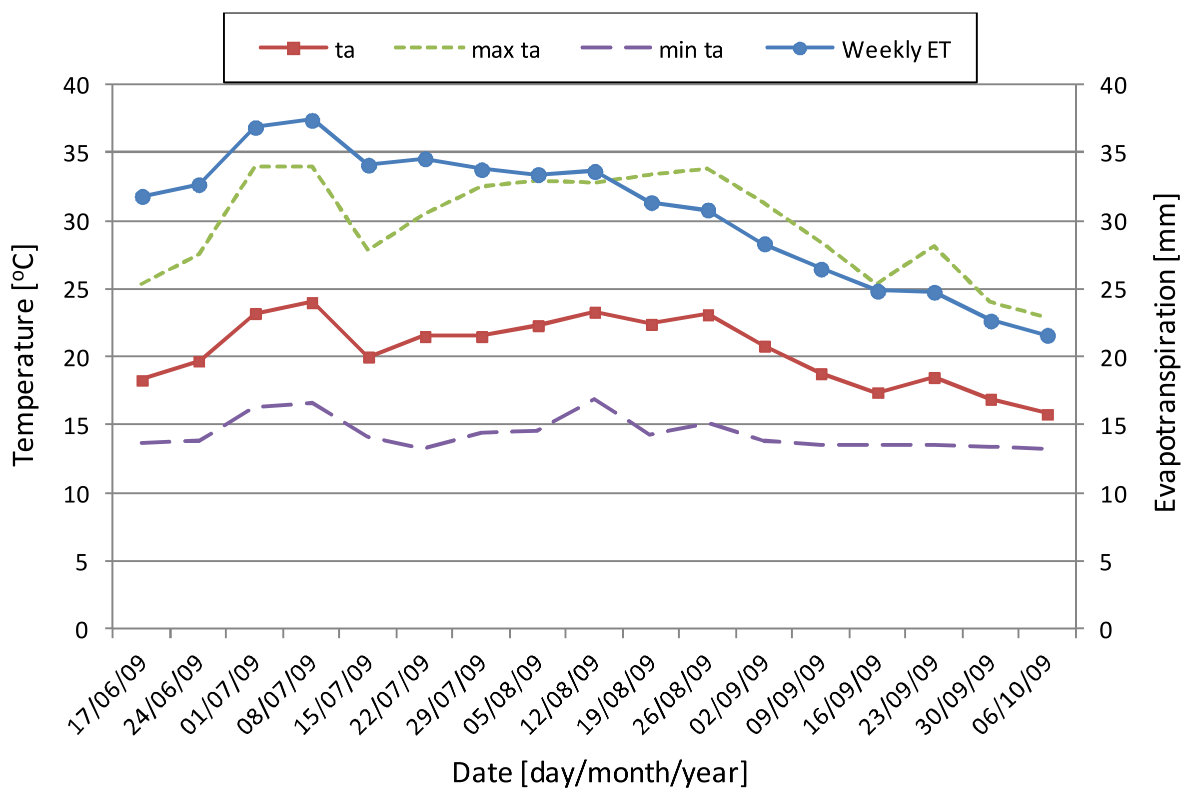


Fig. 5.3. 9: Average weekly evapotranspiration, average air temperature, maximum air temperature, and minimum air temperature during the open-soil experiment

5.3.2.2 Effect of PRDI on soil moisture

Fig. 5.3.10 shows the distribution of the volumetric soil moisture content for the PRDI and CI treatments in the open-field experiment at 20 cm, 40 cm, and 80 cm depths of the soil profile.

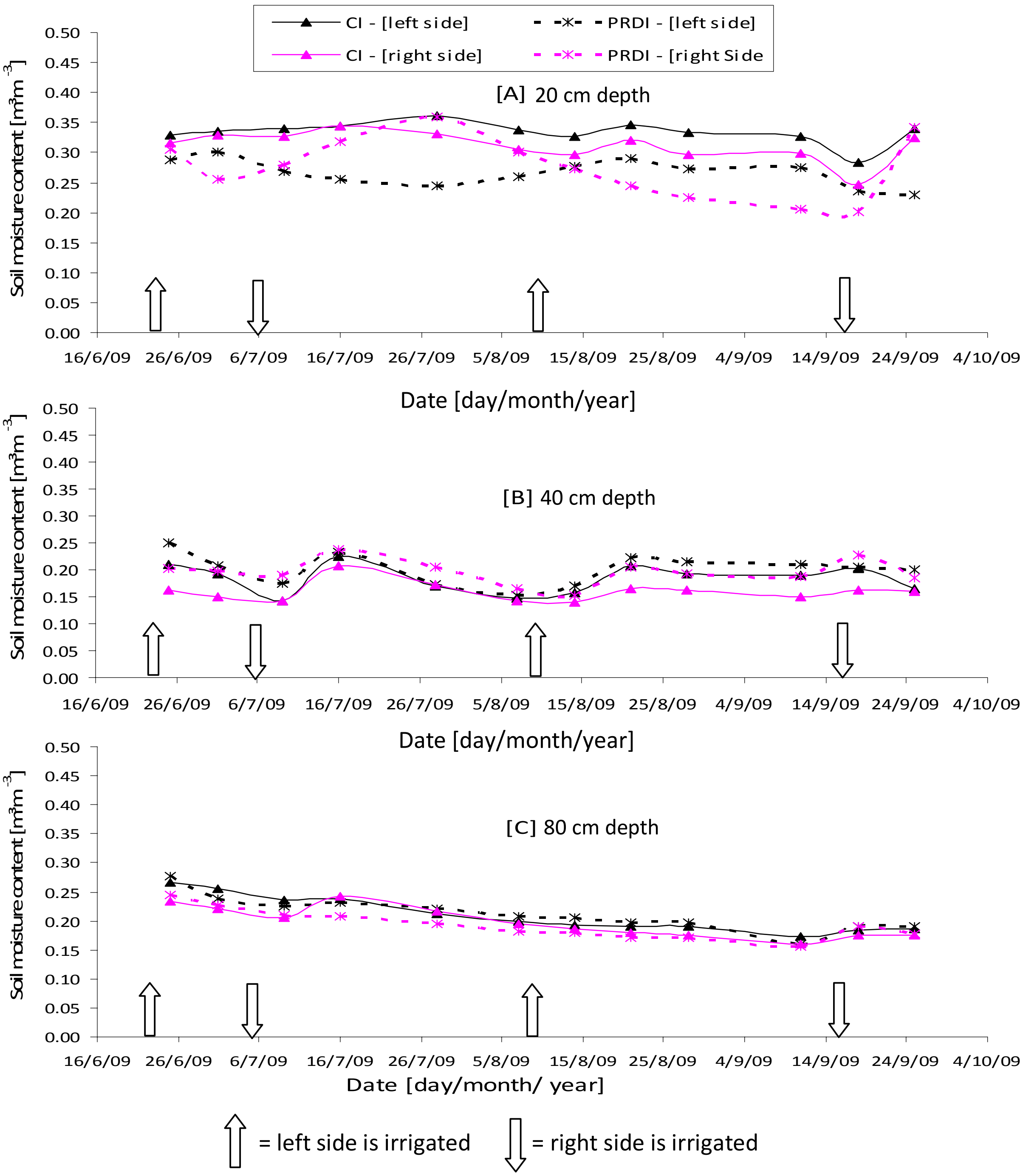


Fig. 5.3. 10: Variation of the soil moisture content in both sides of the different irrigation treatments during the open-soil experiment: (A) 20, (B) 40, and (C) 80 cm below soil surface (n = 4)

As described in the chapter of materials and methods, the PRDI and CI treatments were irrigated with the same amount of irrigation water, but the irrigation water was added only to one side of the PRDI method. The results show that the soil moisture content for each side of the PRDI treatment depended on whether the side of the PRDI was irrigated or not. It could be seen that the irrigation was shifted 4 times during the growing season dates. In comparison to the pot experiments, the difference of the soil moisture between the dry and wet side of the PRDI were lower (at soil depth of 20 cm) and not observable at 80 cm.

The average, maximum and minimum values of soil moisture content in both sides of CI and PRDI during the open-soil experiment are summarized in Table 5.3.3. In the CI method, the average soil moisture content during the irrigation season was higher than in the PRDI method at a soil depth of 20 cm. No differences could be found between the treatments below a soil depth of 40 cm. These results demonstrated that most of applied water in the PRDI method moved to the bottom layers or to the other side of the soil profile. Water movement only worked well in the top layers of the soil, but it was influenced by climatic situations, plant, and soil interactions.

Table 5.3. 3: Average, maximum and minimum values of the soil moisture content for left and right sides of the open-soil experiment (n = 4)

Soil depth [cm]		Volumetric soil moisture [m^3 m^{-3}]			
		CI-65		PRDI-65	
		left side	right side	left side	right side
20	Average	0.334	0.311	0.266	0.276
	Max	0.360	0.345	0.302	0.360
	Min	0.284	0.248	0.229	0.202
40	Average	0.183	0.160	0.201	0.196
	Max	0.225	0.208	0.249	0.239
	Min	0.141	0.141	0.151	0.153
80	Average	0.210	0.197	0.212	0.192
	Max	0.265	0.242	0.277	0.244
	Min	0.174	0.160	0.161	0.157

5.3.2.3 Tomato yield, biomass and root growth

The results of the tomato plant fresh weight, fruit weight, total biomass, and dry matter contents at the end of the open-soil experiment are shown in Fig. 5.3.11.

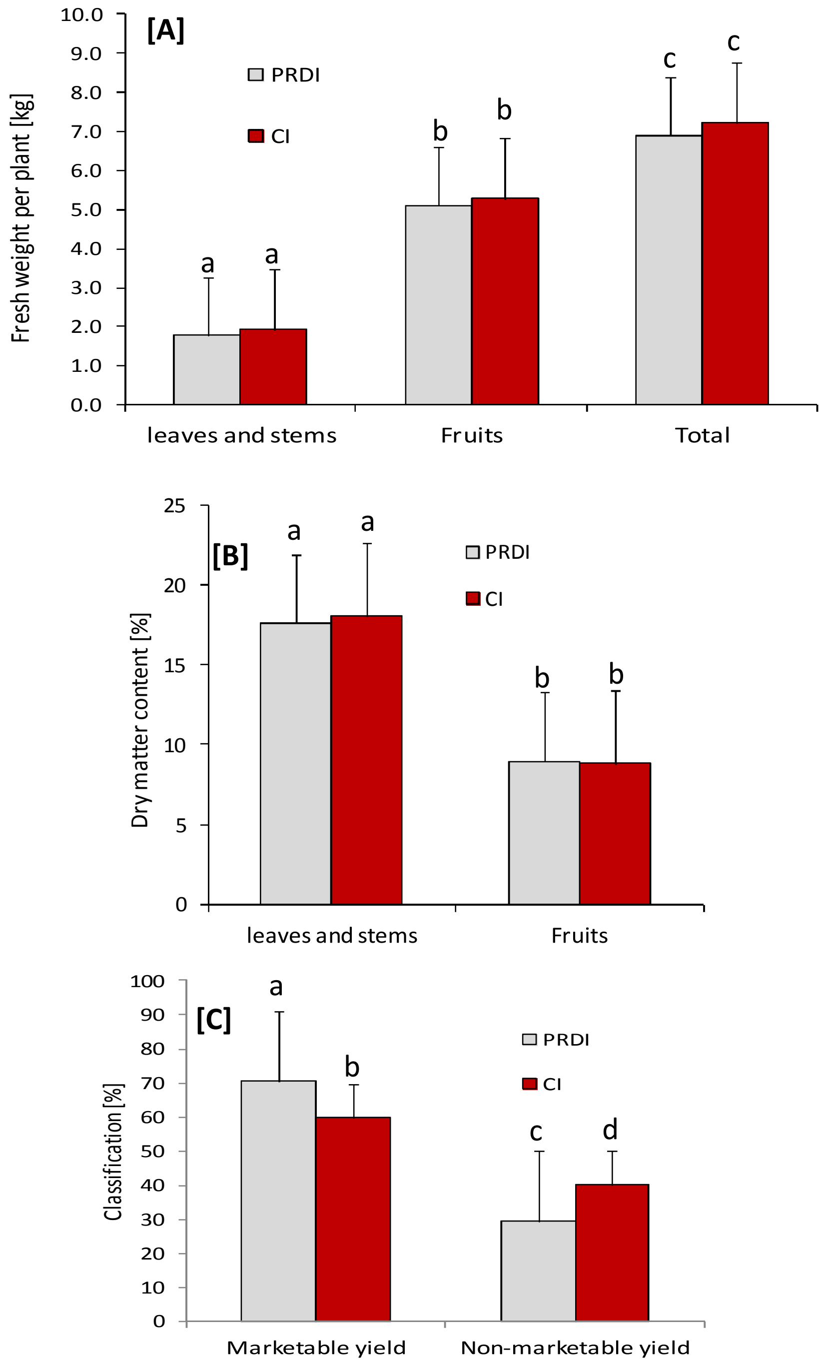


Fig. 5.3. 11: The effect of the CI and PRDI on (A) tomato biomass, (B) dry matter content, and (C) marketable and non-marketable yield during the open-soil experiment (n = 4). Treatments labeled with the same letter do not differ significantly at $p < 0.05$

