IRRIGATION SCHEDULING OF TOMATOES (*Lycopersicon esculentum* Mill.) AND CUCUMBERS (*Cucumis sativus* L.) GROWN HYDROPONICALLY IN COIR

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Abstract

The use of capacitance water sensors for the scheduling of irrigation for hydroponic tomato and cucumber crops grown in coir was investigated in a series of laboratory and glasshouse experiments in the Free State province of South Africa.

Laboratory experiments in a climate controlled chamber were conducted to accurately calibrate ECH_2O capacitance sensors, models EC-10 and EC-20, in coir with an improved calibration procedure. Water content predictions by the coir-specific calibration and manufacturer's calibration equations were compared to actual water content measured from mass loss of the coir sample. The manufacturer's calibration equation indicated a poor accuracy of prediction, which mostly underestimated the volumetric water content, compared to the near perfect prediction of the coir-specific calibration of individual sensors. A rapid calibration procedure for EC-10 and EC-20 sensors was proposed to reduce the calibration time of the sensors and promote their commercial use for irrigation management in coir. The accuracy of prediction by the rapid calibration procedure for the plant available water content range was high for both EC-10 and EC-20 sensors and allowed for the compensation for variation between sensors.

Glasshouse studies aimed to characterise the water retention and ability of coir to supply water to greenhouse tomato and cucumber crops through the continuous monitoring of medium water content in small and large growing bags with the EC-10 and EC-20 capacitance sensors during a drying cycle, compared to well-watered plants. Stages of crop water stress were identified and, based only on the plant's response to the drying cycle, it was suggested that water depletion can be allowed to the point of mild water stress for both greenhouse tomato and cucumber crops, which can be detected by soil water sensors. In a second series of glasshouse experiments, the identified stages of crop water stress were used to determine and apply depletion levels in coir and compare this irrigation strategy to a well-watered treatment for greenhouse cucumber and tomato plants, with regard to the water balance components, yield and water use efficiency for different bag sizes. Results indicated that irrigation was successfully managed to the pre-determined water depletion levels for cucumber and tomato plants in coir, through the use of in situ calibrated capacitance sensors. For both crops the depletion of water varied between bag sizes, indicating that various bag sizes require different irrigation management strategies. Scheduling to the highest pre-determined depletion levels reduced irrigation by 124 L m^{-2} in the small and 240 L m^{-2} in the large bags for cucumbers and 427 L m^{-2} in the small and 487 L m^{-2} in the large bags for tomato plants, compared to the well-watered treatments. Yields achieved by the greenhouse tomato plants in the large growing bags and cucumber plants in the small and large bags were maintained or improved when scheduled to the highest depletion level (approximately 60% available water content) compared to the well-watered treatment. The combination of reduced irrigation and improved or maintained yields resulted in improved water use efficiencies (based on irrigation and transpiration) for the highest depletion level compared to the well-watered treatments. In all glasshouse experiments the well-watered treatment resulted in luxury water use by the plants.

Finally, a study was conducted in order to compare crop water stress of greenhouse cucumber and tomato plants under luxury water supply and cyclic water deficit conditions. The comparison was based on the transpiration ratio and yield, while the use of capacitance sensors was evaluated for irrigation scheduling in coir for both crops. Transpiration data indicated that cucumber and tomato plants subjected to luxury water supply experience water stress earlier than plants subjected to cyclic water deficit conditions, irrespective of bag size. Results also indicated that irrigation scheduling according to water depletion levels in small bags is not yet recommended for greenhouse tomato and cucumber plants grown in coir, until further research is conducted. Scheduling to water depletion levels in large bags is, however, justified by the improved or maintained yields of the greenhouse cucumber and tomato plants. The estimated depletion levels for large bags beyond which yield are reduced was at 85% for tomatoes and 70% for cucumbers.

In conclusion, the results clearly indicated that the use of capacitance sensors in large growing bags improves irrigation management of hydroponic cucumbers and tomatoes in coir by eliminating over-irrigation and improving water use efficiency. More research is needed before a conclusion can be made regarding irrigation scheduling with capacitance sensors in small growing bags.

Uittreksel

Die gebruik van kapasitansie water sensors vir besproeiingskedulering van tamatie en komkommer plante wat hidroponies in kokosveen gegroei is, is ondersoek in ‘n reeks laboratorium en glashuis eksperimente in die Vrystaat provinsie van Suid Afrika.

Laboratorium eksperimente is uitgevoer in ‘n klimaat beheerde kas om ECH$_2$O kapasitansie sensors, modelle EC-10 en EC-20, akkuraat te kalibreer vir kokosveen deur ’n verbeterde kalibrasie prosedure. Waterinhoud voorspellings deur die kokosveen spesifieke kalibrasie en die vervaardiger se kalibrasie vergelykings is vergelyk met die werklike waterinhoud wat gemeet is deur die kokosveen monster se massaverlies te monitor. Akkuraatheid van voorspelling deur die vervaardiger se kalibrasie vergelykings was swak en het meestal die volumetriese waterinhoud onderskat in vergelyking met die byna perfekte voorspelling deur die kokosveen spesifieke kalibrasie van individuele sensors. ’n Vinnige kalibrasie prosedure vir die EC-10 en EC-20 sensors is voorgestel om die kalibrasie tyd te verkort en die kommersiële gebruik van die sensors vir besproeiingsbestuur in kokosveen aan te moedig. Die akkuraatheid van voorspelling deur die vinnige kalibrasie prosedure, binne die grense van plant beskikbare waterinhoud, was hoog vir beide EC-10 en EC-20 sensors, terwyl die prosedure ook voorsiening maak vir variasie tussen sensors.

Glashuis studies is uitgevoer om die water retensie en vermoë van kokosveen om water te voorsien aan tamatie en komkommer gewasse in kweekhuise, te karakteriseer. Dit is bereik deur die mediumwaterinhoud van klein en groot plantsakke deurlopend te monitor met behulp van die EC-10 en EC-20 kapasitansie sensors gedurende ’n uitdroging siklus, en dit te vergelyk met ’n waterryke behandeling vir elke gewas waarvolgens die plante agt keer per dag besproei is. Fases van gewas waterstremming is geïdentifiseer en, volgens die reaksie van die plant tot die drogingsiklus, is dit voorgestel dat wateronttrekking toegelaat kan word tot die punt van matige waterstremming wat aangewys kan word deur kapasitansie water sensors vir beide kweekhuis tamatie en komkommer gewasse. In ’n tweede reeks glashuis eksperimente is die geïdentifiseerde fases van gewas waterstremming gebruik om onttrekkingsvlakke vir kokosveen te bepaal en toe te pas as besproeiingskeduleringstrategie vir kweekhuis komkommer en tamatie plante. Toegepaste vlakke is vir elke gewas vergelyk met ’n waterryke behandeling ten opsigte van die waterbalans komponente, opbrengs en watergebruiksdoeltreffendheid in verskillede sakgroottes. Resultate het aangedui dat besproeiing suksesvol bestuur is tot die voorafbepaalde wateronttrekkingsvlakke vir komkommer en tamatie plante in kokosveen, deur gebruik te maak van in situ gekalibreerde kapasitansie sensors. Die onttrekking van water deur beide gewasse het verskil tussen klein en groot sakke, wat aangedui het dat verskillende sakgroottes verskillende besproeiingsbestuur strategieë vereis. Skedulering tot die hoogste voorafbepaalde onttrekkingsvlak het, in vergelyking met die waterryke behandelings, besproeiing verminder met 124 L m^{-2} in die klein en 240 L m^{-2} in die groot sakke vir komkommers, en 427 L m^{-2} in die klein en 487 L m^{-2} in die groot sakke vir tamatie plante. Opbrengste van kweekhuis tamatie plante in die groot plantsakke en komkommer plante in die klein en groot sakke is gehandhaaf of verbeter deur skedulering tot die hoogste onttrekkingsvlak (ongeveer 60% van beskikbare water inhoud), in vergelyking met die waterryke behandeling. Die kombinasie van verminderde besproeiing en verbeterde of gehandhaafde opbrengste het gelei tot verbeterde watergebruiksdoeltreffendheid (besproeiing en transpirasie) vir die hoogste onttrekkingsvlak, in vergelyking met die waterryke behandelings. In al die glashuis eksperimente het die waterryke behandeling gelei tot oorvloedige watergebruik deur plante.

’n Finale studie is uitgevoer om gewas waterstremming van kweekhuis komkommer en tamatie plante wat onderwerp is aan oorvloedige watervoorsiening deur agt keer per dag te besproei en sikliese watertekorttoestande, te vergelyk. Die vergelyking is gebaseer op die transpirasie verhouding en opbrengs, terwyl die gebruik van kapasitansie sensors vir besproeiingskedulering in kokosveen vir beide gewasse geëvalueer is. Transpirasie data het aangedui dat komkommer en tamatie plante wat onderwerp is aan oorvloedige watervoorsiening vroeër waterstremming ervaar as plante wat onderwerp is aan sikliese watertekorttoestande, ongeag van die sakgrootte. Resultate het aangedui dat besproeiingskedulering volgens wateronttrekkingsvlakke vir klein sakke nog nie aanbeveel kan word vir kweekhuis tamatie en komkommer plante alvorens verdere navorsing gedoen is nie. Skedulering tot wateronttrekkingsvlakke vir groot sakke word egter geregverdig deur die verbeterde of gehandhaafde opbrengste van kweekhuis komkommers en tamaties. Die beraamde laagste onttrekkingsvlakke vir groot sakke wat nie opbrengs betekenisvol sal beïnvloed nie is 85% vir tamaties en 70% vir komkommers.

Ten slotte dui die resultate duidelik daarop dat die gebruik van kapasitansie sensors in groot plantsakke besproeiingsbestuur van hidroponiese komkommers en tamaties in kokosveen verbeter deur oorbesproeiing uit te skakel en die watergebruiksdoeltreffendheid te verbeter. Meer navorsing is nodig alvorens ’n gevolgtrekking gemaak kan word ten opsigte van besproeiingskedulering met kapasitansie sensors in klein plantsakke.

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Notification

- All outcomes of the study are written as stand-alone publications. Therefore, i) a general literature review is not included since each publication contains its own specialized literature review, and ii) some repetition may occur between publications.

- Although publications were submitted or are to be submitted to different international and local journals, all publications are prepared according to the prescriptions of the South African Journal of Plant and Soil for the purpose of this thesis.

- No comments were received from Journal reviewers at the time that the thesis was handed in for examination and therefore no alterations will be done on any of the publications for the purpose of the thesis.

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Chapter 1

Introduction

1.1 Motivation and problem identification

Water is the most important factor limiting yield in agriculture worldwide. South Africa is mostly a semi-arid country with an average rainfall of only 452 mm per annum (Department of Water Affairs and Forestry, 2004), while rainfall is highly seasonal and varies erratically from year to year resulting in unpredictable periods of drought and flood (Davies & Day, 1998). These conditions make year-round production of crops under dryland conditions, in most production areas, impossible.

Although irrigated land accounts for only about 1% (1.3 million hectares) of the total land area of South Africa (Department of Agriculture, 2006), it uses almost 60% of all water used in South Africa (Department of Water Affairs and Forestry, 2004). In spite of the important economic role of agriculture in South Africa, it can be safely assumed that the availability of water for agriculture will decrease because of an increase in demand for water for urban, household and industrial uses (Department of Water Affairs and Forestry, 2004). As water for agriculture become scarcer, the cost of water will increase, adding further pressure on irrigated agricultural. This basically implies that yield per area of land needs to be increased, while less water is used.

The crop water use efficiency and irrigation efficiency of hydroponic crops, both measured as marketable yield per unit of water used, are appreciably higher than that of open field crops. This is because crop water requirements are considerably less in greenhouses than in open fields when aiming for similar levels of production and is a consequence of the much lower evapotranspiration inside greenhouses because of less wind, reduced solar radiation and higher atmospheric humidity (Fernández *et al.*, 2005), while greater protection from temperature fluctuation, wind damage or insect damage improves marketable yield.

At present water use in hydroponic systems in South Africa is not optimal. The main hydroponic growth medium used in South African greenhouses is un-composted pine sawdust and shavings from the wood industry. This growth medium is characterised by a very low water holding capacity and easily available water (Bohne, 2004; Kang *et al.*, 2004), which increases the risk of water stress during active plant growth (Allaire *et al.*, 2004). Because of these characteristics the growth medium needs to be irrigated frequently and with low volumes per irrigation event to prevent water stress (Maree, 1986; Bohne, 2004). Therefore, in most commercial hydroponic systems in South Africa, irrigation is set according to a fixed schedule which is usually determined by trial and error over a couple of production seasons. This comprises of a fixed frequency of six to eight or more irrigation events per day depending on the production season and the stage of crop development. Irrigation is adapted weekly according to percentage drainage or electrical conductivity (EC) expressed as the percentage of drainage EC to irrigation EC (Combrink, 2005). Crops are over-irrigated by 20 to 30% for each irrigation event to ensure that plants are not subjected to water stress and to prevent the accumulation of salts in the medium (Fricke, 1998; Schröder & Lieth, 2002; Giuffrida *et al.*, 2003; Combrink, 2005), while special growing bags with elevated drainage holes are used to create a reservoir in the bag where water can be stored between irrigation events (Maree, 1986).

The use of a growth medium with a larger water holding capacity, such as coir, can result in improved water use efficiency since less water is lost through drainage during production (Rincón *et al.*, 2005; Rouphael *et al.*, 2005). A high content of available water and an adequate air supply are the most important physical characteristics required for growth mediums to achieve optimal growth (Raviv *et al.*, 2002).

Coir is increasing in popularity as growth medium for greenhouse crops world wide (Verhagen, 1999; Noguera *et al.*, 2000) and in South Africa (Combrink, 2005). The gain in popularity can be ascribed to positive results achieved by researchers on yield and fruit quality of tomato and cucumber crops grown in coir compared to rockwool (Böhme *et al.*, 2001; Colla *et al.*, 2003; Halmann & Kobryń, 2003). Coir constitutes of waste materials from coconut (*Cocos nucifera* L.) fruit husks after the removal of industrially-valuable long fibres (used for ropes and matting) (Noguera *et al.*, 2000). It is a lightweight material with a bulk density varying between 0.04 and 0.13 kg m^{-3} depending on the ratio of fibres to dust (Evans *et al.*, 1996; Kang *et al.*, 2004). Recently improved product standards guarantees bulk densities between 0.09 and 0.10 kg m^{-3} ($\text{Pelemix}_{\text{Ind.}}$, Israel). According to Prasad (1997), coir has a relatively high easily available water content of approximately 35%.

Coir varies greatly from sawdust and shavings with regard to water availability. The appropriate irrigation strategy for coir will therefore also vary greatly from that used for sawdust and shavings. However, because coir is a relative new growth medium, experimentation with different irrigation management practices are limited and guidelines on the best irrigation management strategy for coir is not yet published or readily available. Therefore, producers manage irrigation in coir according to practices used for other locally used growth mediums, such as sawdust and shavings in South Africa. Hydroponic crops grown in coir are, therefore, mostly over-irrigated which creates water logged conditions and will have a direct effect on water uptake, oxygen availability and the occurrence of soil-borne diseases, while this may indirectly have a negative effect on yield and water-use efficiency (Kramer & Boyer, 1995; Giuffrida *et al.*, 2003). Because producers often do not know the cause of these problems and therefore how to manage them, they may easily refrain from using coir without realising its potential benefits as a growth medium.

Because of the variation in water requirements of different crops, irrigation management also needs to be crop specific. It is therefore important to find a reliable irrigation management method for a targeted level of plant performance of specific crops, which considers water content changes in the coir due to changes in plant-water status (Warren & Bilderback, 2004). Changes in plant water status may result from changes in environmental conditions, the stage of crop development as well as interactions between these conditions (Tekinel & Cevik, 1994). A specific crop's demand for water at any given time under any given circumstances, therefore, determines the frequency (timing) and amount (volume) of irrigation in commercial hydroponic systems.

Considering these gaps in knowledge on coir water retention and -supply to various greenhouse crops, capacitance water sensors were identified to potentially improve the irrigation management strategy for the growth medium. Irrigation scheduling based on continuous soil water monitoring is an increasingly common practice (Suojala-Ahlfors & Salo, 2005; Fares & Polyakov, 2006; Marouelli & Silva, 2007; Thompson *et al.*, 2007a; Papadopoulos *et al.*, 2008) and in South Africa it is used by companies such as Kennedy Irrigation and Griekwaland-Wes Co-operative to manage irrigation in the summer rainfall field crop production areas. It is suggested by Kiehl *et al.* (1992) and Thompson *et al.* (2007b) that soil water sensors potentially provide the means to irrigate in accordance with the unique characteristics of a given crop in a given soil or growth medium.

1.2 Objectives

The main objective of this study was to address over-irrigation and poor irrigation management practices of tomatoes and cucumbers grown hydroponically in coir through the use of capacitance water content sensors, in order to improve water use efficiency in South African greenhouses. To achieve this, the main objective was divided into more specific objectives:

1. To evaluate existing calibration procedures for the ECH_2O capacitance water content sensors (EC-10 & EC-20) and propose and evaluate new calibration procedures for coir for purposes of research and commercial application in greenhouses (Chapter 2).
    i. To propose a laboratory procedure for calibrating ECH_2O capacitance water content sensors (EC-10 & EC-20) in coir and evaluate the manufacturer's calibration equations for use in coir.
    ii. To propose a rapid procedure for calibrating ECH_2O capacitance water content sensors in coir and evaluate the rapid calibration method for use in coir.

2. To characterize plant water stress of greenhouse cucumber (*Cucumis sativus*) and tomato (*Lycopersicon esculentum* Mill.) plants in coir (Chapter 3).
    i. To describe the development of plant water stress and plant reaction during a drying cycle of greenhouse cucumbers and tomatoes grown in coir.
    ii. To identify different stages of plant water stress as well as criteria for the identification of these stages.

3. To determine the efficiency of pre-determined water depletion levels as a method to irrigate greenhouse cucumber and tomato plants in coir (Chapter 4).

   i. To assess the irrigation management options with regard to bag size and target depletion levels in coir.
   ii. To determine the effect of these management options on the water balance components, yield and water use efficiency of greenhouse cucumbers and tomatoes.

4. To compare crop water stress of greenhouse cucumber and tomato plants under luxury water supply and cyclic water deficit conditions (Chapter 5).
   i. To determine whether the water stress criteria developed for greenhouse cucumbers and tomatoes (based on the relationship between the transpiration ratio and available depletion) for conditions of luxury water supply are sound for application in cyclic water deficit conditions.
   ii. To determine the relationship between depletion level of plant available water and yield, as well as to evaluate the use of capacitance soil water sensors for irrigation scheduling.

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Chapter 2

2.1 Laboratory procedure to calibrate EC-10 and EC-20 capacitance sensors in coir

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Most calibration procedures use only a few gravimetric soil samples to calibrate soil water sensors. A laboratory calibration procedure is proposed based on the principle of the continuous measurement of mass loss of a saturated coir sample during a drying cycle, of which the drying period depends on the evaporative demand of the environment as well as the water retention characteristics of the coir. The continuous monitoring of the sample's mass loss indicated a constant decrease in volumetric water content throughout the duration of the experiment. Hourly logging of sensor output (mV) in the coir indicated that the capacitance sensors responded to the decreasing water content of the coir during the drying cycle, although this decrease in sensor output was not constant. However, a perfect fit, indicated by R^2 values greater than 0.99, for sensor response versus volumetric water content was achieved by a 4th degree polynomial curve for all EC-10 and EC-20 sensors. The volumetric water content predicted by the manufacturer's pre-calibrations was compared to that of the coir specific laboratory calibration using various methods for statistical evaluation. The accuracy of the manufacturer's prediction proved to be poor, mostly underestimating volumetric water content by a large margin compared to the near perfect prediction of the coir specific laboratory calibration of individual sensors. The deviation of the prediction of the measured water content of coir using the manufacturer's calibration amounted to between

0.153 to 0.241 m^3 m^{-3} for the EC-10 sensors. The equivalent deviation for the EC-20 sensors was between 0.176 to 0.206 m^3 m^{-3}. Comparing the D-indexes showed that the laboratory calibrations were between 27-42% and 33-43% more accurate than the manufacturer's calibration for the EC-10 and EC-20 sensors, respectively. The higher accuracy of the coir specific calibration was attributed to differences in the water retention characteristics of coir compared to that of the soil used by the manufacturer for the determination of calibration equations.

Keywords: Capacitance sensors, coir, laboratory calibration, water content, water retention

2.1.1 Introduction

World wide, the automation of irrigation in greenhouse crop production largely enhances productivity. It is a well known fact that water losses due to inefficient irrigation management in South African greenhouses amounts to about 10 to 20% of the total water use of crops (Maree, 1992; Combrink, 2005). Water losses can be controlled with the application of recent advances in soil water sensor technology, provided that the instruments are properly calibrated.

Various authors have experimented with different indirect methods to determine the water content of growth mediums. Dielectric sensors (e.g. time domain reflectometry and capacitance sensors), tensiometers and neutron scattering are the most commonly used field methods (Topp & Davis, 1985; Campbell & Mulla, 1990; Ferré & Topp, 2002; Starr & Paltineanu, 2002; Leib *et al*., 2003; Dorais *et al*., 2005; Fares & Polyakov, 2006). Of these, capacitance techniques have become very popular because of their precision, sensitivity, portability, low cost of construction, simplicity, speed of measurements, continuous monitoring, and lack of radiation (Bell *et al*., 1987; Dean *et al*., 1987). A relatively small amount of water can increase the average dielectric constant of a growth medium significantly (Morgan *et al*., 1999).

Several factors affecting the accuracy of sensor readings include calibration, installation, inherent sensor electronics and properties of the growth medium. Paltineanu and Starr (1997) suggested that the most reliable calibration equations come from laboratory calibrations, which can be applied in the field or laboratory. The principles for field and laboratory calibration is similar and comprise of measuring the sensor reading in the field or in a undisturbed soil core or soil packed to original bulk density in the laboratory, and consequently collecting and drying samples taken close to the sensor to attain gravimetric water content. The sample area containing the sensor is wetted, and repacked if applicable, and the procedure repeated at several water contents (approximately five to seven times until saturation is reached) to attain a calibration curve (Dighton & Dillon, unpublished data as cited by Paltineanu & Starr, 1997; Mead, unpublished data as cited by Paltineanu & Starr, 1997; Seyfried & Murdock, 2001; Cobos, 2006). A more accurate calibration procedure was described by Lane and Mackenzie (2001) and comprise of the slow wetting of an intact core, in a cylindrical PVC casing, containing a time domain reflectometry (TDR) sensor, from below to reach saturation after approximately two weeks, whereafter the core assemblies are suspended from a load cell and allowed to dry through evaporation until no detectable change in mass is observed, roughly after 33-41 days. The cores are oven-dried to determine bulk density and the water content calculated independently for each load cell from gravimetric water content to match each TDR measurement. This method produced good linear calibration fits on a 1:1 basis, although the wet and dry ends produced large errors of -8.6% and 17.2%, respectively. These large errors may be explained by the decreasing sensitivity of the dielectric constant to soil water content under dry conditions as observed by Chanzy *et al.* (1998). In experiments of Tomer and Anderson (1995), the dielectric constant only increased from 3.8 to 6.1 as water content increased from 5 to 12%, which explains why it is so difficult to detect small changes in water content with the capacitance probe in dry or coarse textured soils. Errors at the wet end are usually lower than that at the dry end, because of more free water. Potential errors of this laboratory calibration can be ascribed to non-uniform distribution of water within the core after wetting, structural heterogeneities within the core and the effect of water layering in the core (Lane & Mackenzie, 2001).

Because the capacitance sensors measure the dielectric constant of the soil surrounding the sensor, any air gaps or excessive soil compaction around the sensor can profoundly influence the readings (Bell *et al.*, 1987; Decagon Devices, 2006). To install the sensors, a blade is used to make a pilot hole in which the sensor can be inserted. The blade should then be inserted again a few centimetres away from the sensor to gently force the medium towards the sensor to ensure good contact (Decagon Devices, 2006). Large metal objects in the proximity of the sensors can attenuate the sensor's electromagnetic field. This will also affect output readings. Another challenge is the existing bias of sensors toward greater readings in the field due to root mats (Tomer & Anderson, 1995; Wallach & Raviv, 2008). Capacitance sensors monitor a certain volume of soil surrounding the sensor. This is called the sphere of influence, although this region is not spherical or sharply delineated (Dean *et al.*, 1987). As the sphere is small it is important that the medium surrounding the sensor should represent the total root volume. A radial distance of 10 cm for 99% of all capacitance sensors' responses, and an axial sensitivity of about 5 cm, was observed by Kuraž (1982) and Paltineanu and Starr (1997).