The PRDI method produced a slightly lower fresh weight, fruit yield, and total biomass than the CI treatment (8.35, 3.03 and 4.46 %, respectively), but with no significant differences between both irrigation methods (Fig. 5.3.10A). However, the plant dry matter content of the CI treatment was somewhat higher (2.28 %) than the PRDI treatment, but also without significant difference. The fruit dry matter content of the PRDI was not significantly higher (1.7 %) than in the CI treatment (Fig. 5.3.10B). Generally, there was no significant difference between the treatments. A small difference between PRDI and CI could be found concerning the fruit quality. The PRDI treatment resulted in a significantly higher marketable yield compared to the CI treatment (Fig. 5.3.10C). The PRDI method produced a lower percentage of damaged fruits than the CI treatment (Table 5.3.4). To summarize, it can be stated that the PRDI improved the marketable yield.

Table 5.3. 4: Classification of the fruit size at the end of the open-soil experiment (n = 4)

Treatment denomination	Classification of fruit size [%]					
	damaged	< 40 g	40 g - 60 g	60 g - 80 g	80 g - 100 g	> 100 g
CI	16.59	40.14	37.35	11.23	8.79	2.48
PRDI	10.32	29.45	30.97	27.93	8.15	3.49

Fig. 5.3.12 shows the fruit yield of a specific plant together with the three replications. The fruit yield of the plants differed from one plant to another inside the replication row; but no especial effect could be detected based on the irrigation water distribution.

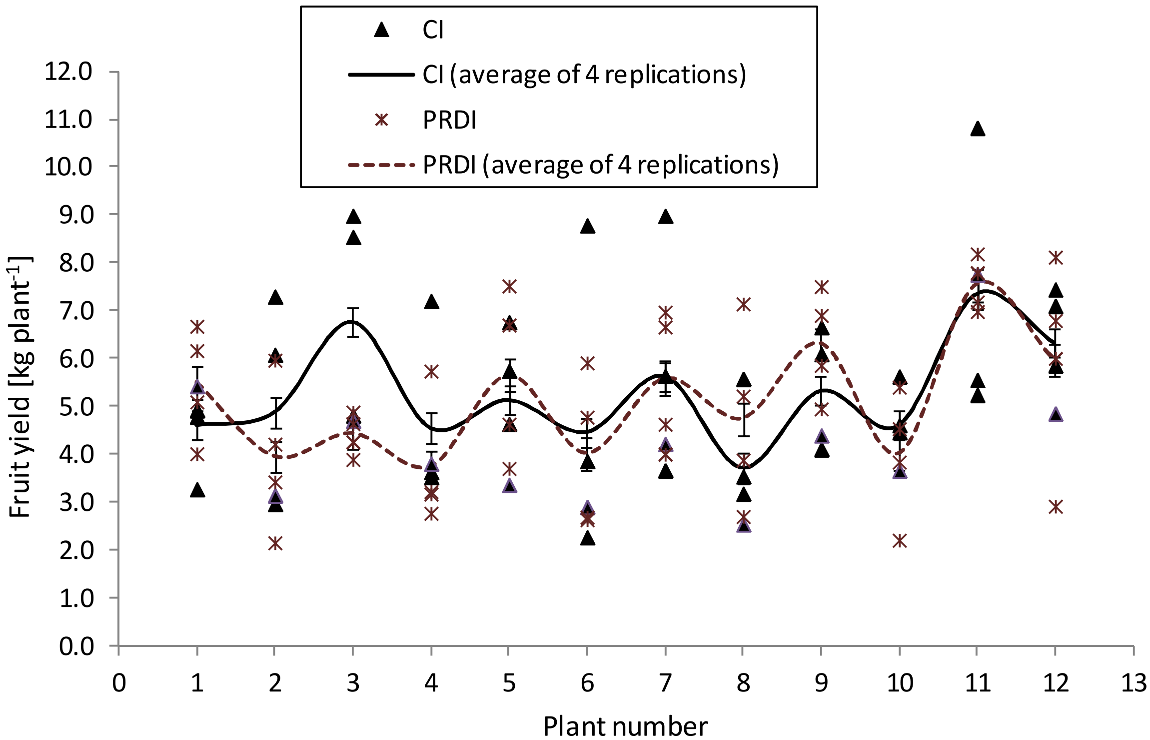


Fig. 5.3. 12: Tomato fruit yield for every plant of the 4 replication rows

The root systems of the plants showed that the growth of the roots within the PRDI treatment was higher than within the CI treatment with long and hard roots; the roots within the CI treatment were more intensive and more shortly than under PRDI (Fig. 5.3.13, see also the similar results of the pot experiment in Chapter 5.3.1.2).

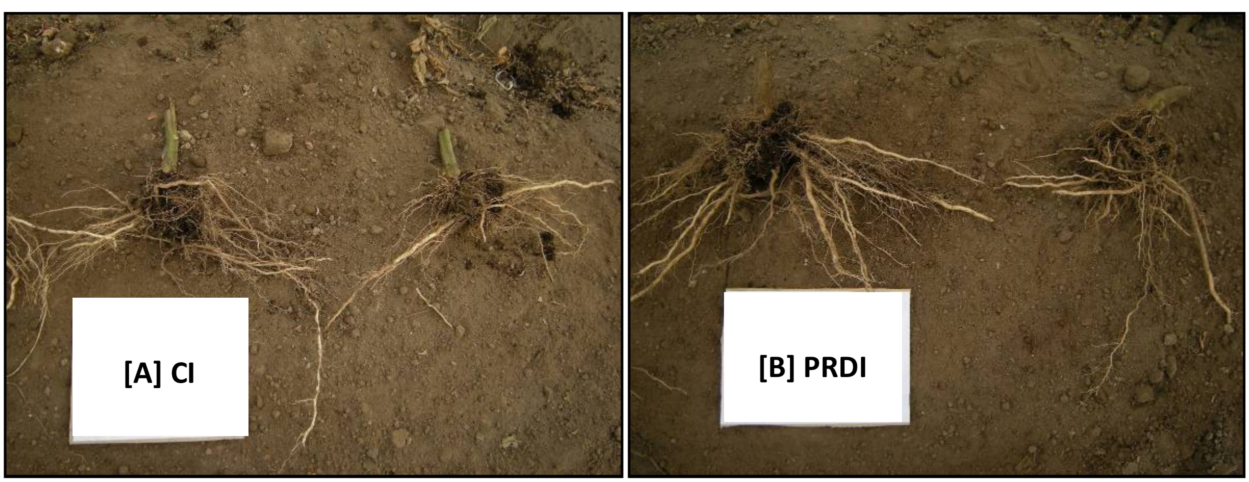


Fig. 5.3. 13: Root growth of the tomato plants of the open-soil experiment for: (A) CI and (B) PRDI

5.3.2.4 Effect of PRDI on soil salinity

Fig. 5.3.14A shows the distribution of sodium in the soil profile after the open-soil experiment. The depth function of Na indicated that the sodium concentration in the first 30 cm was lower in the PRDI method than in the CI method. There was no significant difference between both treatments in soil layers below 30 cm. In Fig. 5.3.14B the distribution of chloride in the soil profile after the open-soil experiment is shown. There were no significant differences between the treatments within any of the analyzed layers in the substrate (Fig. 5.3.14B).

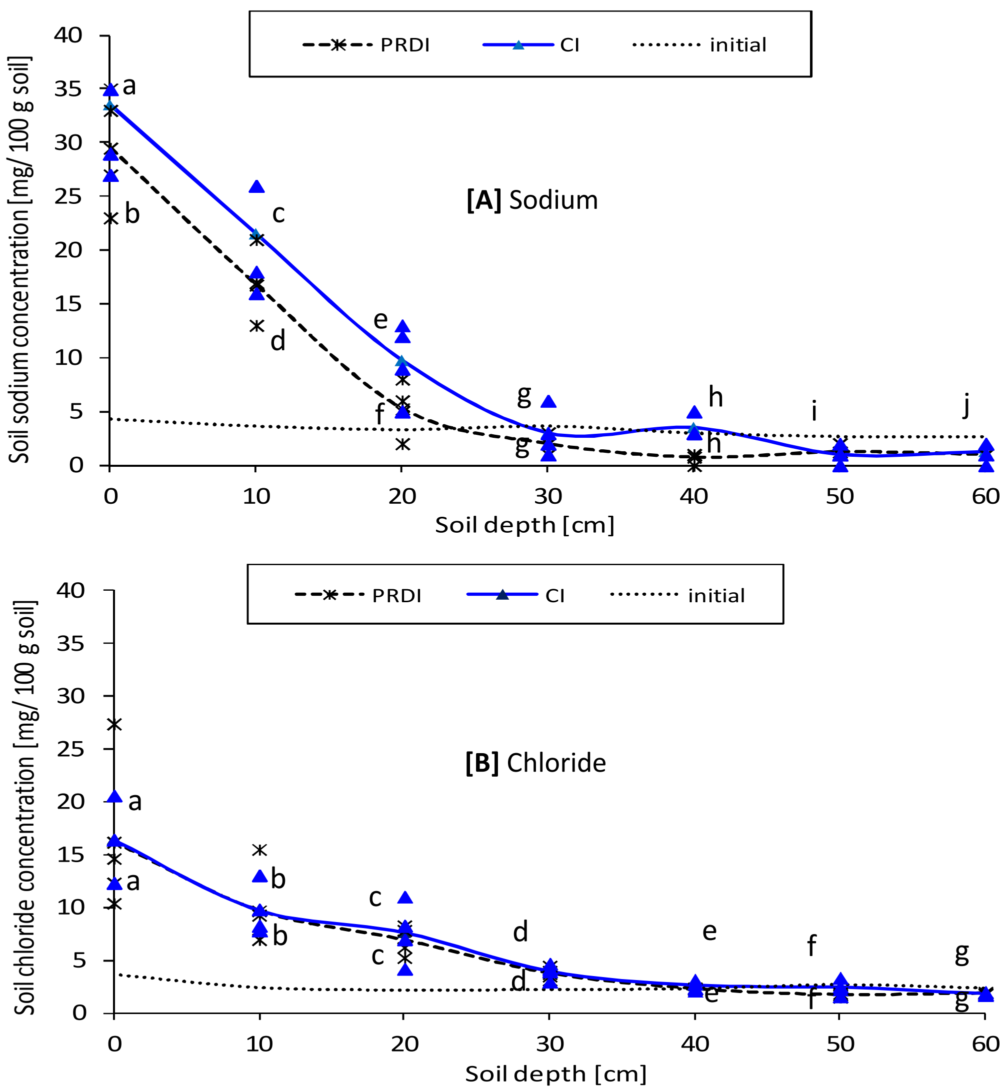


Fig. 5.3. 14: Soil salinity accumulation in the rootzone within the open-soil experiment: (A) sodium concentration, and (B) chloride concentration (n = 4). Treatments labeled with the same letter at each depth do not differ significantly at $p \leq 0.05$.