Growth mediums differ with regard to their dielectric properties (Baumhardt *et al*., 2000; Seyfried & Murdock, 2001; Fares *et al*., 2007). Any molecule with electric dipoles that respond to the frequency of an electric field can contribute to the dielectric constant (Dean *et al*., 1987). The overall response is a function of the molecular inertia, the binding forces and the frequency of the electric field (Dean *et al*., 1987), although the greatest contribution to the dielectric constant is most likely the free water held in pores by surface tension (Bell *et al*., 1987). The ratio of bound to free water varies between different soil types, soil water contents and soil temperatures (Or & Wraith, 1999), while bound water has a dielectric constant much lower than that of free water (Dobson *et al*., 1985 as cited by Seyfried & Murdock, 2001). The challenge of laboratory calibration is to keep the sample used as close to field conditions as possible. Therefore salinity, bulk density and texture, which may have an effect on the dielectric constant in the soil (Tomer & Anderson, 1995), should be reproduced in the laboratory. Existing calibration equations of manufacturers and other scientists have generally been developed for specific soil textures. For example, because ECH_2O sensors come pre-calibrated for most soil types, excluding extremes such as soils with high sand or salt content (Decagon Devices, 2006), these equations may over- or under estimate the volumetric water content when used in different types of mediums (Morgan *et al*., 1999). Customers are therefore encouraged by the manufacturers to perform medium-specific calibrations. This is especially critical in growth mediums with high proportions of bound to free water, especially at low water contents (Hilhorst *et al*., 2001; Seyfried & Murdock, 2001; Fares & Polyakov, 2006).

An exponential relationship between sensor frequency and soil water content provides the best fit for different soil types (Paltineanu & Starr, 1997; Baumhardt *et al.*, 2000). In contrast, Bell *et al*. (1987) concluded that even though the relationship between a capacitance sensor reading and water content is not linear over all soil types, a linear approximation is adequate for individual soil types. Campbell (2001) found a near linear relationship between sensor output (mV) and volumetric water content for loamy sand, sandy loam, loam, silt loam, silt clay loam and silt clay soils, although the regressions for soils with high sand content were considerably different from those of the other soil types. The objectives of this study were, i) to propose a laboratory procedure for calibrating ECH_2O

capacitance water sensors (EC-10 & EC-20), and ii) to evaluate the manufacturers' calibration equations for use in coir.

2.1.2 Material & methods

2.1.2.1 The capacitance sensors

Eight ECH$_2$O capacitance sensors, comprising of four EC-10 and four EC-20 sensors from Decagon Devices Inc., were used in this experiment. The frequency of the sensors is ~8 MHz, which makes readings vulnerable to salts in the water (Paltineanu & Starr, 1997), and relatively insensitive to temperature, although the manufacturer (Decagon Devices, 2006) specified that the sensors have a comparatively low sensitivity to saline and temperature effects in the soil. According to Campbell (2001) the EC-10 and EC-20 sensors' circuitry minimizes effects due to temperature variation, while the sensor coating somewhat minimizes salinity effects. It has therefore been assumed that an operating environment of between 0 and 50ºC will have little effect on the sensor output (Decagon Devices, 2006). A data logger, model CR1000 of Campbell Scientific, was used to record hourly water content measurements of the sensors in mille Volts (mV).

The manufacturer's recommended the following linear equations for the calibration of the EC-10 and EC-20 sensors, where θ_v is the volumetric water content and mV is the raw electrical output:

EC-10: $\theta_v\ (m^3\ m^{-3}) = 0.000936\ mV - 0.376$

EC-20: $\theta_v\ (m^3\ m^{-3}) = 0.000695\ mV - 0.290$

2.1.2.2 Water characteristic curve

The water characteristic curve is a function of water content and matric suction of the growth medium. Samples were analyzed in the suction range between 0 to 10 kPa by means of a hanging water column apparatus, and by pressure plate apparatus in the suction range between 10 and 1500 kPa. Samples were packed to a bulk density (D_b) of 0.1 g cm^{-3} and saturated in a vacuum chamber. D_b was previously determined by packing a known volume with air dried coir similar to the density at which a growing bag is filled and find a mass to volume ratio. Individual samples were repeatedly equilibrated to a certain suction head for different values below 10 kPa with the hanging water column. For pressures of 10 kPa and more, the pressure of the air phase needed to be increased and this was achieved by placing the samples in a pressure chamber. A range of suction values was applied successively and water content measured repeatedly at each suction pressure.

The drained upper limit (Ratcliff, 1983) was also determined in the laboratory. Oven dried coir was packed at D_b into 10 cm depth x 10 cm diameter rings (876 cm^3) and weighed. The samples were saturated under vacuum and thereafter placed on a wet coarse sand bed to reduce the suction gradient between the sample and the bed, and covered with a plastic sheet to prevent evaporation from the sand bed as well as the samples. The samples were allowed to drain until drainage was negligibly low, i.e. sample mass remained constant. This point was observed after 48 hours and the samples were weighed again and the volumetric water content was taken as the drained upper limit.

2.1.2.3 Equipment and material for the proposed laboratory procedure to calibrate ECH_2O sensors

Equipment required comprises of (i) a perforated cylinder in which the growth medium is packed to a known bulk density, (ii) a vacuum chamber to saturate the sample, (iii) load cells and a data logger for monitoring mass loss, and (iv) a controlled climate chamber for controlling temperature.

A 50 cm long x 10.5 cm diameter PVC pipe was perforated manually with random holes at a density of approximately two holes per cm^2 (Figure 2.1.1). In order to obtain relative homogenous packing of the growth medium in the cylinder, the oven dried medium was packed into the cylinder in separate portions each with the same bulk density. One EC-10 sensor and one EC-20 sensor was inserted from either sides of the cylinder, leaving a radial and axial measuring distance of approximately 10 cm and 5 cm, respectively (Kuraž, 1982; Paltineanu & Starr, 1997).

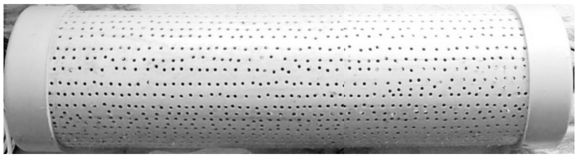

Figure 2.1.1 A 500 mm long calibration cylinder constructed from a standard 10.5 cm diameter PVC pipe and lids. The 6 mm holes were manually drilled at a density of approximately 2 holes per cm^2 to create uniform drying of the growth medium packed in the cylinder.

Saturation of the cylinders was attempted by submerging them in distilled water for 24 hours. This produced a water content of 0.580 $m^3 m^{-3}$, a value similar to the laboratory determined drained upper limit determined for coir, *viz*. 0.607 $m^3 m^{-3}$. Complete saturation of a smaller sample of coir using a vacuum chamber in the laboratory produced a volumetric water content of 0.910 $m^3 m^{-3}$.

Load cells were calibrated by increasing the mass on the cells by known increments and finding a linear relationship between the mV reading from the load cells and the mass on the cells. The cylinders packed with the growth medium were suspended on the load cells as shown in Figure 2.1.2. Hourly mass readings were recorded for the duration of the experiment with a Campbell Scientific (CR1000) data logger. The volumetric water content within a cylinder at any given time was determined by subtracting the dry mass of the growth medium and all equipment from the total mass, and multiplying this with the bulk density of the coir.

A controlled climate chamber was used to maintain a constant temperature of 28ºC for the duration of the drying cycle to eliminate the diurnal effect of temperature on the dielectric constant of water and sensor electronics.

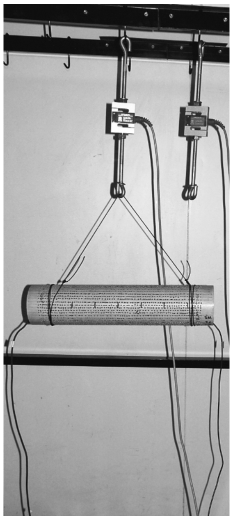

Figure 2.1.2 The calibration cylinder hanging from a load cell mounted in the controlled climate chamber.

2.1.2.4 Measurements and statistical analysis

Millivolt readings and volumetric water content of both EC-10 and EC-20 sensors were plotted over time to present the change in water content throughout the drying cycle. Volumetric water content predicted from the manufacturer’s equations, and the coir specific laboratory determined calibration equations were compared using statistics proposed by Willmott (1982). A deviation area of 4% from a 1:1 line was allowed in which predictions may vary, based on the specifications of the EC-10 and EC-20 sensors with regard to accuracy. Statistical analysis comprised of the determination of the root mean square error (RMSE), unsystematic root mean square error ($RMSE_U$), systematic root mean square error ($RMSE_S$), the index of agreement (D-index) and the regression coefficient (R^2). For a good fit the $RMSE_S$ should approach zero, the index of agreement should approach one, and the $RMSE_U$ should be as close as possible to the RMSE, while R^2 values give an indication of the accuracy of the line fit and not the accuracy of the prediction.

2.1.3 Results & discussion

2.1.3.1 Laboratory procedure to calibrate ECH$_2$O sensors

Most calibration procedures use only a few gravimetric soil samples to calibrate soil water sensors (Bell *et al.*, 1987; Paltineanu & Starr, 1997; Morgan *et al.*, 1999; Seyfried & Murdock, 2001; Cobos, 2006). Such results may not reflect detailed sensor response to water content changes in the growth medium. The proposed procedure is based on the principle of continuous measurement of mass loss of a saturated coir sample during a drying cycle of at least one week. Drying is created by evaporation and the length of the drying period depends on the evaporative demand of the environment as well as the water retention characteristics of the growth medium.

The drying cycle employed was long enough for the growth medium to dry out beyond the lower limit of plant available water. It was therefore assumed that the calibration between the drained upper limit and the air dried state achieved from the drying cycle would be sufficient, since irrigation scheduling will mostly occur between these points.

The response of volumetric water content (θ_v) over the drying cycle was nearly linear (Figure 2.1.3). This graph shows that variation between cylinders was small. Differences between them is probably due to one of the following reasons: differences in the conductivity of the growth medium due to spatial variations in bulk density (the packing of the coir); variation in saturation values between different cylinders; differences in the density of the perforations between cylinders; differences caused by the relative positions of cylinders in the controlled climate chamber.

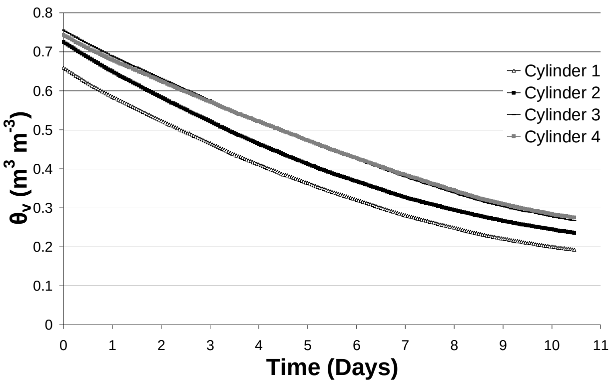

Figure 2.1.3 Volumetric water content (θ_V) of coir measured continuously (n = 252) over the duration of a drying cycle for four different calibration cylinders each containing one EC-10 and one EC-20 sensor.

2.1.3.2 Sensor response over time

The sensor response, expressed in mV, was non-linear over the complete drying cycle for both EC-10 and EC-20 sensors (Figure 2.1.4). Variation in sensor response between three of the four EC-10 sensors was small. The third EC-10 sensor behaved differently in the wet range between day zero and day three of the drying cycle (Figure 2.1.4a). Variation in sensor response between the four EC-20 sensors was high (Figure 2.1.4b). Sensor No. 1 generally gave a lower reading than the others over the first six days of the drying cycle. No obvious reason could be found for this phenomenon except that it indicated that some sensors responded uniquely to water content changes.

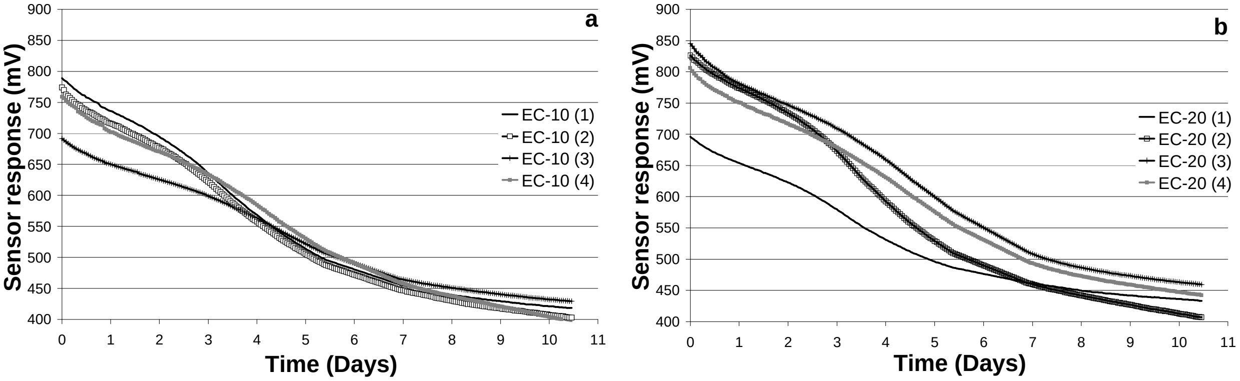

Figure 2.1.4 a) EC-10 and b) EC-20 ECH$_2$O sensor response (mV) to changes in the water content of coir (n = 252) measured over the duration of a drying cycle.

The mV response of individual sensors was also related to the θ_v. Due to very little variation in the shape of the curves of individual sensors, only one randomly chosen curve for each of the EC-10 and EC-20 sensor types is presented in Figure 2.1.5. R^2 values greater than 0.99 prove that a 4th degree polynomial equation provides an almost perfect fit for the relationship for all the EC-10 and EC-20 sensors (Table 2.1.1). Although small, some variation in the function equations indicates that individual sensors are unique and should therefore be calibrated separately.

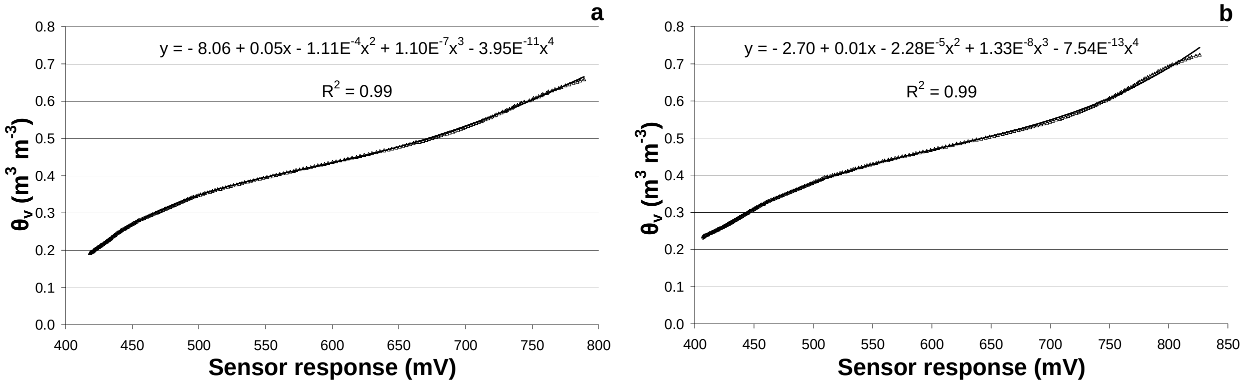

Figure 2.1.5 Graphs showing the relationship between sensor response (mV) and volumetric water content (θ_v) of coir for individual EC-10 and EC-20 sensors, (a) sensor No. 6 and (b) sensor No. 7, respectively; and the equations that describe the curves ($y = \theta_v$ and $x = mV$).

Table 2.1.1 The 4th degree polynomial equations that describe the relationships between sensor response (mV) and volumetric water content (θ_v) of coir for all the EC-10 and EC-20 sensors used for the laboratory calibration ($y = \theta_v$ and $x = mV$).

Sensor type and number	4th degree polynomial equation	R^2-value
EC-10 (1)	$y = -8.06 + 0.05x – 1.11E^{-4}x^2 + 1.10E^{-7}x^3 - 3.95E^{-11}x^4$	0.99
EC-10 (2)	$y = -5.93 + 0.04x – 8.31E^{-5}x^2 + 8.19E^{-8}x^3 – 2.92E^{-11}x^4$	0.99
EC-10 (3)	$y = -33.39 + 0.23x – 6.05E^{-4}x^2 + 6.95E^{-7}x^3 – 2.97E^{-10}x^4$	0.99
EC-10 (4)	$y = -6.20 + 0.04x – 9.75E^{-5}x^2 + 1.03E^{-7}x^3 – 4.03E^{-11}x^4$	0.99
EC-20 (1)	$y = -22.46 + 0.14x – 3.40E^{-4}x^2 + 3.63E^{-7}x^3 – 1.43E^{-10}x^4$	0.99
EC-20 (2)	$y = -2.70 + 0.01x – 2.28E^{-5}x^2 + 1.33E^{-8}x^3 – 7.54E^{-13}x^4$	0.99
EC-20 (3)	$y = -16.04 + 0.10x – 2.23E^{-4}x^2 + 2.23E^{-7}x^3 – 8.23E^{-11}x^4$	0.99
EC-20 (4)	$y = -13.10 + 0.08x – 1.91E^{-4}x^2 + 1.96E^{-7}x^3 – 7.40E^{-11}x^4$	0.99

2.1.3.3 Evaluation of the manufacturer's calibration equations

The predicted θ_v of coir using the manufacturer's calibration for soil was compared with results obtained with the proposed laboratory calibration equations for the four individual EC-10 and EC-20 sensors in Figure 2.1.6 and Figure 2.1.7, respectively.

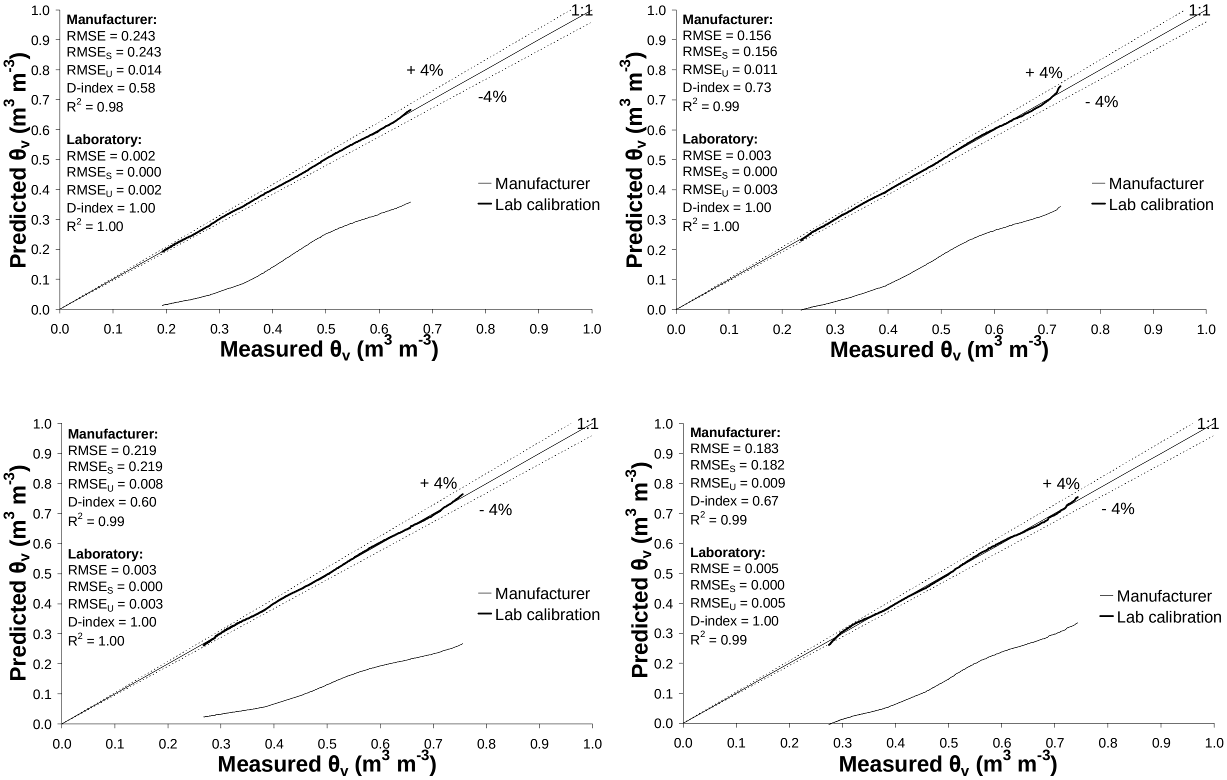

Figure 2.1.6 Graphs showing the relationships between measured volumetric water content (θ_V) of coir (n = 252) and θ_V predicted using the manufacturer's and the proposed laboratory calibration procedures for four EC-10 capacitance sensors. The 1:1 line and the specified 4% accuracy boundary lines are also presented.

Figure 2.1.6 and 2.1.7 clearly indicate that the proposed laboratory calibration for coir is much more accurate than the manufacturer's prediction. To verify the relative reliability of the two procedures, the relationships between predicted and measured θ_v values for all the sensors were compared statistically. Compared to the manufacturer's prediction, the accuracy of the proposed laboratory calibration procedure proved to be very reliable for all the sensors: RMSE$_S$ approached zero; the

D-index approached one; RMSE$_U$ was either equal or nearly equal to the RMSE; R^2 was 0.99 or better.

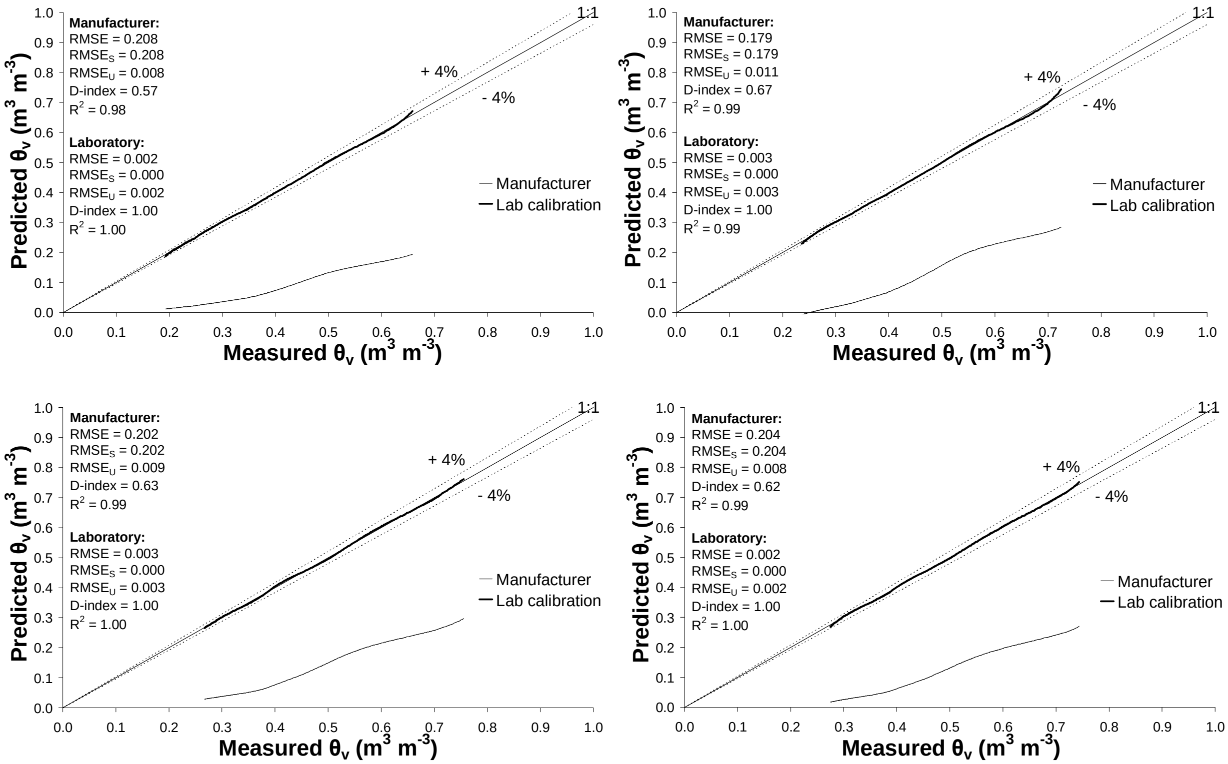

Figure 2.1.7 Graphs showing the relationships between measured volumetric water content (θ_v) of coir (n = 252) and θ_v predicted using the manufacturer's and the proposed laboratory calibration procedures for four EC-20 capacitance sensors. The 1:1 line and the specified 4% accuracy boundary lines are also presented.

In contrast the comparable values for the manufacturer's calibration were as follows for the various EC-10 and EC-20 sensors: RMSE varied between 0.156 and 0.243 m^3 m^{-3}; RMSE$_S$ generally contributed almost all the error; RMSE$_U$ varied between 0.008 and 0.014 m^3 m^{-3}; the D-index varied between 0.58 and 0.73; R^2 varied between 0.98 and 0.99.