5.3.3 Simulation of salt movement and distribution

5.3.3.1 Evaluation of the simulation

In Fig. 5.3.15 and Fig. 5.3.16 a comparison between the simulated and measured sodium concentration under CI and PRDI methods is demonstrated. Although there are visible differences, the trends in both the simulated and the measured sodium concentration are similar. Overall, a model-bias could be stated in the PRDI and CI simulation with an offset of 4.4 (for PRDI) and 5.5 (for CI) mg /100 g soil (see r^2 in Fig. 5.3.16).

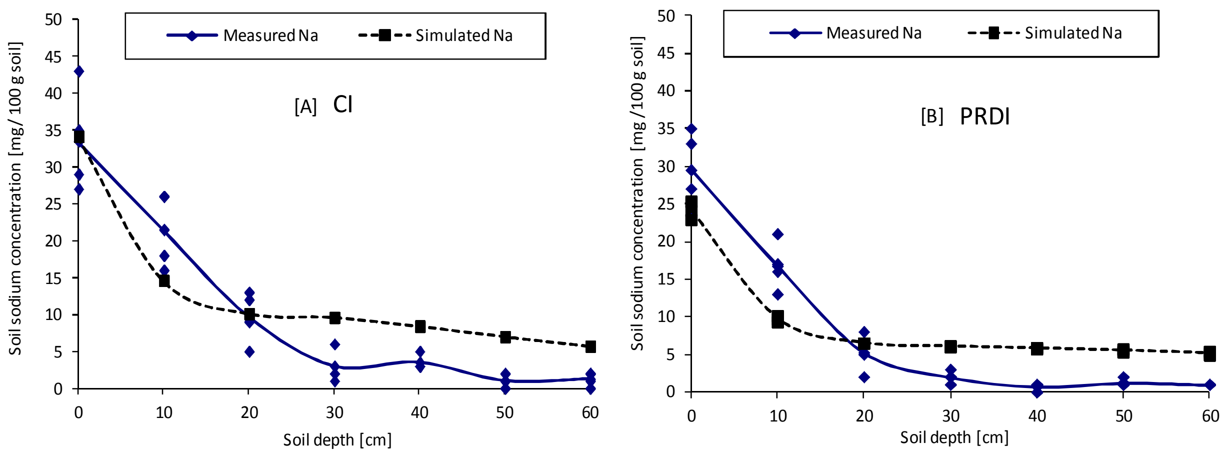


Fig. 5.3. 15: Simulated and measured soil sodium concentration at the end of open-soil experiment for CI and PRDI

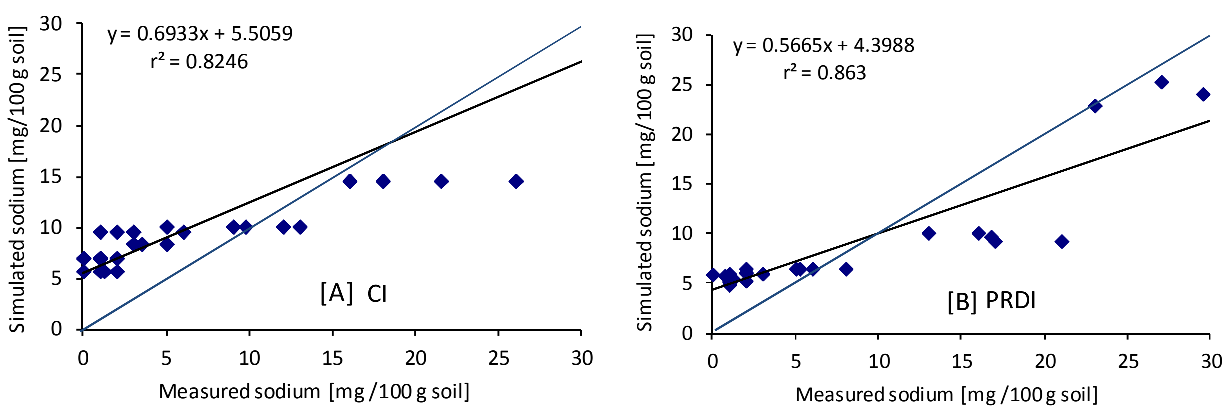


Fig. 5.3. 16: Comparison between simulated and measured soil sodium concentration for CI and PRDI

The results of the chloride simulation are similar (Fig. 5.3.17). The simulation here offset is a little smaller with 3.3 (for PRDI) and 2.8 (for CI) mg / 100 g soil (see r^2 in Fig. 5.3.18).

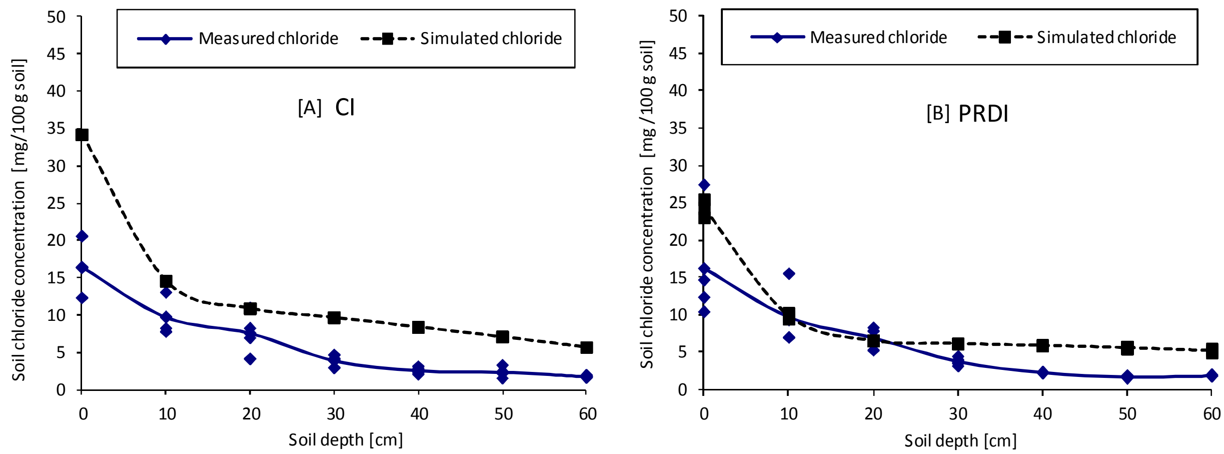


Fig. 5.3. 17: Simulated and measured soil chloride concentration at the end of the open-soil experiment for CI and PRDI

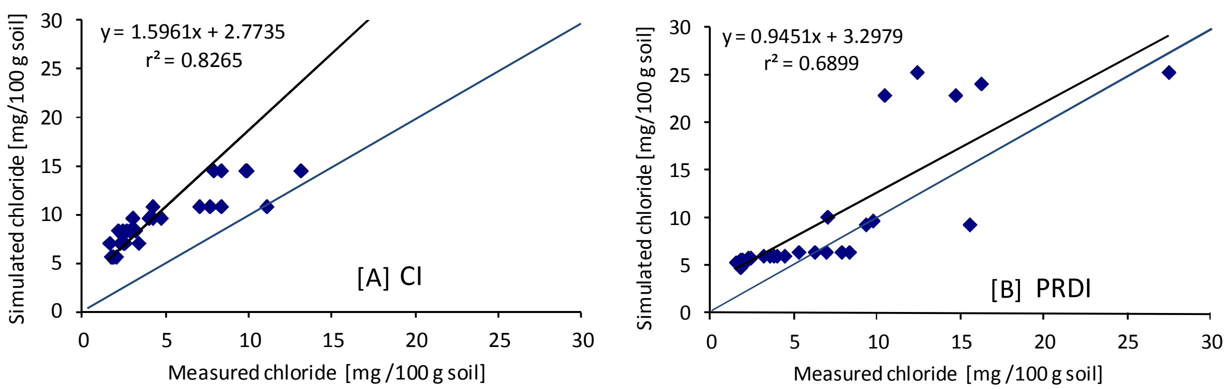


Fig. 5.3. 18: Comparison between simulated and measured soil chloride concentration for CI and PRDI

5.3.3.2 Comparison of PRDI and CI by simulation

Fig. 5.3.19 compares the simulated soil salinity under the CI and PRDI methods for sodium and chloride concentration. The results showed that the soil sodium concentration were lower under PRDI method than in the CI method in the simulated soil profile (within the top 60 cm of the soil profile, as shown in Fig. 5.3.19A). Similar results were obtained for the soil chloride (Fig. 5.3.19B). These results confirmed that the application of PRDI could reduce the soil salinity within the top soil layers, as already recorded in the open-soil experiment.

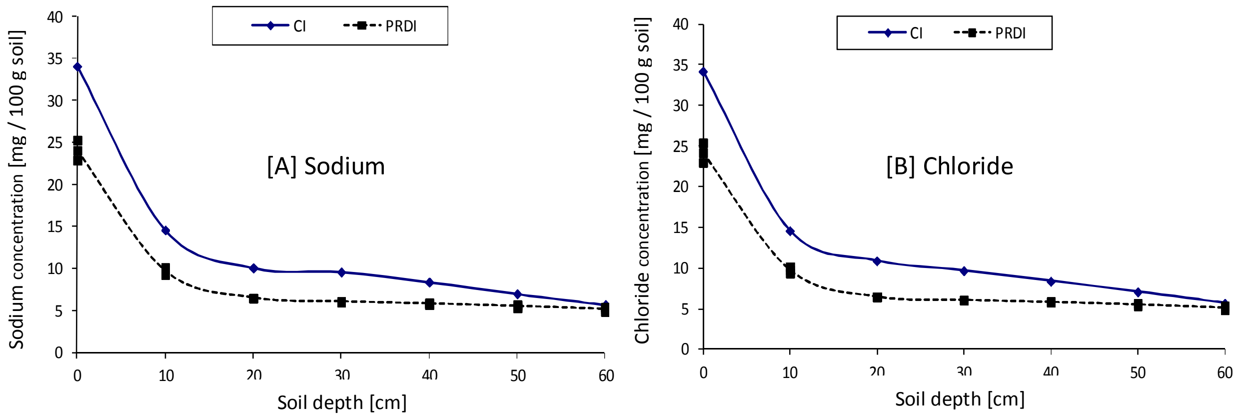


Fig. 5.3. 19: The comparison between the concentrations of (A) simulated sodium, and (B) simulated chloride in soil as a result of CI and PRDI methods

5.3.3.3 Soil salinity under Egyptian situations

The simulated soil salinity under both the CI and PRDI method using 5, 15, and 30 days to shift the irrigated side of the PRDI method is shown in Fig. 5.3.20. The simulated soil sodium concentration in the PRDI method was lower than in the CI method in the top soil layers (within the first 30 cm of soil profile). The soil salinity reduction depended on the PRDI setup (irrigation time shift from one side to the other side). The simulation of the Egyptian conditions (clay loam soil with very high evapotranspiration) confirmed that using the PRDI method can reduce the soil salinity within the top 30 cm soil layers, as recorded in the open-soil simulation results and the experimental results of split-root and open-soil experiments. Also, it shows that the longer the shifting time (or the stronger the PRDI strategy) is, the higher the positive salt leaching effect in the top soil layers becomes. More salts were moved and accumulated between 80 cm to 100 cm of soil layers in all simulations. The results of chloride concentration were similar to sodium concentration (data for chloride concentration are not shown).

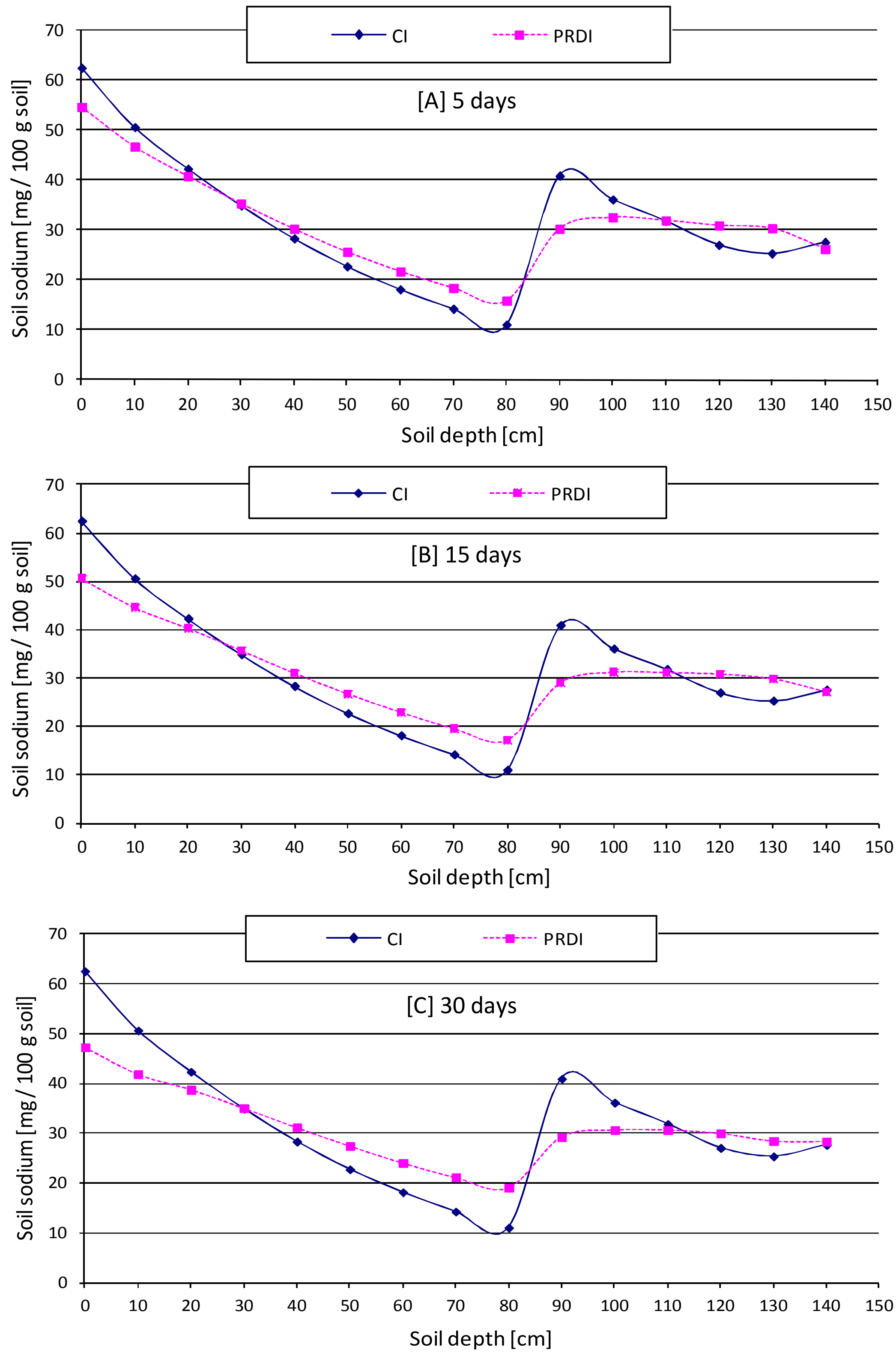


Fig. 5.3. 20: The comparison between the concentrations of simulated sodium in soil (after 27 weeks) under (A) 5, (B) 15, and (C) 30 days to shift irrigated side of the PRDI method to the other side

6 Discussion

6.1 General

The present study was divided into two parts. In the first part, the effect of the PRDI method on soil salinity relocation and soil moisture content was determined. In the second part, a simulation of the soil salinity (individual soil salinity ions sodium and chloride as tracers) under the PRDI and CI methods to transfer of the simulation results to another location under arid and semi-arid conditions (Egypt as an example) was carried out.

The first part of this work was split into three experiments: preliminary, pot, and open-soil experiments. The preliminary and pot experiments (split-root) were carried out in big pots arranged inside a greenhouse. The root system of the tomato plants was split into two parts. Each part was planted in a separate plastic bag. During the filling of the pots, the soil was compacted by hand inside the pots. Soil moisture sensors (ML2x ThetaProbe and access tubes of PR2 Profile Probe) were placed inside the soil as described in the materials and methods (Fig. 4.10 and Fig. 4.11).

The open-soil experiment was carried out in an open-soil surface inside a greenhouse under drip irrigation. The drip irrigation of each row consisted of four drip lines; two drip lines were placed at each side of the plant root system to control the irrigation. The water inlet for one drip line started at the beginning of the plant row and the other drip line started at the end of the plant row to avoid the effect of water pressure loss on the emitter's discharge. Both sides of the CI treatment were watered, while only one side of the PRDI treatment was watered during each irrigation application by the same amount of water used in the CI treatment.

In all experiments of this work the comparison of CI and PRDI was based on the application of the same amount of water. This provides more information on the reasons and the effects of the PRDI itself. Up to date, the publication on PRDI focused on irrigating with only 50 % of the irrigation water conventionally used in CI method (dos Santos et al. 2003; Kirda et al. 2004;

Zegbe et al. 2004; Kaman et al. 2006; Shahnazari et al. 2007; Poni et al. 2009; Hua et al. 2010; Jovanovic et al. 2010; Li et al. 2010; Tang et al. 2010; Zegbe and Pérez 2011).

6.2 Evaluation of the experimental set up and the measurements

6.2.1 General

Due to an increase in the world's water demand, it is very important to investigate alternative irrigation methods that save irrigation water without affecting the plant production or soil salinity. The PRDI method has been already used successfully with a numbers of crops such as tomato (Kirda et al. 2004; Zegbe et al. 2004; Kaman et al. 2006), cotton (Kaman et al. 2006,2008; Tang et al. 2010), maize (Kang and Zhang 2004; Hua et al. 2010; Li et al. 2010), grapevines (dos Santos et al. 2003; Poni et al. 2009), apple (Leib et al. 2004; Zegbe and Pérez 2011), or potato (Shahnazari et al. 2007; Jovanovic et al. 2010; Ahmadi et al. 2010), using only 50 % of irrigation water compared to a conventional irrigation (CI). Therefore, the effects on crop production could be ascribed to a reduction of irrigation water and not specifically to the PRDI method. The effect of the PRDI method on the soil salinity distribution is yet unknown.

6.2.2 Optimum water application level for the PRDI

Choosing the right water application level is very important to provide sufficient soil moisture content for growing plants. Water application levels can be chosen according to soil moisture content or/and according to the evapotranspiration. Kang et al. (1998) reported that the water content of growing media should be maintained above 55 % or 65 % of its field capacity. Shao et al. (2008) applied the irrigation water when the soil water content was lower than 80 % of the field capacity. In the present work, the irrigation is also applied according to the soil water content. Three levels of irrigation (minimum to maximum soil moisture) were chosen during the preliminary experiment; 70 % to 80 % of FC as a control treatment (no water stress), 55 % to 80 % of FC as a mild water stress and 40 % to 80 % of FC as a severe water stress. The result of these water applications rang lead to the fact that the overall amounts of the irrigation water were increased by increasing application range and irrigation intervals. In other words, the small application range consumed the lowest amount of irrigation water and the high application range consumed the highest amount of irrigation water, because the irrigation water move to deeper soil layers. In conclusion, the water application levels should have different boundary (lower and upper) limits for irrigation. In order to have small ranges, the pot experiment focused solely on two water application levels, which were 65 % - 80 % of FC as a control (no water stress) and 50 % - 65 % of FC as a water stress treatment. The range (15 %) between the lower and upper boundary of irrigation is the same. The soil moisture content of the CI method was considered the lower boundary for irrigation. This meant that when the soil moisture content of both sides of the CI reached to the lower boundary (65 % and 50 % of FC, respectively), the substrates of the treatments were irrigated. According to these irrigation strategies, the amount of water used for each irrigation treatment was the same. The irrigation intervals and the number of irrigation, however, were different. This strategy permits an optimum possibility to interpret the results and it is strategically better than the methods used up to now.

6.2.3 Root splitting

To manage the PRDI method, it is very important to split the root of the plants. Stoll (2000) has reported on the importance of a split-root system for field-grown grapevines since it constituted as a model system, which was not affected by soil water movement and reduced the impact of other treatments. Therefore, the two sides of the root system were separated by a vertically buried plastic sheet, which ensured that a lateral water movement could not affect the test vine. Splitting methods have also been used successfully for tomato plants by Stikic et al. (2003) and Kang et al. (2004) and for maize plants by Kang et al. (1998; 2000) and Kang and Zhang (2004). Therefore in the present study, the tomato plants were planted in plastic pots (pot experiments) and each pot was split into two compartments by two plastic bags. It is clear that splitting the root cannot be used for every plant since it could destroy the plants. For the tomato experiments, however, it worked very well and increased the accuracy of the experiments. The root systems at the end of the experiments showed that the plant were not damaged or affected by the root-splitting. The open-soil experiment showed that all the effects were visible even without splitting the roots.

6.2.4 Irrigation drippers

It is very useful and essential to know how much water is being applied to different plants since it is an important input factor for any irrigation scheduling. The uniformity of irrigation water determines whether all plants receive the same amount of water. When irrigation is uniformly applied, some plants are over-watered while others are under-watered. This becomes even more important when nutrients are applied in the irrigation water or different levels of water stress are tested as in this study. Therefore, a calibration of the irrigation drippers was performed before the experiments in order to evaluate the performance and accuracy of the emitters during water distribution.

The results showed that the discharge within the plant line was homogenous except for the first and last points of the irrigation line. This information is useful to ensure that the variations of the tomato plants and soil salinity distribution can be attributed to the irrigation methods itself (either CI or PRDI method). The calibration was repeated at the end of the experiment to test whether commissioning a new block and after any major changes. Generally, the discharge levels were reduced compared to the starting conditions by dripper clogging; but it was randomly and affected both treatments (CI and PRDI) in the same way. Therefore it can be concluded that the results are not affected by the distributions of irrigation drippers, because the distribution within the plants rows are homogenous during the growing period.

6.2.5 Usage of salts as tracers

It is very important to add tracer salts to irrigation water to test the effect of irrigation methods on the movement of salts in soil profiles. Therefore, sodium chloride was chosen as a tracer salt, because its movement in soil is related to the irrigation method as well as the amount of irrigation water. The plant nutrition chosen in the present study was free of sodium chloride to ensure that the irrigation water was only the source of sodium chloride. The results of applying

the sodium chloride can be transferred to any other salt which is not adsorbed in the substrate; but in this case, the response of the plant to salt should be taken into consideration.
Munns and Tester (2008) mentioned that soils are classified as saline when the EC is 4 dS m^{-1} or more, which is equivalent to approximately 40 mM of NaCl generating an osmotic pressure of approximately 0.2 MPa. This definition of salinity derived that the EC significantly reduces the yield of most crops. Also, Shannon and Grieve (1999) stated that increasing the soil salinity increases the percentage of yield reduction. Soil salinity with 4 dS m^{-1} does not significantly affect the yield; but at about 12 dS m^{-1}, the yield is reduced by 50 %. El-Gamal (2000) recorded that the most beneficial effect of sodium chloride on tomato plant growth was obtained at 150 mmol L^{-1} of sodium chloride.