The results in Figure 2.1.6 show that for the four EC-10 sensors the laboratory calibration procedure predicted the measured θ_v better than the manufacturer's calibration procedure by between 0.153 and 0.241 m^3 m^{-3}. Comparing the D-index values showed that the laboratory calibration was between 27 and 42% more accurate than the manufacturer's calibration.

The statistical results (Figure 2.1.7) for the four EC-20 sensors were similar to those for the EC-10 sensors. The results in Figure 2.1.7 show that the laboratory calibration procedure predicted the measured θ_v better than the manufacturer's procedure by between 0.176 and 0.206 $m^3\ m^{-3}$. Comparing the D-index values showed that the laboratory calibration was between 33 and 43% more accurate than the manufacturer's calibration.

All statistics therefore pointed to poor reliability of the manufacturer's calibration equations for coir. The importance of medium specific calibrations for material used in greenhouses is accentuated. The poor predictions achieved by the manufacturer's calibration equations is attributed to the difference in water retention characteristics between coir and other growth mediums such as different soils. To illustrate this, the water retention characteristics of coir and a sandy soil (8.6% clay) are plotted together in Figure 2.1.8. Coir was saturated at 0.910 $m^3\ m^{-3}$ compared to 0.410 $m^3\ m^{-3}$ for the sandy soil. The high value for coir is ascribed to its high porosity, reported as approximately 94% by Noguera *et al.* (2000) and Kang *et al*. (2004). The drained upper limit for coir was reached at 0.607 $m^3\ m^{-3}$, approximately 0.270 $m^3\ m^{-3}$ more than the equivalent value for the sandy soil. From the large difference in water retention characteristics between these two mediums, it can be concluded that for capacitance sensors such as those used in this study, predictions of θ_v from equations developed for soils, will probably generally under estimate the θ_v of coir. This can lead to the mismanagement of irrigation practices in greenhouses.

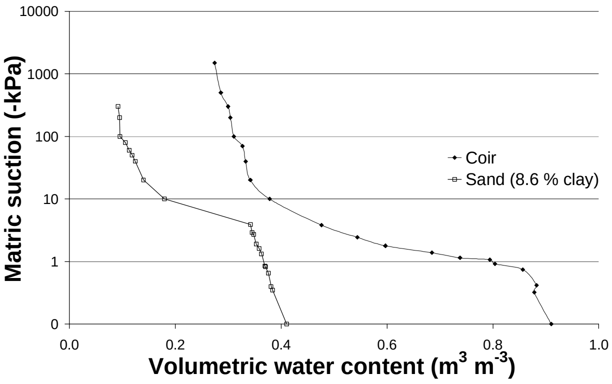

Figure 2.1.8 Water retention characteristics of coir and a sandy soil with 8.6% clay.

2.1.4 Conclusions

A simple but sound scientific procedure was developed and tested to calibrate ECH_2O (EC-10 and EC-20) capacitance sensors. The procedure is based on the continuous weighing of a coir sample, packed in a perforated PVC cylinder, during a drying cycle after the sample had been saturated.

The gravimetric water content decreased consistently over the drying period of ten days, while the mV output responded in a similar way. The results suggested that the sensor response was sensitive enough to measure volumetric water content between the drained upper limit and saturation. Small differences in individual sensor response to water content further suggested that sensors are unique and should therefore be calibrated separately.

A nearly perfect fit, indicated by R^2 values greater than 0.99 for individual sensor response to volumetric water content was achieved by a 4th degree polynomial curve for all EC-10 and EC-20 sensors. This result was compared with the manufacturer's calibration equations for both types of sensors. Various methods used for statistical evaluation of the manufacturer's calibration functions for soil indicated poor accuracy for the prediction of volumetric water content for both EC-10 and EC-20 sensors in coir. This is attributed to differences in the unique water retention characteristics of coir compared to that of soils. It is therefore concluded that specific calibration of growth mediums used in the greenhouse industry in South Africa, other than soil, is essential for the calibration of EC-10 and EC-20 capacitance sensors. This will result in accurate estimations of volumetric water content for the purpose of improved irrigation scheduling.

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2.2 Rapid procedure to calibrate EC-10 and EC-20 capacitance sensors in coir

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A rapid calibration procedure for EC-10 and EC-20 sensors is introduced to promote the commercial use of these sensors for irrigation management in coir for South African greenhouse producers. The method is comprised of taking one sensor reading and one gravimetric sample, both at drained upper limit, for each sensor installed under production conditions, to determine an individual sensor's deviation from an accurate general laboratory calibration equation developed for coir. The rapid calibration procedure was evaluated for four separate EC-10 and EC-20 sensors. To verify the relative reliability of the rapid procedure, statistical analysis was performed separately for all data points and for data points between the drained upper limit and permanent wilting point of coir. From the statistical parameters used, it was observed that all the predictions in the plant available water content range were good with RMSE values < 0.030 $m^3\ m^{-3}$ for the EC-10 and < 0.021 $m^3\ m^{-3}$ for the EC-20 sensors. The D-index also pointed to a high accuracy of prediction in the plant available water content range, with values above 0.98 and 0.99 for the EC-10 and EC-20 sensors, respectively. Since a degree of variation remained between sensors, it is confirmed that sensors should be calibrated individually. The rapid procedure proves a simple but scientifically sound method to calibrate sensors and is easy to apply to individual sensors in the field.

Keywords: Capacitance sensors, coir, rapid calibration, water content

2.2.1 Introduction

Although a very accurate and precise determination of volumetric water content through the use of capacitance sensors is targeted, the practical application of these instruments to improve irrigation management is even more important. A balance should therefore be found between accuracy of calibration for research purposes and scientifically sound simplicity of calibration, even if it is slightly less accurate, to promote the use of capacitance sensors for irrigation management in greenhouse growth mediums.

Standard calibration procedures can be executed in the field or laboratory (Paltineanu & Starr, 1997). Field calibration comprises the installation of capacitance sensors in the field, recording sensor data and the gravimetric determination of soil water content through sampling (Bell *et al*., 1987; Morgan *et al*., 1999). Field calibration, however, is laborious and time-intensive due to the large scale of operation (Starr & Paltineanu, 2002). Measurement errors in the field often result from the gravimetric calibration method where the sample taken is not representative of the capacitance sensor's sphere of influence (Tomer & Anderson, 1995; Chanzy *et al*., 1998; Lane & Mackenzie, 2001), while soil heterogeneity may cause big differences in water content within a small volume of soil (Lane & Mackenzie, 2001). The latter disadvantage strongly promotes the possibility that the gravimetric method of calibration is not optimal for capacitance sensors. Another problem with regard to the accuracy of capacitance sensors is found in the occurrence of air gaps caused by poor field installation (Evett & Steiner, 1995; Morgan *et al*., 1999).

In an effort to simplify field calibration of capacitance sensors to a less time-consuming procedure, Geesing *et al*. (2004) compared calibration equations developed from various amounts of gravimetric samples for different sites and situations. Combining data points of different sites resulted in over- and under-estimation of volumetric water content due to differences in soil texture and site-specific calibration was emphasised for heterogeneous fields. However, according to the authors, the reduction in the collection of samples to 35 per site sampled in one day, produced satisfactory results for predicting volumetric water content with a root mean square error (RMSE) of 0.040 m^3 m^{-3}.

Laboratory calibration comprises recording sensor readings in soil packed at a known bulk density, and consequently, collecting and drying samples to attain gravimetric water content. This procedure is then repeated at several water contents (approximately five to seven times until saturation is reached) to attain a calibration curve (Dighton & Dillon and Mead, unpublished data as cited by Paltineanu & Starr, 1997; Seyfried & Murdock, 2001; Cobos, 2006).

Young *et al*. (1997), Lane & Mackenzie (2001) and Nemati *et al*. (2008) proposed rapid and improved laboratory calibration procedures for time domain reflectometry (TDR) sensors. Young *et al*. (1997) used the upward infiltration method for determining soil water content to calibrate TDR sensors. The method comprises the pumping of water at a constant rate (0.53-1.0 cm h^{-1}) from the bottom of a column containing the sensor. The TDR sensor data and mass of the column are logged every three minutes for 7-13 hours until water starts leaking from the upper end of the column. The soil is oven-dried at the end of the experiment to determine volumetric water content from gravimetric water content and bulk density. Advantages of this method are shorter experimental times, collection of many data points with a data logger and once-off packing of the soil column (Young *et al*., 1997), which eliminates the effects of variable bulk density on the dielectric constant (Dirksen & Dasberg, 1993). A very possible problem with this method may be that capillary pressure hysteresis can cause significant differences in the observed volumetric water content (Wallach & Raviv, 2008) between the wetting curve as created in this calibration and the drying curve that occurs under normal irrigated field conditions.

The rapid calibration method used by Lane & Mackenzie (2001) comprises the slow wetting of an intact core in a cylindrical PVC casing containing a TDR sensor, from below to reach saturation after approximately two weeks, whereafter the core assemblies are suspended from a load cell and allowed to dry through evaporation until no detectable change in mass is observed, roughly after 33-41 days. The cores are oven-dried to determine bulk density and the water content is calculated independently for each load cell from gravimetric water content to match each TDR measurement. This method produced good linear calibration fits on a 1:1 basis, although the wet and dry end produced large errors of -8.6% and 17.2%, respectively. These large errors may be explained by the decreasing sensitivity of the dielectric constant to soil water content under dry conditions, as observed by Chanzy *et al*. (1998). In experiments conducted by Tomer & Anderson (1995), the dielectric constant only increased from 3.8 to 6.1, which explains why it is so difficult to detect small changes in water content with the capacitance probe in dry- or coarse-textured soils. However, these conditions often fall outside (below or above) of the water content range used by the plant and thus may not exercise a large effect on the accuracy of prediction (Chanzy *et al*., 1998). The rapid calibration method of Lane & Mackenzie (2001), however, was much more accurate than the field calibration executed by the same authors. Potential errors of this rapid laboratory calibration can be ascribed to non-uniform distribution of water within the core after wetting, structural heterogeneities within the core and the effect of water layering in the core (Lane & Mackenzie, 2001). Although less labour-intensive, the rapid calibration method proposed by Lane and Mackenzie (2001) still requires an extended saturation and drying period, which remains time-consuming.

Nemati *et al*. (2008) developed a single third-degree polynomial equation for the relationship between volumetric water content and the dielectric constant of 30 organic growth mediums based on TDR and gravimetric measurements. Although the calibrations were accurately executed, prediction of volumetric water content with the single calibration equation was not verified gravimetrically in any of the 30 growth mediums used.

From all the calibration procedures studied, specific calibration of capacitance sensors for different growth mediums remains the order of the day and may be supported by the following observations: Ould Mohamed *et al*. (1997) observed a linear relationship between the dielectric permittivity and the volumetric water content for a silty clay loam soil for a narrow range of volumetric water contents between 0.250 $m^3 m^{-3}$ and 0.400 $m^3 m^{-3}$. However, according to Bell *et al*. (1987) and Nemati *et al*. (2008), a large range in water content changes the linear relationship between dielectric constant and volumetric water content to a nonlinear relationship. Bell *et al*. (1987) also observed that soils with low bulk densities seem to be responsible for a steeper gradient of the calibration compared to soils with higher bulk densities. The great variability of the dielectric properties of a particular growth medium are confirmed by various authors (Baumhardt *et al*., 2000; Seyfried & Murdock, 2001; Fares *et al*., 2007) who also recommend that capacitance sensors need to be calibrated for a specific growth medium. In contrast, Morel *et al*. (2008) concluded that ECH_2O capacitance sensors need not be calibrated for different growth mediums. However, the authors only used two similar growth mediums to develop the calibration equation, where both contained 75% Irish sphagnum peat, while the equation was also never tested by the authors.

Great variation between individual sensors commonly occurs due to variable sensor installation and location in the field, and since the variation cannot be predicted, sensors must be calibrated individually (Chanzy *et al*., 1998). Individual sensor calibration is also supported by Seyfried & Murdock (2001), Bandaranayake *et al*. (2007), and Morel *et al*. (2008). The variation in the intercept values can be related to variation of soil texture (Ould Mohamed *et al*., 1997) or differences in bulk density. Bandaranayake *et al*. (2007) further observed that the sensor output in air and water is not constant and depends on quality aspects, such as temperature and humidity in the case of air, and temperature and salinity in the case of water. They concluded that, because the quality parameters of air and water are not interdependent, output values in air and water are not useful for normalisation which is normally used in an effort to minimise sensor-to-sensor variation.