During the preliminary experiment, sodium chloride was added to the irrigation water at 100 mmol L^{-1}. The plants in this experiment were under high stress, because the sodium chloride was applied with high levels. Applying these amounts of sodium chloride affected the growth and the yield of tomato plants (see Brewer et al. 2011), and resulted into a salt-affected soil with high concentrations of ions, particularly sodium and leading to a cytoplasmic toxicity as reported by Ashraf (2004) and Brewer et al. (2011). Therefore, the amount of sodium chloride was reduced in the main experiments to 50 mmol L^{-1}. Nevertheless salt concentrations at the end of experiments compared with literature show that the tracer salts affected the treatments (more discussion in details in Chapter 6.3.3).

6.2.6 Soil moisture measurements

In order to manage the irrigation by measuring the soil moisture content, it is very important to have adequate sensors. All information on these sensors should be known. There are two possibilities to measure soil moisture content in different soil depths: use similar sensors at different depths or use one sensor with different measurement points. In this study, the soil moisture content was measured by the ML2x ThetaProbe and the PR2 Profile Probe. These sensors have different sensitivities at different measurements points. Therefore, the accuracy and sensitivity of the sensors should be taken into consideration.

For the testing of the soil moisture sensors, sandy soil was chosen due to its properties of easy vertical or downward movement of water and the possibility of oven drying. The results generated thereby could then be used to predict what possible results could be expected in other type of soils with different texture. The experimental setup was carried out in plastic containers to prevent a dielectric effect on the generated readings. Some experiments were performed to determine the three dimensional (3D) sensitivity of The ML2x ThetaProbe. All experiments carried out for the three shield rods showed that the same readings were basically generated when the same amount of water was applied at an equal distance. Therefore the sensors could be used in the pot as well as the open field experiments.

Miller and Gaskin (2011) reported that the sensing volume of the ML2x ThetaProbe was determined to be a cylinder of about 6 cm (rod length) with a diameter of 6 cm. This is difficult to determine in practice since it is a function of soil density and particularly of the soil water content. The results of the investigations show that the highest readings were generated at a 3 cm distance from the center rod and the readings decreased with an increasing distance from the center rod due to the small sensing volume of the ML2x ThetaProbe (Muňoz-Carpena, 2004; Muňoz-Carpena et al. 2009; Delta-T Devices, 1999; and Miller and Gaskin, 2011). Since the sensitivity of the sensor was biased towards the center rod (Delta-T Devices, 1999; Miller and Gaskin, 2011), the more the distance of application increased, the lesser the sensor was able to detect the moisture in the soil. Some of the readings might be influenced by this small sensitivity range of the sensor, which should be taken into consideration when evaluating them. Nevertheless no better sensor systems were available on the market at the time of the experiments.

The results of the ML2x ThetaProbe showed that the best placement of the sensors on the field was achieved by installing the sensors in a position that allowed the sensor rods to come into contact with the applied water or with the soil moisture. Therefore, the sensors should not be placed too far from the irrigation drippers or plants root systems in order to obtain good readings. An ideal placement of the ML2x ThetaProbe in the soil could be achieve by either of these three positions: (1) vertical with the rods facing downwards, (2) vertical with the rods facing upwards or, (3) placement of the sensor with rods at an inclined angle. A placement of the sensor with the rods facing downwards is very easy without damaging the soil structure, but the body of the sensor prevents a contact of water with the sensor rods, thereby leading to low readings. A placement of the sensor with rods facing upwards results in good readings, but it is very hard to install it thusly, additionally to a destruction of soil structure during the installation. A placement of the sensor with the rods at an inclined angle could be a conclusion, but it results in some problem with the soil structure because of the difficulties during the installation. In the present study, the ML2x sensors were placed with the rods facing downwards, because the plants were irrigated manually during the pot experiments and by a drip irrigation system during the open-soil experiment, so that the shading effect could be neglected. Nevertheless, it has to be mentioned that the readings were very sensitive, because of the above mentioned aspects, especially when the sensors were completely installed in the soil. But in the effect of none destroying the soil around the plants was given a higher importance than the losses of sensor sensitivity.

In order to overcome the installing problems of the ML2x sensor in different soil depths, the PR2 Profile Probe was installed additionally in the experiments. This sensor presents an effective solution for measuring the soil moisture content in different depths of soil profile. The PR2 Profile Probe replaced the PR1 Profile Probe in 2005 due to some problems with the PR1 Profile Probe. Kelleners et al. (2004) reported about some problems associated with the PR1 Profile Probe that most of the electromagnetic field did not go well into the soil outside the access tube. Also the range of axial sensitivity of the PR1 Profile Probe decreased as water content increased and it was larger than the distance between the bottom and the top of the electrodes (Evett et al. 2002). The sensed volume decreased as the volumetric water content increased and this leads to problematic field calibration and poor calibration results (Evett et al 2002). According to Delta-T Devices Ltd (2008), the electromagnetic field of the PR2 Profile Probe extends about 10 cm into the soil. The results of the present study showed that the electromagnetic field extends only up to 4 cm into the soil. Moreover, no readings were generated at a distance of more than 8 cm from the access tube for any of the moisture contents and vertically measurements points. This might derive from the electromagnetic field not extending well enough into the soil outside the access tube (Kelleners et al. 2004). The color charts and the comparisons between the various moisture contents (Fig. 5.1.5) show that the strength of the sensor lies within 4 cm and is strongest when the moisture is closer to the access tube. Also, the access tube influenced the soil profile in an artificial way, since the installation of the access tube damaged the structure of the soil. Therefore, the PR2 Profile Probe should not be used in deficit irrigation programs. It is more usable to control the effect of irrigation in the soil profile when its poor sensitivity and the results losses (signal ratio) are taken into consideration.

6.2.7 Greenhouse use

In order to limit the effects of rain and other climatic parameters on the experimental results, the experiments were conducted inside a greenhouse. The humidity levels in the greenhouses depended on the inside temperature since warm air is capable to hold more moisture than cold air before it becomes saturated. A humid atmosphere is harmful to some plants because the rate of evapotranspiration is reduced in a very humid condition. The highest relative humidity in the greenhouse is generally found between the plant canopies, where moisture is generated from soil evaporation and leaf transpiration. There it is stored due to insufficient air movement and ventilation. Under open field situations, the movement of air is free and the air removes the high humidity from the plant canopies. Therefore the rate of evapotranspiration increases. Increasing the rate of evapotranspiration, results in a higher water uptake from the soil. This results in changes of the soil moisture content distribution in the soil profile under different irrigation methods. That is why the results generated in greenhouses or rain shelter experiments cannot be generalized without an adaptation to different situations especially under open field situations where the rate of evapotranspiration is higher due to the lower air humidity and free wind speed. On the other hand the results of the present experiments showed that the climatic conditions in both greenhouses used here were very homogenous, so there are no unknown factor affected the experimental results. Irrigation experiments without any rain shelters are not possible, so the use of suitable greenhouses were necessary to control the experimental treatments. The simulation experiment was performed to overcome the problems of the greenhouse in irrigation results, which has given important information as well as the importance of the results in open-field conditions.

6.3 Experimental results

6.3.1 Soil moisture content in general

Water moves in soil in three directions. Water moves horizontally, vertically (downwards and upwards) and into plant roots, and eventually into the atmosphere through transpiration. The rate of horizontal and vertical movement depends on the soil texture, microstructure and bulk density (percentage of clay, silt and sand in soil). The particle size and pore space of clay soils are very small and thus results in clay soils holding water tightly by capillary action. The gas phase of the substrate as necessary as water for root growth also has difficulty moving through the soil. Therefore, in clay soils the rate of horizontal movement is faster than the vertical movement; in sandy soil the movement of vertical movement is faster than the horizontal movement. However, loamy soils have good movement of water in both directions. During the night, when transpiration is greatly reduced, water moves from highly water saturated parts of the soil between roots into soil adjacent to absorbing roots that has dried during the previous day (Gardner 1998). In the preliminary experiment and in the pot experiments it was difficult to obtain a homogeneous soil structure because the soil was compressed by hand during the pot filling. Therefore, the soil inside the pots had inhomogeneous soil properties such as soil bulk density, soil pores, soil hydraulic conductivity, resulting in a so called artificial soil. These properties affected the water movement in the soil. In the present study, loamy sandy soil was used since the movement of water is related to the soil type and the physical properties. In a loamy sandy soil, the vertical movement of water is higher than the horizontal movement. Therefore the results of the experiments would be different if the growing medium is changed to other soil textures for example clay soil or heavy clay soil; where the horizontal movement of water is higher than the vertical movement. Nevertheless, the basic results of the experiments can be transferred to other situations (e.g. the results of soil moisture content can be transfer to different soil textures. But in this case the movement of water in these soils should be taken in consideration).

The irrigation of the PRDI treatment increased the soil moisture content of the irrigated side. This is logical because half of the plant area was irrigated with double amount of water compared to the CI method. The soil moisture content for each side of the PRDI treatment depended on whether the side of the PRDI was irrigated or not. These results are depended on the irrigation management and cropping system. Similar results were also reported for drip irrigated tomato in open-soil conditions inside a greenhouse by Kirda et al. (2004) and Kaman et al. (2006), in wooden boxes under furrow irrigation by Zegbe et al. (2004), in big pots with splitting roots by Savić et al. (2008) and Stikic et al. (2003), for furrow irrigated cotton under open-field conditions by Kaman et al. (2006), and for apple under open-field conditions by Leib et al. (2004). When comparing CI and PRDI Kang et al. (2002), Kirda et al. (2004), Kaman et al. (2006), Zegbe et al. (2004), Leib et al. (2004), and Savić et al. (2008) reported for different crops and different irrigation systems that the soil moisture content in the irrigated side of the PRDI treatment was lower than either side of the CI treatment. In the present work, the PRDI resulted in higher moisture in the irrigated side than in the CI because of the application of the same amount of water in both treatments. The only available publication where the same amount of water was used for both CI and PRDI is De la Hera et al. (2008) but the soil moisture content under PRDI was not measured. Therefore, the results of the present study can be used to separate the actual effect of the PRDI from the effect of the deficit irrigation (DI) on the soil moisture content.

6.3.2 Soil moisture content in pot and open-soil experiments

The results of the present work show that there were discrepancies between the soil moisture content of the split-root experiments and the open-soil experiments. One explanation for these discrepancies was that the split-root experiment was performed in pots using plastic bags to split the root system of the plants. These plastic bags prevented any horizontal water movement from one side to the other. In other words, the irrigated area was horizontally controlled and limited. In the open-soil experiment on the other side, the plants were grown in open-soil situations. There is the water moved freely both horizontally and vertically (Gardner 1998). The horizontally moving of water increased the irrigated area under open-soil conditions. Therefore, the soil moisture content was reduced faster. There are a lot of factors which influence the water movements. Stoll (2000) reported that the amount of water available to the plant from the soil layers is heavily influenced by the soil water potential. The soil water potential is also affected by the soil depth, the soil texture, and the soil structure. Most of the water movement follows a gradient from the soil layers of high matric potential to the soil layers of low matric potential. This phenomenon is described as hydraulic lift (Richards and Caldwell 1987), hydraulic redistribution (Burgess et al. 1998), or downwards siphoning (Smith et al. 1997). Due to the experimental set-ups, these phenomenons differ between the split-root and open-soil experiments and are a possible explanation for the different results

6.3.3 Tomato yield and biomass

Table 6.1 compares the results of plant biomass, fruit yield, and total biomass under the different experimental conditions. The results of present study show that the differences in 2 of 15 cases were significant. So overall the PRDI treatment has no effect on the total tomato yield. Under deficit water, the biomass was little reduced under the PRDI method, but the fruit yield was similar or higher in both pot experiments and open-soil experiment. The dry matter content of fruits and plants in most treatments was also a little lower under the PRDI treatment. To interpret the results one has to consider that the production of plants under pot conditions is uncommon in comparison to open-soil conditions and the commercial production of tomato. This stems from the fact that the plants in the pots were grown under water stress and may be under salt stress which could have the following reasons:

- The growing soils differ from one pot to the other in their soil compaction rate.
- The soil volume may not be sufficient for root growth.
- The water moved very fast to the bottom soil layers (artificial soil).