During testing of the performance of ECH_2O sensors, model EC-20, in a well-drained sandy soil, Bandaranayake *et al*. (2007) occasionally found some sensors unexpectedly failed to produce an output in a normal soil water range but became active again after a short period, while others completely failed to operate for no apparent reason. This was attributed to water leakage into the sensor circuitry since the sensors which failed in the field worked well after removal and storage under dry conditions (Bandaranayake *et al*., 2007). However, these errors can be avoided by using replicated sensors and programming the data logger to discard output values below a certain point (Bandaranayake *et al*., 2007). Therefore, although it is possible to monitor soil water content at the field scale, with only a few individually calibrated capacitance sensors (one to three), the use of more than one to avoid serious irrigation failure is recommended. The objectives of this study were, i) to propose a rapid procedure for calibrating ECH_2O capacitance water sensors, and ii) to evaluate the rapid calibration method for use in coir.

2.2.2 Material and methods

2.2.2.1 Equipment and material

Sixteen ECH_2O capacitance probes (eight EC-10 and eight EC-20, Decagon Devices, Inc.) were used in this experiment, of which eight were used to develop the laboratory calibration equation for each sensor type, while the remaining eight were used to evaluate the rapid procedure.

2.2.2.2 Laboratory calibration procedure

The eight sensors used to determine the laboratory calibration equations were calibrated through the continuous measurement of mass loss of a saturated coir sample during a drying cycle of at least one week. Four coir samples were packed in four perforated cylinders at a known bulk density containing one EC-10 and one EC-20 sensor each. All cylinders were saturated by submerging them into deionised water. Each cylinder was suspended from a load cell, placed inside a temperature controlled chamber directly after saturation, and drying was performed through evaporation (Figure 2.1.2). A data logger, model CR10X of Campbell Scientific, recorded mass loss measured from the load cells and mille volt (mV) readings from the ECH_2O sensors. The volumetric water content within a cylinder was determined by subtracting the dry mass of the growth medium and all equipment from the wet mass measured with the load cell, and multiplying this with the bulk density of the growth medium. The response (mV) of individual sensors was related to the volumetric water content of the growth medium, and a 4th degree polynomial curve was fitted to the combined sensor data for both EC-10 and EC-20 sensors.

2.2.2.3 Rapid calibration procedure

The rapid method is based on the general laboratory calibration equation per sensor type (EC-10 or EC-20), corrected by specific values of individual sensor output (x_{DUL} , mV) and measured volumetric water content (y_{DUL}) at the drained upper limit (DUL). To get measurements at DUL firstly requires the installation of the capacitance sensor in the growth medium where it will be used for irrigation management. Thereafter the growth medium is thoroughly wetted; the surface covered and allowed to drain for at least 48 hours. This point is considered as the DUL. The sensor output is recorded from the point of wetting and the point of DUL is identified as soon as the sensor readings remain near constant after approximately 48 hours. Consequently, gravimetric sampling from the growth medium at DUL is done and volumetric water content (θ_v) determined by multiplying gravimetric water content with the bulk density of the growth medium.

Suspecting that variation in the saturation and packing of coir will always be a problem in the commercial use of these sensors, sensor response (mV) and measured θ_v were converted to relative sensor response (x_{Rel}) and relative θ_v (y_{Rel}) in an effort to reduce variation between individual sensors. The sensor reading at DUL was used instead of the reading at saturation, because saturation is difficult to reach without a vacuum chamber, and irrigation scheduling mostly occurs in the plant available water content range between the DUL and the lower limit of the plant available water. Therefore, x_{Rel} and y_{Rel} were determined by dividing both sensor response (x) and measured θ_v (y) by their respective maximum values at DUL, namely x_{DUL} and y_{DUL}:

$$x_{Rel} = x / x_{DUL}$$

$$y_{Rel} = y / y_{DUL}$$

Since the general calibration equation for coir is based on relative sensor output and relative θ_v, y will be equal to the general equation multiplied by y_{DUL}:

$$y_{Rel} = a + bx_{Rel} + cx_{Rel}^2 + dx_{Rel}^3 + ex_{Rel}^4$$

$$y = (a + bx_{Rel} + cx_{Rel}^2 + dx_{Rel}^3 + ex_{Rel}^4) \times y_{DUL}$$

Therefore, x_{Rel} is determined from any given x value (mV) by dividing it by x_{DUL} (mV), which was measured by the sensors at DUL, while y_{DUL} is the θ_v determined at DUL.

2.2.2.4 Statistical analysis

Volumetric water content predicted from the rapid calibration equation was compared to a 1:1 line (Willmott, 1982) and 4% accuracy was allowed based on the specifications of the EC-10 and EC-20 sensors, while the predictions were evaluated statistically according to the procedure of Willmott (1982). Statistical analysis was comprised of the determination of the RMSE, unsystematic root mean square error ($RMSE_U$), systematic root mean square error ($RMSE_S$) and the D-index. Accordingly, for a good fit the $RMSE_S$ should approach zero, the D-index should approach one, and the $RMSE_U$ should be as close as possible to the RMSE, while R^2 values only gave an indication of the accuracy of the line fit and not the accuracy of the prediction.

2.2.3 Results and discussion

2.2.3.1 General principles

Most calibration procedures are too elaborate, time-consuming and complicated for practical use in greenhouses. The proposed rapid procedure was based on the measurement of one sensor reading (mV) at DUL and the consequent gravimetric sampling at DUL, for the determination of volumetric water content (θ_v) for each sensor used under real-time production conditions. These two measurements were used to determine an individual sensor's deviation from the general calibration equation developed for coir through an accurate laboratory calibration procedure.

2.2.3.2 Sensor response

Variation in the relationship between θ_v and sensor response (mV) was evident for both EC-10 and EC-20 capacitance sensors, which will result in errors should a general calibration equation be derived from various individual calibration equations (Figure 2.2.1). This variation between sensors is not unique to this experiment and is commonly experienced by other researchers (Ould Mohamed *et al.*, 1997; Chanzy *et al.*, 1998; Seyfried & Murdock, 2001; Bandaranayake *et al.*, 2007; Morel *et al.*, 2008). The difference between sensors in this study is mainly ascribed to errors in the saturation of the coir and therefore also, to a lesser extent, to the packing of the growth medium in the calibration column. Differences in measurement between sensors may also be due to individual sensor variation in electronics.

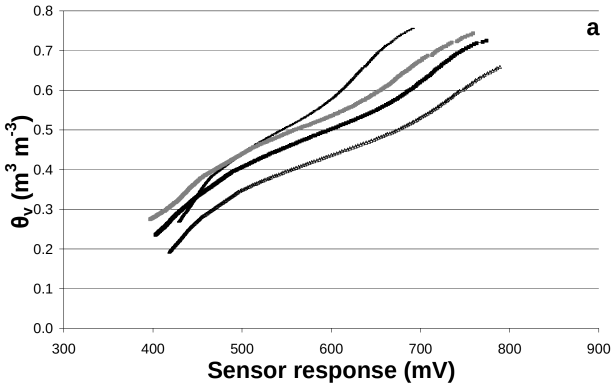

Figure 2.2.1 The relationship between measured volumetric water content (θ_v) and sensor response (mV) (n = 252) for a) four EC-10, and b) four EC-20 capacitance sensors.

The conversion to relative values of sensor response and measured θ_v reduced variation between sensors, although one outlier was observed for both EC-10 and EC-20 sensors as seen in Figure 2.2.2. This conversion eliminated large errors at the wet end, as experienced by Lane and Mackenzie (2001), while errors in the dry end fell outside of the water content range of coir. A 4th degree polynomial curve, fitted over the combined sensor data for both EC-10 and EC-20 sensors, remained the best fit for the accurate prediction of y_{Rel} from x_{Rel} (Figure 2.2.2).

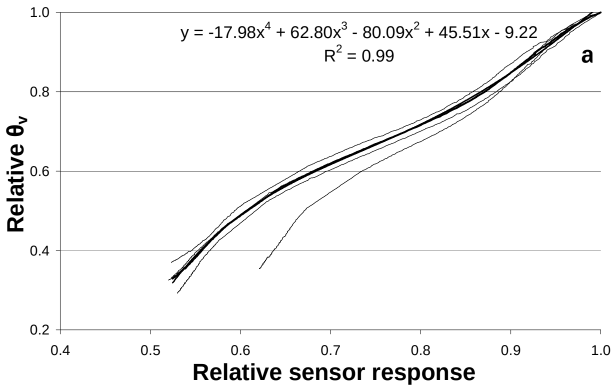

Figure 2.2.2 The relationship between relative measured volumetric water content (θ_v) and relative sensor response (mV) (n = 252) for a) four EC-10, and b) four EC-20 capacitance sensors; and the combined equations and R^2 values that describe the curves ($y = \theta_v$ and x = mV).

2.2.3.3 Evaluation of the rapid calibration procedure

To evaluate the rapid calibration procedure, x_{DUL} and y_{DUL} were determined in coir for four independent sensors of EC-10 and EC-20, respectively. From this, x_{Rel} was determined for various readings of x and the corresponding y determined from the general calibration equation multiplied by y_{DUL}. The predicted θ_v of coir using the proposed rapid calibration equations for the EC-10 and EC-20 sensors was compared to a 1:1 line with 4% deviation boundaries in Figure 2.2.3 and Figure 2.2.4 respectively. The lower sections of one EC-10 curve (Sensor no. 2) and three EC-20 curves (Sensor no. 1, 3 and 4) under-estimated θ_v. However, according to the retention curve developed for coir in a previous experiment, the permanent wilting point (PWP), determined at 1500 kPa, is reached at 0.275 $m^3\ m^{-3}$, meaning that this under-estimation will not influence the prediction of θ_v in the available water content range for coir. Deviation from the 1:1 line at the dry end, predicted by TDR, as experienced by Chanzy *et al.* (1998), also fell outside of the available water content range for the soil used and therefore was not significant for the purpose of irrigation management within the available water content range.

The figures clearly indicate that the proposed rapid calibration for coir is reasonably accurate, especially between DUL and PWP for most EC-10 and EC-20 sensors. To verify the relative reliability of the rapid procedure, statistical analysis was done separately for all data points and for data points between DUL and PWP.

The accuracy of the proposed rapid calibration procedure proved to be equally reliable over all data points and for data points between DUL and PWP for all EC-10 sensors: the D-index approached one; R^2 was 0.97 or better (Figure 2.2.3). $RMSE_S$ generally contributed much of the error, while RMSE varied between 0.012 and 0.030 $m^3\ m^{-3}$ for the prediction of θ_v between DUL (0.607 $m^3\ m^{-3}$) and PWP (0.275 $m^3\ m^{-3}$) with the proposed rapid calibration procedure.

Compared to all data points, the accuracy of the proposed rapid calibration procedure for data points between DUL and PWP proved to be more reliable for all EC-20 sensors: the D-index approached one; R^2 was 0.99 or better (Figure 2.2.4). Again, $RMSE_S$ generally contributed much of the error, while RMSE varied between 0.014 and 0.021 $m^3\ m^{-3}$ for the prediction of θ_v between DUL (0.607 $m^3\ m^{-3}$) and PWP (0.275 $m^3\ m^{-3}$) with the proposed rapid calibration procedure.