- Increasing the water content in bottom soil layers leads to a reduction of the available oxygen.

Table 6. 1: Comparison of the results of plant biomass, fruit yield, and total biomass during the pot and the open-soil experiments

	[(PRDI/CI)-1]*100 [%]									
	Plant biomass based on [kg/plant]		Fruit yield based on [kg/plant]		Dry matter of plant based on [%]		Dry matter of fruit based on [%]		Total biomass based on [kg/plant]	
	Water application level									
	65	50	65	50	65	50	65	50	65	50
Pot results	-4.5 NS	-5.5 NS	+0.8 NS	+43.2 S	+2.7 NS	+2.0 NS	+4.7 NS	-8.4 S	-3.1 NS	+4.8 NS
Open-soil results	-8.4 NS	………	-2.3 NS	………	-3.0 NS	………	+1.7 NS	………	-4.5 NS	………

Loveys et al. (2001) and Stamp (2003) reported that during each irrigation cycle it is important that water is supplied with sufficient frequency to the wet side in order to prevent an excessive soil drying as well as to meet the needs of the whole plant. It is now understood that water in the PRDI crops is re-distributed from the wet-side roots to the dry-side roots during the night, thus providing a supply of water to the dry roots that can contribute to the transpiration flow in the following day, thereby facilitating the transport of root-derived chemical signals such as Abscisic acid (ABA). This re-distribution also ensures that the dry side roots are maintained in a healthy condition and do not become overly stressed. Separating the root system of the plants with the plastic foils in the pot experiment avoided the movement of the water from the wet side to the dry side during the night, as stated necessary by Stamp (2003). This might be one of the reasons for the different results in the pot and the open-soil experiments.

Stamp (2003) reported that, as roots are the first part of the plant to be exposed to changes in soil moisture, it is to be expected that their structure may be affected by the PRDI. It has been observed that withholding water from one side of the root system causes roots to grow deeper into the ground soil profile (Dry et al. 2000). In the present work, the analysis of the root system of the tomato plants show similarly that the CI tomato plants watered on both sides had a higher percentage of roots in soil layers closer to the surface than the PRDI tomato plants. These roots were prolonged and grew to a deeper soil layer. The larger number of roots in deeper soil layers in the PRDI method may contribute to the water stress tolerance of these plants during the drying period of the PRDI method (Stamp 2003). However, Chaves et al. (2007) observed a tendency to develop a deeper root system in the PRDI vines, while the CI plants showed a more homogeneous root distribution throughout the different soil layers. In this case, the PRDI produced a longer and deeper root system than the CI method (see also Kang et al. 2002).

Stamp (2003) reported that the irrigation water use efficiency (IWUE) for commercial application of the PRDI compared to a CI method was on average increased by 75 %. The amount of water was reduced by 47 % whilst the yield was lower by 7 % on average (Stamp 2003). This further supports the results of the present study and earlier observations by Dry et al. (1996) and Loveys et al. (1998). The results of the present study showed that the PRDI method increased the IWUE on average by 43 % compared to the CI method when applying it under water stress (see Table 6.2). The possibility for the improved IWUE under PRDI came from the analysis of the soil water distribution. The soil water content and the depth of the soil profile is almost positive in the PRDI method because the irrigation water moved to deeper soil layers, and there was an upward soil water content gradient in their rootzone (Kang et al. 2002). Therefore, the PRDI method offered a very useful technique to produce fruit with good commercial qualities; similar results were reported by Stikic et al. (2003) and Kirda et al. (2004).

From the summary of the effect of PRDI on fruit yield, it can be derived that the yield is not affected by the PRDI. No effects were reported between the irrigation methods except from investigations of De la Hera et al. (2007) who had clear positive effects using similar water strategies (using the same amount of water for both irrigation treatments). In the present study, a positive effect could be found for the PRDI method under deficit water situations. The IWUE increased significantly by PRDI under low water applications; this is in agreement with the reported results of available literature.

Table 6.2 shows the comparison between the results of the present experiments and the literature. It demonstrates that the observed effect of PRDI is close to the observations in the available publications. Zegbe et al. (2004) mentioned that the total fresh mass of the plants (leaves and stems of plant) was significantly reduced in the PRDI method when compared to the CI method. The number of fruits, mean biomass and total fresh mass of the fruit, as well as the total dry mass of the fruit was not affected by the PRDI method. The results of the present work show that the effect of the PRDI method on fruit yield was limited under applying sufficient amount of irrigation water.

The PRDI method increased the production of fruit yield when applying it under low irrigation water (with increasing deficit water, see Table 6.2 of experiments from this study). The PRDI method increase fruit yield, because it decreases the number of fruits per truss, and the individual fruit weight was increased. The reason might be the same as for the results from Pulupol et al. (1996) and Zegbe-Dominguez et al. (2003). They stated that tomato plants are sensitive to water deficit during flowering and fruit set, so flower abortion might occur. This could have caused a reduction of the number of fruits and total dry matter content in the PRDI method. The open-soil experiment showed that the PRDI resulted in a small and not significant reduction of the fruit yield and the biomass (see Table 6.2); but the effect is small and might be a result of horizontal reduction of the PRDI strategy. A similar effect might have influenced the plant dry matter content because the total dry matter content was also reduced in the PRD treatment. On the other hand, the dry matter content of the fruits was increased in the PRDI treatment compared to CI treatment. Increasing the dry matter content of fruit improves its quality because the high matter content is good for processing due to low energy required for processing.

Table 6. 2: Comparison between the results of the different experiments and the literature

Author & year	crop	*root splitting	applied water (PRDI/CI) [-]	results as [(PRDI/CI)-1]*100 of		
				IWUE [%]	total biomass [%]	yield [%]
Stikic et al. (2003)	Tomato	yes	0.5	+	- 22 to -26	- 30
Zegbe et al. (2003)	Tomato	No	0.5	NM	NS	NS
Kang et al. (2004)	Tomato	yes	0.5	+	- 6 to -11	NS
Kirda et al. (2004)	Tomato	No	0.3 & 0.5	+ 56	- 17 to - 28	+ 10 to + 27 MY
Zegbe et al. (2004)	Tomato	No	0.5	+ 70	NS	NS
Kaman et al. (2006)	Tomato	No	0.5	+ 88 to 95	NM	NM
Kaman et al. (2006; 2008)	Cotton	No	0.5	+ 88 to + 95	NM	+ 3 to + 6.4
Tang et al. (2010)	Cotton	No	0.7	+	NS	+ 4.44 NS
Kang et al. (1998; 2000)	Maize	yes	0.5	+	- 6 to -11	NS
Kang and Zhang (2004)	Maize	yes	0.5	+	NS	NS
Hua et al. (2010)	Maize	No	0.5	+	NS	NS
Li et al. (2010)	Maize	No	0.5	+13.6 to + 41.8	-	NS
Kang et al. (2002)	Pear orchard	No	0.48 to 0.77	+ 12 to 28	NS	NS
dos Santos et al. (2003)	Grapevines	No	0.5	NM	NS	NS
Poni et al. (2009)	Grapevines	No	0.5	+ 54.5	NS	NS
Leib et al. (2004)	Apple	No	0.5	+	NS	NS
Zegbe and Pérez (2011)	Apple	No	0.5	+	NS	+ FQ
Dorji et al. (2005)	Hot pepper	No	0.5	+	- 19	- 20 FN

Gençoğlan et al. (2006)	Green bean	No	0.5	+	NS	NS
Spreer et al. (2007)	Mango	No	0.5	+	NS	+ FS and + MY
Shao et al. (2008; 2010)	Hot pepper	No	0.5	+ 52.1	- 7.3 to - 44.1	- 23.98
Shahnazari et al. (2007)	Potato	No	0.5	+ 61	NS	+ 20 MY
Ahmadi et al. (2010)	Potato	No	0.65	+	NS	NS
Jovanovic et al. (2010)	Potato	No	0.5	+ 38 to 61	NS	NS
De la Hera et al. (2007)	Grapevines	No	1	+ 40	+	+ 43 (+ 27 to + 38 FS)
Pot experiment (at 65 % of FC)	Tomato	yes	1	+0.8 NS	- 3.1 NS	+ 0.8 NS
Pot experiment (at 50 % of FC)	Tomato	yes	1	+43.2 S	+ 4.8 NS	+43.2 S
Open-soil experiment (at 65 % of FC)	Tomato	No	1	- 3.0 NS	- 4.5 NS	- 2.3 NS

(*) Root splitting means the root of experimental plants were split into separated containers

(+): the PRDI practice increased this factor
(-): the PRDI practice decreased this factor
(NS): no significant differences
(NM): not measured
(MY): marketable yield
(FS): fruit size
(FQ): fruit quality
(FN): fruit numbers

Williams and Matthews (1990) and Stoll (2000) reported that the fruit weight can be very responsive to water stress. They concluded that if only a limited amount of water is available, the PRDI is more efficient than conventional irrigation, allowing water penetration to deeper soil layers thereby avoiding water stress. Compared to commercial production and literature, the production under the present open-soil conditions experiment resulted in a normal production, with a yield of 1.9 to 6.8 kg per tomato plant depending on the growing season and the growing conditions (Mutwiwa 2007). It is important to understand that the PRDI method did not induce water deficit in the plant since one half of the crop root system is sufficient to maintain a favorable water status throughout the aerial parts of the plant (Loveys et al. 2001 and Stamp, 2003).

In the present work, sodium chloride was added to the irrigation water to use it as a tracer salt (Chapter 6.2.5). Salt concentrations at the end of the experiments result in that the tracer salt was affected the treatments since sodium chloride influence the soil salinity and the tomato plants are sensitive to moderate levels of salt in the soil. The results of the preliminary experiments in the present work show that the tomato yield are affected by the tracer salt since the tomato yield were small compared to the results of literature and commercials production of tomato. Therefore the concentration of sodium chloride was reduced from 100 mmol L^{-1} in the preliminary experiment to 50 mmol L^{-1} in the pot and open-soil experiments. Reducing the sodium chloride concentration affected the results of tomato yield since the yield of tomato during the pot and open-soil experiments are higher than the results of the preliminary experiment and are in agreement with the results of literature and commercials production of tomato.

6.3.4 Soil salinity movement and distribution

When applying a new irrigation method, it is not enough to evaluate only the crop production. It is very important to evaluate the soil salinity movement under the respective irrigation method. It has to be mentioned that the soil salinity is affected by several factors: soil texture, climatic conditions, irrigation methods, quality of irrigation water, and amount of irrigation water applied. The main factors causing high soil salinity levels are: high irrigation water salinity, uneven water distribution, presence of soil salts, and salinization of the rootzone by ground water tables. The main effects of high soil salinity are (1) the increase of the osmotic pressure which results in a reduced water availability for plants and reduced plant growth, (2) specific toxicity, because some elements or ions, especially sodium, chloride and boron may be toxic to crops, (3) change the physicomechanical properties of the soil, and thus limit water, air, and root movement in the soil (Keren, 1985 and Pearson, 2011). Soil salinity is affected by irrigation water and climatic conditions, where the soil salts' movement is related to the soil water moving. During irrigation, the salts relocate to deeper soil layers as a result of a leaching process. Opposite to this, salts move to the top soil layer with evapotranspiration.

Table 6.3 compares the results of the soil salinity under different experimental conditions with the two publications available.

Table 6. 3: Comparison of the results of soil salinity during different experiments under PRDI method

	[(PRDI/CI)-1]*100 [%]			
	Soil salinity 0-30 cm soil depth based on mg/100g dry soil		Soil salinity 30-60 cm soil depth based on mg/100g dry soil	
	Water application level			
	65	50	65	50
Pot results (Na)	-33.3 S	-18.7 S	-25.0 NS	+85.7 S
Pot results (Cl)	-9.1 NS	-29.8 S	+22.1 NS	+38.7 NS
Open-soil (Na)	-20.1 S	………	-44.4 NS	………
Open-soil (Cl)	-2.6 NS	………	-11.1 NS	………
Simulation (Na)	-22.9	………	-20.0	………
Simulation (Cl)	-21.7	………	-18.3	………
Kaman et al. (2006)	+30	………	NS	………
Kaman et al. (2006 & 2008)	+ 35	………	NS	………

Kaman et al. (2006) and Richards (2011) reported that salt accumulation measured by electrical conductivity (EC) under full conventional irrigation (CI) was proportionally lower in the surface soil layers within 30 cm of depth compared to the PRDI method. There was essentially no difference in the soil layers below 40 cm of soil depth (Kaman et al. 2006 and 2008), but they did not apply the same amount of irrigation water for either the PRDI or CI methods. On the contrary the present work showed that the salt accumulation under the PRDI treatment was lower in the top surface soil layers within 40 cm depth than in the CI treatment (see Table 6.3). This can be explained by the way the PRDI leached the salts if the same amount of water was used in the CI and PRDI. The depth of the reduction of the soil salinity changed according to the water applied. The reduction under highly applied water was higher than under low applied water (deficit water). These results confirm that the depth of reduction of soil salinity depends on the water application levels (Keren 1985; Pearson 2011).

When the same amount of irrigation water was applied in both irrigation methods (CI and PRDI), the irrigated area in the PRDI method was half of that in the CI method. Therefore, the amount of evaporated water was reduced by PRDI and the soil salt in the irrigated area of the PRDI was moved downwards (more than in the CI) because proportionally higher leaching occurred (Kaman et al. 2008). Applying the PRDI method in this case increased the leaching fraction which was sufficient to control the soil salinity and move it to deeper soil layers.

If the PRDI and CI were applied without water stress, the movements of the salts are equal in both cases because the irrigation water is sufficient to move the salts. But when applying the PRDI and CI under water stress, the movement of the salts is higher in the PRDI method than in the CI method because the applied water in the PRDI method is sufficient to move the salts to the bottom soil layers than within the CI method. The movement of chloride is affected more by irrigation water than the movement of soil sodium (White and Broadley 2001). The results of the PRDI investigations indicate that the soil sodium and chloride accumulation under a high level of water application is proportionally lower than under a low level of water application.

Therefore, under limited water availability the PRDI method is the practical way to reduce the soil salinity in the rootzone of growing plants, where the evapotranspiration rate in the CI treatment moved the soil salts to the upper soil layers. Changing the irrigation levels result in different irrigation frequencies. In general, the irrigation frequency under a high level of water application is higher than under a low level of water application. High irrigation frequencies increases the soil salinity in the top soil layers more than in bottom soil layers due to a higher salinity of the upper layer under smaller irrigation pulses (Meiri et al. 1999). So the best way to reduce the salinity level in the top layer is to apply PRDI with a low time shifting (see also the results of the simulation).

Munns and Tester (2008) mentioned that plants differ greatly in their tolerance of salinity, as reflected in their different growth responses. Tomato is sensitive to moderate levels of salt in the soil. Applying moderate salinity during fruit development of plant can change the rate of photosynthate and improve soluble solids in tomato (Shannon and Francois, 1978; Cornish, 1992; Shannon and Grieve, 1999); and any small yield decrease due to salinity might be partially offset by the higher marketable quality of the fruit. The results of the soil salinity of the present study show that the levels of soil salinity are not high at the end of the experiments. Therefore there is no negative effect of soil salinity on tomato growth and production. These results indicate that the differences between treatments due to the irrigation strategies (PRDI and CI).

6.3.5 Long-term use of the PRDI and soil salinity

In the present work, the results show only the effects of one season of the PRDI on soil salinity movements and accumulation. Moreover the effects of long-term of the PRDI on soil salinity movements and accumulation are unknown. The long-term effects are related to some different factors, for examples, climatic conditions, soil type, irrigation water quantities and quality, the time between the irrigations, and shifting time of irrigated side, etc. Changing the climatic conditions to arid or semi-arid situations with long-term application, increase the rate of evapotranspiration, therefore increase the salts accumulation in the top soil layers. Also, using different irrigation water quality influences the salts movement and accumulation on soil layers under long-term of the PRDI. Up to date, there is no information available about the effects of long-term of the PRDI method on soil salinity movements. Therefore, more studies of the PRDI with long-term applications are very necessary.

6.4 Simulation of soil salinity

6.4.1 Evaluation of the simulation model

The LEACHC model has not been used to simulate the soil salinity under PRDI method up to date. Therefore, it is important to evaluate and validate the LEACHC model under CI and PRDI conditions using the data of the open-soil experiment (natural growth). The comparison shows significant differences between simulated and measured values. To explain this, one has to consider that the LEACHC model is based on a tow-dimensional water movement (Hutson and Wagenet 1992; Ali et al. 2000a&b) whereas water and salt in reality moves in two and three-dimensional ways. The two-dimensional water movement occurs within the soil when only a part of the soil surface is wetted (e.g. furrow and surface drip irrigation). Similarly, three-dimensional water and salt movement occur when water is added only at some points below the soil surface according to Raine et al. (2007). Beside the problem of dimensionality, there is also a problem in comparable the plant growth in reality into the simulation. The crop growing factor changes according to the plant's growing stage. The simulation in the LEACHC model, however, is based on a constant value during the whole simulation time. Also, the crop factor in the simulation is not affected by water deficit or water shifting time.

Ali et al. (2000a) used the LEACHC model to simulate the soil sodium and chloride concentration in the soil. They stated that the LEACHC model performed reasonably well in simulating solute transport above a saline water table. Less reactive ions (soil sodium and soil chloride) were predicted well while calcium concentrations were under-predicted. When comparing the PRDI in the present investigation to the simulation, an agreement was obtained for using the LEACHC model, because the measured soil sodium values are close to the simulated values, but some variations do occur. The simulated soil salinity (sodium and chloride) concentration under the CI did not correspond well the measured soil sodium concentration. This agrees with the results reported by Ali et al. (2000a). The calculated differences between the measured and the simulated values of the soil sodium concentration show that they are higher in the top soil layer within the top 10 cm of soil depth. This could be ascribed to the accuracy of the LEACHC model as well as the method of calculating the evapotranspiration. Additionally, the horizontal differentiations for simulation are not included into the simulation model.

6.4.2 Transferring the simulation to arid situations (Egypt)

One has to consider that the experiments performed in this study were carried out under artificial conditions. The real conditions are often different from experimental setups. Changing the climate for example, influence the rate of evapotranspiration which could lead to an accumulation of salts in the soil profile. Therefore, it is very important to test the obtained results of the PRDI method under realistic arid conditions. The results of the simulation under Egyptian preconditions demonstrated that the soil sodium concentration under PRDI is lower than under CI in the top soil layers within the first 30 cm of the soil profile. These results confirm that it is possible to use the PRDI method in Egypt for the reduction of the soil salinity in the top soil layers. This, of course depends on the amount of irrigation water (Meiri et al. 1999). Both the simulation results and the experimental results in pot and open-soil experiments suggested a possible reduction. The yield and crops qualifying under Egyptian conditions were not simulated. Therefore, no information can be given on the effects of PRDI on yield and biomass in Egypt; but all the results indicate that there are no negative effects. Nevertheless, the simulation produces the same trends so one can use the simulation to transfer the measured results to new conditions. One has to mention that the results of simulation are only for one season. However the results of one year give no information about the effects of different years (long-term use of the PRDI), since the results of long-term use of the PRDI could be differing than these results.

7 Conclusions and Outlook

The conclusions of the present work using PRDI in tomato plant cultivation with drip irrigation are:

- PRDI reduces the soil salinity at the top soil layers within the depth of 30 cm without affecting the fruit yield of tomato.
- PRDI increases the percentage of the marketable yield in comparison to the CI.
- PRDI improves the irrigation water use efficiency (IWUE) when applying it under deficit water.
- Under arid and semi-arid natural conditions (Egypt as example), the PRDI can be used to reduce the soil salinity in the top soil layers.

From the present study, the following topics are suggested for future research:

- Field studies of the PRDI under arid and semi-arid situations. In order to investigate the time between irrigation and the sufficient period to shift the irrigated side of the PRDI to the other side.
- Field studies of the PRDI under different soil types and different soil salinity. In order to investigate the most important factors affecting on the PRDI strategy.
- More research are required to study the effects of PRDI on Abscisic Acid (ABA) hormone and the mechanism of its working to avoid the effect of deficit water on plant growth.
- Economic evaluation of applying the PRDI method, because it is one of the most important factors affecting the evaluation of PRDI method in comparison with CI method. It has to consider that more labors are needed to apply the PRDI method when manually controlled as in furrow irrigation; but more instruments and equipments are needed to apply it when automatic controlled as in drip irrigation. Therefore, the costs of applying the PRDI method should be taken into consideration.

- Improving the application of PRDI method to transfer it to the practical and commercial production of crops. In order to evaluate it with long-scale and long-term production and to study the effect of the PRDI with long-term on salts movements and accumulation in the soil profile

8 Summary

Water supplies are limited worldwide since water use has been growing at more than twice the rate of population increase in the last century, and the numbers of regions that are chronically short on water are increasing. Therefore the problems of water scarcity are mostly acute and there is an urgent need to identify and improve effective irrigation management method under the condition of water scarcity. Partial rootzone drying irrigation (PRDI) is a potential water-saving irrigation method. Using special irrigation methods which save water usually lead to soil salinity problems. Several factors influence the soil salinity levels of irrigated land. Some of the factors are the irrigation method and the intensive use of water combined with high evaporation rates.

The main goal of this research was to investigate the partial rootzone drying irrigation (PRDI) and compare to the conventional irrigation (CI) when applying the same amount of water in both irrigation methods. The influence of PRDI on soil salinity movement and distribution were also investigated.

The experiments were performed in big pots as well as in the open-soil of a greenhouse. The PRDI method was investigated under different irrigation water levels by splitting the root system. Sodium chloride was added to the irrigation water as a tracer salt. The soil moisture distribution, tomato yield, biomass, and soil salinity were measured. Moreover, the soil salinity (soil sodium and soil chloride) was simulated under different conditions to compare it to measured results of soil salinity.

The results of the pot experiments showed that the soil sodium concentration under PRDI method was lower in the top surface soil layers up to 40 cm depth in comparison to the CI method. There was essentially no difference within the irrigation methods in soil layers below 40 cm depth (within the measured soil profile). The concentration of chloride in the soil under the PRDI method was also lower in the top surface soil layers up to 40 cm depth than under CI

treatment. The distribution of chloride in soil profile corresponded to the soil sodium concentration.

The results of the open-soil experiment showed that the soil sodium concentration in the upper soil layers (within the first 30 cm of the soil profile) was lower in the PRDI method than in the CI method. There was no significant difference between irrigation methods (PRDI and CI) in soil layers below 30 cm of the soil profile. The soil chloride in the soil profile indicated that there was no significant difference between irrigation methods (PRDI and CI) within soil layers of soil profile.