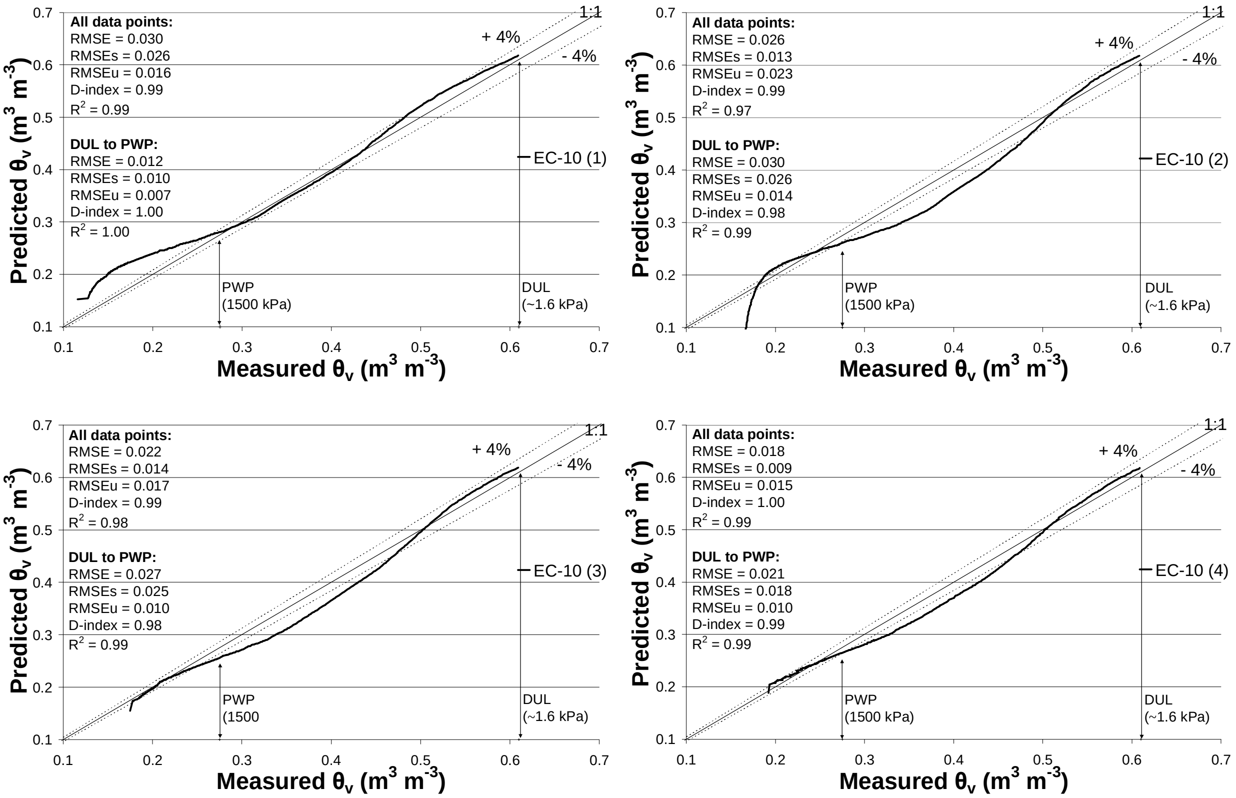

Figure 2.2.3 The relationship between measured volumetric water content (θ_v) (n = 252) and θ_v predicted using the rapid calibration procedure for four EC-10 capacitance sensors. The 1:1 line, the specified 4% accuracy boundary lines as well as drained upper limit (DUL) and permanent wilting point (PWP) for coir are also presented.

The comparable values for all data points for the EC-20 sensors were as follows: RMSE varied between 0.021 and 0.066 m^3 m^{-3}; $RMSE_S$ contributed almost all the error; the D-index varied between 0.95 and 0.99; R^2 varied between 0.94 and 0.99 (Figure 2.2.4).

The statistical results in Figure 2.2.4 show that the proposed rapid calibration procedure yielded a good prediction of the θ_v for data points between DUL and PWP, while the statistical results in Figure 2.2.3 were similar for the prediction of θ_v for all data points and data points between DUL and PWP. Since the 4% accuracy of prediction for EC-10 and EC-20 sensors indicated by the manufacturer is based on more accurate and time-consuming calibration procedures, slight deviation from these boundaries may be acceptable when compared to the benefit of using the rapid calibration procedure in the field and the ease of applying it to individual sensors.

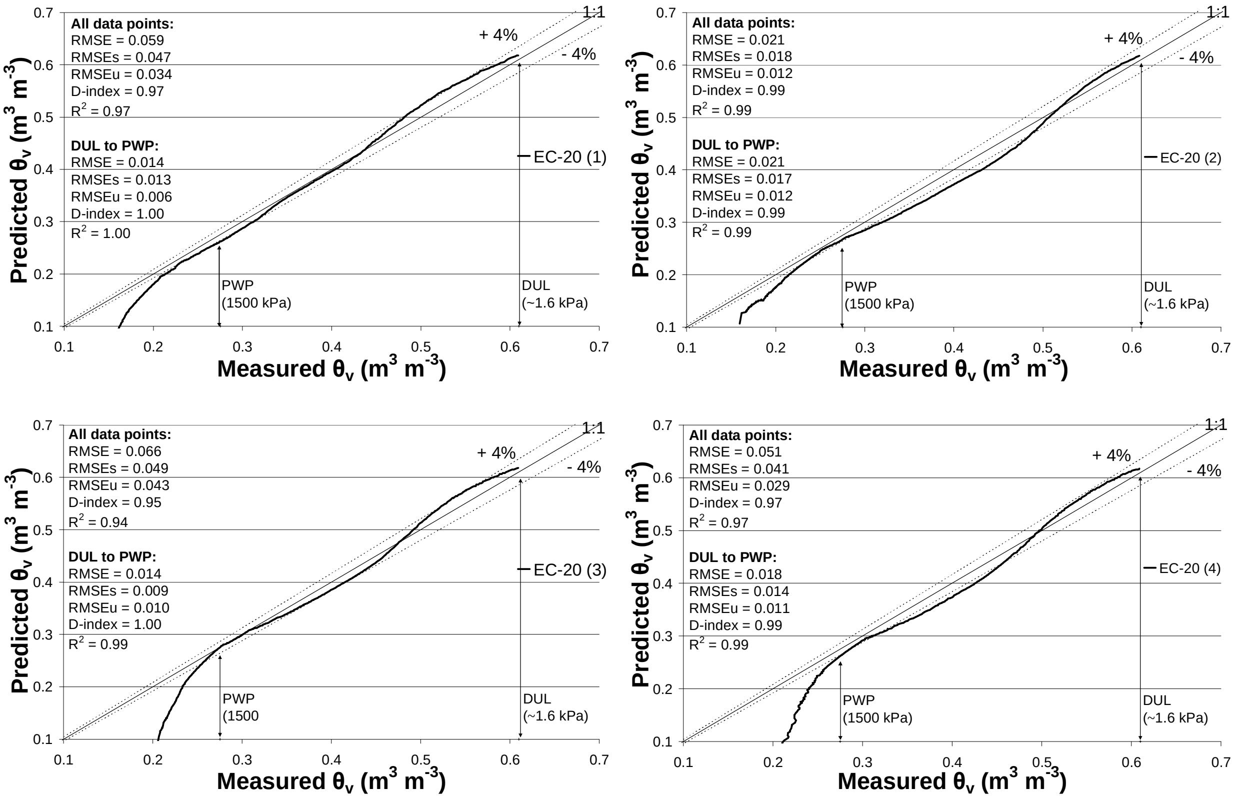

Figure 2.2.4 The relationship between measured volumetric water content (θ_v) (n = 252) and θ_v predicted using the rapid calibration procedure for four EC-20 capacitance sensors. The 1:1 line, the specified 4% accuracy boundary lines as well as drained upper limit (DUL) and permanent wilting point (PWP) for coir are also presented.

2.2.4 Conclusions

A simple procedure was developed and tested for the rapid calibration of ECH_2O (EC-10 and EC-20) capacitance sensors in an operational environment. The method is based on the taking of only one sensor reading and one gravimetric sample, both at DUL, for each sensor in the environment where they will be used to manage irrigation, to determine an individual sensor's deviation from the accurate general laboratory calibration equation developed for coir.

The general calibration equation for coir was obtained for half of the sensors through an accurate laboratory calibration procedure. Great variation between sensors, with regard to the relationship between sensor output and θ_v, posed the problem of high percentages of over- and/or under-estimation of water content if data for the individual sensors were to be combined into a calibration equation for each sensor type (EC-10 and EC-20). Sensor response and measured θ_v were converted to relative sensor response and relative θ_v by dividing both sensor response and measured θ_v with their respective maximum values at DUL. This conversion reduced sensor-to-sensor variation. A nearly perfect fit, indicated by R^2 values greater than 0.99 for the relationship between relative sensor response and relative θ_v was achieved by a 4th degree polynomial curve for both EC-10 and EC-20 sensors in coir. The equation consequently incorporated the measured sensor response and measured θ_v at DUL in operational conditions in the greenhouse.

The calibration equations for EC-10 and EC-20 were evaluated with different sensors of which only the sensor output and θ_v, determined through gravimetric sampling, were measured at DUL for each sensor. Various methods used for statistical evaluation of the rapid calibration pointed to a good accuracy for the prediction of θ_v between DUL and PWP, for both EC-10 and EC-20 sensors in coir. The rapid method, based on a growth medium specific calibration with relative values of sensor output and measured θ_v, should perform equally well in other growth mediums. In conclusion, it must be accentuated that individual sensor calibration in the laboratory is essential for the accurate prediction of θ_v for a specific growth medium, while the rapid calibration procedure for ECH_2O capacitance sensors will simplify their use in commercial greenhouses, for the purpose of improved irrigation management in coir. Companies supplying the sensors to farmers or agricultural research stations, e.g. University laboratories, should be contracted to do these medium specific laboratory calibrations on which the rapid procedure is based.

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Chapter 3

3.1 Characterisation of plant water stress of greenhouse cucumbers (*Cucumis sativus*) grown in coir

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Greenhouse cucumber plants grown in coir are mostly over-irrigated when irrigation is scheduled according to the standard method used in South African greenhouses for sawdust and shavings. This results in luxury uptake that is not preferable for maximum yield. Improved irrigation techniques are required to decrease water loss from drain-to-waste greenhouse production systems in South Africa. The objectives of this study were to describe the development of plant water stress and plant response during a drying cycle of greenhouse cucumbers grown in coir, to identify different stages of plant water stress and set criteria for the identification of these stages, and to determine the implication for irrigation management. From this study, mild water stress was identified as the point from where the T_d:T_w (transpiration ratio where T_d = transpiration of unwatered and T_w = transpiration of well-watered plants as determined using the water-balance equation) does not recover under continuous drying of the medium. Visual wilting indicated moderate crop water stress, while severe water stress was identified as the point where changes in the slope of T_d:T_w, plotted over time, becomes negligible and about 75% of all plants are irreversibly wilted. Based on the plant response it is recommended that water depletion can be allowed to the point of mild water stress before the next irrigation event is started, although possible effects on yield was not considered and will be addressed in follow on Chapters. Soil water sensors calibrated to measure

volumetric water content in coir or tensiometer measurements converted to volumetric water content from a laboratory-determined retention curve for coir, may be used to trigger irrigation the point of mild water stress.

Keywords: Capacitance sensors, coir, drying cycle, greenhouse cucumber, water stress

3.1.1 Introduction

With the increasing demand for water due to expanding industrial and household needs, the best use of available water resources are required in irrigated agricultural systems, while minimising environmental pollution. Irrigation scheduling in South African greenhouses consists mostly of a fixed frequency, which varies between seasons and crop growth phases, while the volume is increased throughout the growing season according to drainage percentage or drainage electrical conductivity (EC) (Combrink, 2005). This method works well for greenhouse crops grown in sawdust and shavings, due to low plant available water content of about 13%, which can increase up to 23% as the medium decomposes throughout the season and therefore needs to be irrigated frequently and with low quantities per pulse to prevent water stress (Bohne, 2004). In South Africa, special growing bags with elevated drainage holes are used to create a reservoir where water can be stored between irrigations because of the low water holding capacity of the substrate. In contrast, the plant available water content of coir can be as high as 35% (Prasad, 1997). As more producers start to use coir as a growing medium, they often over-irrigate their crops since coir can hold up to about 700% of its dry mass in water. The lack of information on irrigation scheduling in this medium demands a detailed characterisation of its water retention characteristics and its ability to supply water to greenhouse crops.

In a glasshouse where irrigation and drainage can be measured accurately and evaporation can be controlled by covering the surface with mulch, the only unknown components in the water balance are the water content of the medium and transpiration (Loomis & Connor, 1996). The transpiration flux of water vapour into the atmosphere from the plant foliage depends on the availability of water in the root zone. The daily cycle of net water loss and gain of irrigated plants can be divided into two stages. The first stage stretches from sunrise to midday when uptake lags behind transpiration due to the continuously declining tissue potential, while the second stage occurs in the late afternoon when transpiration slows and uptake recovers the plant to a more favourable potential in the evening

(Hsiao *et al*., 1980). In unwatered plants, expansive growth is the first physiological process which is restricted by mild water stress (Hsiao *et al*., 1976a). The reduction of expansive cell growth reduces leaf area development which in turn indirectly limits photosynthesis through reduced CO_2 assimilation (Hsiao *et al*., 1976b). Because the process of cell division can only commence when a certain minimum cell size is reached, reduced cell expansion therefore also limits cell division, thereby restricting the leaf initiation and potential leaf area of a plant (Hsiao *et al*., 1976b). Leaf drooping or curling occurs as the leaf water status is reduced and causes a reduction in the radiation load on leaves (Hsiao *et al*., 1976b). As the medium dries out further and the plant suffers moderate to severe water stress, the water supply in the medium becomes insufficient to meet loss by transpiration, and constant turgor loss causes the stomata to first close partially and eventually fully (Hsiao *et al*., 1976a; Marshall & Holmes, 1988). Partial and full stomatal closure increases leaf resistance (r_l) (s m^{-1}) and reduces leaf function and growth (Loomis & Connor, 1996). At this stage (moderate to severe water stress), xylem conductance of water is severely reduced (Hsiao *et al*., 1976a). According to Loomis and Connor (1996), leaf water potential (Ψ_l) defines the internal water status of a crop, but it is not possible to understand the nature of the response to water shortage without the associated measurements of r_l. Stomatal resistance of cucumber increases as the medium dries out, although it may be reduced again as the plant lowers its net photosynthetic rate (Wang & Zhang, 2002). Cucumber is furthermore very sensitive to a large vapour pressure deficit (>1 kPa) especially when accompanied by high solar radiation and closes its stomata quickly under these conditions (Chamont *et al*., 1995).