The simulated soil salinity showed that the sodium concentrations in the soil were lower under the PRDI method than in the CI method within the simulated soil profile (the top 60 cm of soil profile). Similar results were found for the concentration of chloride in the soil. The simulated soil salinity under Egyptian conditions demonstrated that the sodium concentration under PRDI method was lower than in the CI method in the upper soil layers (within 30 cm of soil profile). The simulation results of the open-soil and in the arid situations confirmed that using the PRDI method reduced the soil salinity within the top soil layers.

In general, using the PRDI method reduced the soil salinity in the top soil layers in comparison to the CI method without affecting the yield. Also, the PRDI improved the irrigation water use efficiency (IWUE) and increased the percentage of marketable yield compared to the CI methods, when applying it under deficit water. Simulation results of soil salinity under arid and semi-arid situations (Egypt as an example) confirmed that the PRDI reduced the soil salinity in the top soil layers as confirmed by the present measured results and can be used to reduce the soil salinity in arid and semi-arid conditions.

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10 Appendix

Table A. 1: Number of irrigations and the irrigation water composition of the open-soil experiment

Date	Irrigation [mm]				Ion concentration [mmol L^{-1}]					
	CI		PRDI							
	left side	right side	left side	right side	Ca	Mg	Na	K	Cl	SO4
06/05/09	5.9	5.9	5.9	5.9	2.12	0.17	26.30	0.085	26.37	1.24
10/05/09	2.9	2.9	2.9	2.9	2.12	0.17	26.30	0.085	26.37	1.24
12/05/09	2.9	2.9	2.9	2.9	2.12	0.17	26.30	0.085	26.37	1.24
15/05/09	2.9	2.9	2.9	2.9	2.12	0.17	26.30	0.085	26.37	1.24
19/05/09	2.9	2.9	2.9	2.9	2.12	0.17	26.30	0.085	26.37	1.24
23/05/09	5.9	5.9	5.9	5.9	2.12	0.17	26.30	0.085	26.37	1.24
26/05/09	5.9	5.9	5.9	5.9	2.12	0.17	26.30	0.085	26.37	1.24
29/05/09	5.9	5.9	5.9	5.9	2.12	0.17	26.30	0.085	26.37	1.24
01/06/09	11.7	11.7	11.7	11.7	2.12	0.17	26.30	0.085	26.37	1.24
06/06/09	8.8	8.8	8.8	8.8	2.12	0.17	26.30	0.085	26.37	1.24
11/06/09	8.8	8.8	17.6	----	2.12	0.17	26.30	0.085	26.37	1.24
18/06/09	8.8	8.8	17.6	----	2.12	0.17	26.30	0.085	26.37	1.24
24/06/09	8.8	8.8	17.6	----	2.12	0.17	26.30	0.085	26.37	1.24
29/06/09	8.8	8.8	17.6	----	2.12	0.17	26.30	0.085	26.37	1.24
03/07/09	8.8	8.8	----	17.6	2.12	0.17	26.30	0.085	26.37	1.24
07/07/09	8.8	8.8	----	17.6	2.12	0.17	26.30	0.085	26.37	1.24
10/07/09	8.8	8.8	----	17.6	2.12	0.17	26.30	0.085	26.37	1.24
16/07/09	8.8	8.8	----	17.6	2.12	0.17	26.30	0.085	26.37	1.24
23/07/09	8.8	8.8	----	17.6	2.12	0.17	26.30	0.085	26.37	1.24
28/07/09	8.8	8.8	----	17.6	2.12	0.17	26.30	0.085	26.37	1.24
03/08/09	8.8	8.8	17.6	----	2.12	0.17	26.30	0.085	26.37	1.24
07/08/09	8.8	8.8	17.6	----	2.12	0.17	26.30	0.085	26.37	1.24
13/08/09	8.8	8.8	17.6	----	2.12	0.17	26.30	0.085	26.37	1.24
20/08/09	8.8	8.8	17.6	----	2.12	0.17	26.30	0.085	26.37	1.24
03/09/09	8.8	8.8	17.6	----	2.12	0.17	26.30	0.085	26.37	1.24
18/09/09	8.8	8.8	----	17.6	2.12	0.17	26.30	0.085	26.37	1.24

Table A. 2: Number of irrigations and the irrigation water composition of the Egypt simulation (the irrigated side of the PRDI was shifted every 15 days)

Date	Irrigation [mm]				Ion concentration [mmol L^{-1}]					
	CI		PRDI							
	left side	left side	left side	left side	Ca	Mg	Na	K	Cl	SO4
01/05/09	16.6	16.6	16.6	16.6	6.00	4.2	31.55	0.17	20.72	10.70
06/05/09	16.6	16.6	16.6	16.6	6.00	4.2	31.55	0.17	20.72	10.70
11/05/09	16.6	16.6	16.6	16.6	6.00	4.2	31.55	0.17	20.72	10.70
16/05/09	16.6	16.6	16.6	16.6	6.00	4.2	31.55	0.17	20.72	10.70
21/05/09	16.6	16.6	16.6	16.6	6.00	4.2	31.55	0.17	20.72	10.70
26/05/09	16.6	16.6	16.6	16.6	6.00	4.2	31.55	0.17	20.72	10.70
01/06/09	16.6	16.6	33.2	----	6.00	4.2	31.55	0.17	20.72	10.70
06/06/09	16.6	16.6	33.2	----	6.00	4.2	31.55	0.17	20.72	10.70
11/06/09	16.6	16.6	33.2	----	6.00	4.2	31.55	0.17	20.72	10.70
16/06/09	16.6	16.6	----	33.2	6.00	4.2	31.55	0.17	20.72	10.70
21/06/09	16.6	16.6	----	33.2	6.00	4.2	31.55	0.17	20.72	10.70
26/06/09	16.6	16.6	----	33.2	6.00	4.2	31.55	0.17	20.72	10.70
01/07/09	16.6	16.6	33.2	----	6.00	4.2	31.55	0.17	20.72	10.70
06/07/09	16.6	16.6	33.2	----	6.00	4.2	31.55	0.17	20.72	10.70
11/07/09	16.6	16.6	33.2	----	6.00	4.2	31.55	0.17	20.72	10.70
16/07/09	16.6	16.6	----	33.2	6.00	4.2	31.55	0.17	20.72	10.70
21/07/09	16.6	16.6	----	33.2	6.00	4.2	31.55	0.17	20.72	10.70
26/07/09	16.6	16.6	----	33.2	6.00	4.2	31.55	0.17	20.72	10.70
01/08/09	16.6	16.6	33.2	----	6.00	4.2	31.55	0.17	20.72	10.70
06/08/09	16.6	16.6	33.2	----	6.00	4.2	31.55	0.17	20.72	10.70
11/08/09	16.6	16.6	33.2	----	6.00	4.2	31.55	0.17	20.72	10.70
16/08/09	16.6	16.6	----	33.2	6.00	4.2	31.55	0.17	20.72	10.70
21/08/09	16.6	16.6	----	33.2	6.00	4.2	31.55	0.17	20.72	10.70
26/08/09	16.6	16.6	----	33.2	6.00	4.2	31.55	0.17	20.72	10.70
01/09/09	16.6	16.6	33.2	----	6.00	4.2	31.55	0.17	20.72	10.70
06/09/09	16.6	16.6	33.2	----	6.00	4.2	31.55	0.17	20.72	10.70

11/09/09	16.6	16.6	33.2	----	6.00	4.2	31.55	0.17	20.72	10.70
16/09/09	16.6	16.6	----	33.2	6.00	4.2	31.55	0.17	20.72	10.70
21/09/09	16.6	16.6	----	33.2	6.00	4.2	31.55	0.17	20.72	10.70
26/09/09	16.6	16.6	----	33.2	6.00	4.2	31.55	0.17	20.72	10.70
01/10/09	16.6	16.6	33.2	----	6.00	4.2	31.55	0.17	20.72	10.70
06/10/09	16.6	16.6	33.2	----	6.00	4.2	31.55	0.17	20.72	10.70
11/10/09	16.6	16.6	33.2	----	6.00	4.2	31.55	0.17	20.72	10.70
16/10/09	16.6	16.6	----	33.2	6.00	4.2	31.55	0.17	20.72	10.70
21/10/09	16.6	16.6	----	33.2	6.00	4.2	31.55	0.17	20.72	10.70
26/10/09	16.6	16.6	----	33.2	6.00	4.2	31.55	0.17	20.72	10.70

Table A. 3: Average results of weekly evapotranspiration, air temperature, maximum temperature, minimum temperature, and amplitude during the open-soil experiment

Date	Week no.	Weekly ET_o [mm]	T_a [°C]	T_{Max} [°C]	T_{Min} [°C]	Amplitude [°C]
17/06/09	1	31.8	18.3	25.3	13.7	11.6
24/06/09	2	32.7	19.7	27.6	13.9	13.7
01/07/09	3	36.9	23.2	34.0	16.3	17.7
08/07/09	4	37.4	24.0	33.9	16.6	17.3
15/07/09	5	34.1	20.0	27.8	14.1	13.8
22/07/09	6	34.6	21.5	30.4	13.3	17.1
29/07/09	7	33.8	21.5	32.5	14.4	18.1
05/08/09	8	33.4	22.3	32.9	14.5	18.4
12/08/09	9	33.6	23.3	32.8	16.9	16.0
19/08/09	10	31.3	22.4	33.4	14.2	19.2
26/08/09	11	30.8	23.1	33.8	15.2	18.6
02/09/09	12	28.3	20.8	31.3	13.8	17.5
09/09/09	13	26.5	18.8	28.4	13.6	14.8
16/09/09	14	24.8	17.4	25.4	13.5	11.9
23/09/09	15	24.8	18.5	28.1	13.6	14.4
30/09/09	16	22.7	16.9	24.0	13.4	10.6
06/10/09	17	21.6	15.8	22.9	13.2	9.6

Table A. 4: Collected data of weekly evapotranspiration, air temperature, maximum temperature, minimum temperature, and amplitude during the simulation time of the Egypt conditions

Date	Weekly ET_O [mm]	T_a [°C]	T_{max} [°C]	T_{min} [°C]	Amplitude [°C]
07/05/09	109.6	23.6	30.6	16.9	13.7
14/05/09	123.9	24.1	31.1	17.1	14.0
21/05/09	136.1	25.4	32.0	18.0	14.0
28/05/09	137.0	26.0	32.6	18.7	13.9
04/06/09	142.2	26.9	33.0	19.4	13.6
11/06/09	141.3	27.0	33.3	20.7	12.6
18/06/09	145.9	28.0	34.0	21.0	13.0
25/06/09	144.2	28.0	34.0	21.7	12.3
02/07/09	143.3	28.0	34.0	22.0	12.0
09/07/09	143.0	28.0	34.0	22.0	12.0
16/07/09	141.7	28.0	34.0	22.0	12.0
23/07/09	140.7	28.0	34.0	22.0	12.0
30/07/09	141.0	28.0	34.0	22.0	12.0
06/08/09	138.9	28.0	33.3	22.0	11.3
13/08/09	135.5	28.0	33.0	22.0	11.0
20/08/09	132.3	28.0	33.0	22.0	11.0
27/08/09	126.9	28.0	33.0	22.0	11.0
03/09/09	123.6	27.0	33.0	22.0	11.0
10/09/09	121.1	27.0	33.0	21.0	12.0
17/09/09	116.5	27.0	32.0	21.0	11.0
24/09/09	112.3	26.4	32.0	20.4	11.6
01/10/09	107.2	26.0	31.6	19.6	12.0
08/10/09	101.5	25.3	31.0	19.0	12.0
15/10/09	91.7	24.0	29.9	18.6	11.3
22/10/09	84.2	23.4	28.9	18.0	10.9
29/10/09	79.3	22.6	27.9	17.3	10.6

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Prophet Mohammad (Prayers and peace be upon the Messenger of ALLAH)

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