The crop's ability to cope with diurnal internal water deficit will determine the length of time that the plant will survive if the medium water is not refilled. It is evident that a crop nears irreversible water stress as ET_a/ET_p nears zero (ET_a = actual evapotranspiration and ET_p = potential evaporation). Botha *et al*. (1983) defined this relationship between ET_a and ET_p as the supply-induced plant water stress index (SI), which correlates the increasing severity of stress with the ratio nearing zero. According to Loomis and Connor (1996), the relationship between ET_a and ET_p is maintained until the relative available water content of the medium falls below the 0.3 ratio, whereafter the decline of ET_a/ET_p is linear for a wide range of crops and soil textural classes irrespective of the soil water potential. The objectives of this study were i) to describe the development of plant water stress and plant reaction during a drying cycle of greenhouse cucumbers grown in coir, ii) to identify different stages of plant water stress as well as criteria for the identification of these stages, and iii) to describe the implication thereof for irrigation management.

3.1.2 Material and methods

3.1.2.1 Location and cropping details

The experiment was conducted in a 48 m^2 temperature-controlled glasshouse at the University of the Free State in the Free State province of South Africa (26º11’20” E, 29º06’33” S, 1409 m altitude). Cucumber (*Cucumis sativus*) seed of the cultivar Airbus were sown on 15 January 2008 and transplanted at a mean density of 2 plants m^{-2} on 4 February 2008. Seedlings were transplanted to 9 L and 20 L bags filled with coir. Drainage holes were punched into the bottom of all bags to prevent the build-up of a reservoir in the bag. All coir used in the experiment (30 x 5 kg blocks) was processed before the bags were filled to minimise variation in bulk density between bags. Compressed coir blocks were soaked in water, excess water was drained and the coir was spread out on plastic sheeting and mixed to ensure uniform distribution of coir dust and fibres between all bags. The medium was flushed within the bags using municipal water of EC 0.2 mS cm^{-1} until the EC of the drain water was equal to that of the input water. Plants were fertigated through a drip irrigation system with a balanced nutrient solution of EC 1.8 mS cm^{-1} (Maree, 1994) which was prepared from feeding municipal water. Plants were allowed to grow indeterminately by trellising one side shoot per plant downwards from the top horizontal wire. This was necessary to supply sufficient leaf area to compensate for destructive measurements.

3.1.2.2 Treatments and experimental design

Plant response to irrigation treatments were evaluated in two bag sizes. Planted bags were organised in eight single rows which were divided into two blocks, resulting in four single rows of 12 plants per bag size *viz*. 9 L and 20 L. The cucumber plants were grown to full maturity, reaching the horizontal trellising wire 2 m above the bag surface and in full production, in accordance to local practice, before the irrigation treatments were applied randomly in each bag size block. Before the irrigation treatments started, all plants were irrigated according to the standard irrigation method used in South African greenhouses which consists of a fixed irrigation frequency of eight irrigation events over the daylight period. The volume applied was increased throughout the growing period to maintain a drainage percentage of approximately 20% to prevent the build-up of salts. The irrigation treatments which started on 20 March 2008 consisted of an unwatered treatment with no irrigation to create a drying cycle and induce water stress and a well-watered control treatment which was irrigated as described. This drying cycle lasted about five days for the small bags and eight days for the large bags, whereafter the experiment was terminated.

3.1.2.3 Measurements

Echo 10 and Echo 20 capacitance water sensors (Decagon Devices Inc.) were installed vertically in the 9 L and 20 L bags respectively. The distance of 7 cm between the sensor, emitter and plant was constant for all treatments and replications (Thompson *et al.*, 2006). A data logger (model CR1000, Campbell Scientific Africa) recorded water content measurements of the sensors in mV every 20 minutes. Readings were converted to volumetric water content values ($m^3\ m^{-3}$) using in situ calibrations. The exposed surface area of the medium was fully covered with cardboard to prevent evaporation losses. Transpiration (T) was determined from the water balance equation: $T = I - D - \Delta\theta$; where I = irrigation (m^3), D = drainage (m^3) and $\Delta\theta$ is the change in water content (m^3) measured by the capacitance sensors. Irrigation and drainage volumes of four plants per irrigation treatment and medium volume were measured once a day. Xylem potential of the stems of mature leaves, located at the top of the canopy, was measured daily at dawn and midday with a Scholander pressure chamber. Measurements were taken within one minute after each leaf was removed to prevent significant changes in leaf water status, while four leaves were measured per irrigation treatment and bag size. Leaf removal was spread evenly over replications (single plants) ensuring that only one leaf was removed per plant (20-25 leaves per plant) approximately every 2-3 days. Stomatal resistance ($s\ m^{-1}$) was measured with a steady state diffusion porometer (model SC-1, Decagon Devices Inc.), as indicator of plant water stress, on four plants per irrigation treatment and bag size. Stomatal resistance was measured daily at dawn and midday. Well-watered treatments were used as reference data for comparison with unwatered treatments.

3.1.2.4 Methods used to identify and classify different stages of crop water stress

Various approaches can be used to determine the stages of crop water stress during a continuous drying cycle. The first approach uses daily water loss to identify a point where the medium displays a critical change in water content or a breaking point (Starr & Paltineanu, 1998). Starr and Paltineanu (1998) identified two stages of water loss, consisting of a first phase which is characterised by a relatively high rate of water loss, followed by the second phase where the rate of water loss has slowed down drastically and crop water uptake is limited by the limited amount of water in the medium. They identified the transition between these two stages as the commencement of crop water stress. A similar approach was used by Thompson *et al*. (2007) where great changes in the water content between successive days was used as an indication of the onset of crop water stress and in the event of this trend continuing to the following day, it is considered confirmation of crop water stress. A similar approach used by Thompson *et al*. (2007) involves water content changes in the medium during the night. According to Thompson *et al*. (2007), crop water stress commences when night time changes of the water content become negligible, due to the lack of water within the medium to be redistributed to drier areas. The second approach involved daylight transpiration (mm 12 h^{-1}), with the onset of stress as soon as the transpiration ratio (T_d:T_w where T_d = Transpiration unwatered and T_w = transpiration well-watered or reference transpiration (ET_p)) starts to decrease, and reaching severe stress as the ratio nears zero and differences between measurements become negligible. The third approach in identifying crop water stress involves xylem potential (kPa) (Hsiao, 1990) and stomatal resistance (s m^{-1}) (Loomis & Connor, 1996), as well as visual symptoms of wilting. The commencement of crop water stress was identified as the point where the xylem potential and stomatal resistance of unwatered plants starts to decrease relative to that of well-watered plants, with the severity of stress increasing as the xylem potential and stomatal resistance of unwatered plants decreases further relative to that of well-watered plants.

After the identification and classification of the different stages of crop water stress, plant available water content was determined and introduced as an indicator of the various stages of water stress. This was done in an effort to create a universal indicator which will overcome differences between systems, e.g. different bag sizes. Plant available water content was determined as the water content between the drained upper limit (DUL) and the lower limit of water availability. DUL was determined in the laboratory using three samples packed to a density of 0.1 g cm^{-3} in 876 cm^3 columns. Samples were first saturated under vacuum (-50 kPa) before being transferred to a wet sand bath where they drained for three days. Mass were recorded and water content expressed on a volumetric basis. The lower limit was determined during the experiment as a point in the drying cycle when all plants suffered from wilting. Millivolt readings at this point were used to calculate the lower limit for each bag size on a volumetric basis.

3.1.2.5 Statistical analyses

A one-way analysis of variance (ANOVA) was performed on the volumetric water content, plant available water content, daily water loss, T_d:T_w and stomatal conductance results of the different bag sizes for the different water stress levels. P-values were used to compare means at a 5% probability level, using STATISTICA version 8.0 (StatSoft Inc., 2004).

3.1.3 Results and discussion

3.1.3.1 Development of plant water stress and plant response

The effect of the main treatments (well-watered and unwatered) was evident in the change in the volumetric water content over time in both the small (Figure 3.1.1a) and large (Figure 3.1.2a) bag sizes. Water contents of well-watered treatments oscillated in a narrow band of 0.550 to 0.650 $m^3 m^{-3}$ for the small bags and 0.600 to 0.688 $m^3 m^{-3}$ during the drying cycle in the large bags, except when it dropped temporarily to 0.550 $m^3 m^{-3}$ in the large bags on day 7. The water content of both bands was close to the laboratory-determined DUL for coir *viz*. 0.607 $m^3 m^{-3}$. Total drainage expressed as a percentage of the total irrigation application over the measuring period amounted to 29% and 18% in the small and large bags respectively. Although these results were derived from a relatively short period of irrigation, it reflected on the unproductive water losses induced by the irrigation method or strategy commonly used by greenhouse producers in South Africa. The impact of stopping irrigation as indicated by the unwatered treatments can clearly be seen in the decline of the volumetric water content over time in both bag sizes. In this case the plants were forced to rely on the coir reservoir to supply water to meet the daily requirements. This treatment provided the opportunity to study the development of water stress during a drying cycle (Figure 3.1.1a-h, 3.1.2a-h), which lasted about five days for the small bags and eight days for the large bags. In spite of the difference in the length of the drying cycles, trends of all data were similar for small and large bags; therefore some of the results will be discussed without special reference to individual bag sizes, although both are implicated.

Daily (24-hour periods) water loss of the unwatered treatments can be divided into two different phases, similar to the observations made by Starr and Paltineanu (1998). The first phase was characterised by an initial reduction in water loss whereafter the plants recovered to more conservative values of water loss (Figure 3.1.1b, 3.1.2b). From these figures it was evident that the plants experienced a shock condition from the onset of water stress and restricted transpiration severely. The plants reacted quickly, though, and were able to condition and adapt their water loss to more conservative values. This indicates possible luxurious uptake in response to the high frequency irrigation scheduling, although an increased uptake may not necessarily be required for optimal plant growth and production. The effect of the conditioned state on yield and quality of the produce, and therefore water use efficiency, however, remains unknown and will be evaluated in the near future. The second phase was characterised by a continuous decline in water loss by the plants without any further recovery (Figure 3.1.1b, 3.1.2b). The reduced daily water loss of unwatered treatments from early in the drying cycle indicated that the plant gradually restricted its water uptake according to water availability. It was further observed that there was a considerable reduction in the water content of the medium during night time for both irrigation treatments (Figure 3.1.1c, 3.1.2c), as also observed by Thompson *et al*. (2007). Again, the difference between water loss for well-watered and unwatered treatments increased towards the end of the experiment. The cause of water loss during the night remains uncertain since no measurements of stomatal conductance were taken during the night. It may be explained through equilibration of the plant, root and medium potentials as described by Loomis and Connor (1996) or could be due to incompletely closed stomata during the night, depending on the size of the vapour pressure deficit (Richards *et al*., 2002; Caird *et al*., 2007). Mead *et al*. (1996) as cited by Baumhardt *et al*. (2000) attributed diurnal water content fluctuation in the medium to vapour transport which increases water content as medium temperature increases. Further research will include measurements during the night to determine the cause of water loss, since water loss without carbon gain will decrease crop water use efficiency as well as crop productivity due to reduced plant water status (Caird *et al*., 2007).

As with daily water loss, T_d:T_w decreased rapidly early in the drying cycle, but also recovered partially as the plant conditioned itself to the changed water levels in the medium (Figure 3.1.1d, 3.1.2d). Since the medium water condition kept on deteriorating, a constant slower reduction in T_d:T_w occurred as the plant approached permanent wilting, although the reduction was not linear for most crops, as observed by Loomis and Connor (1996).

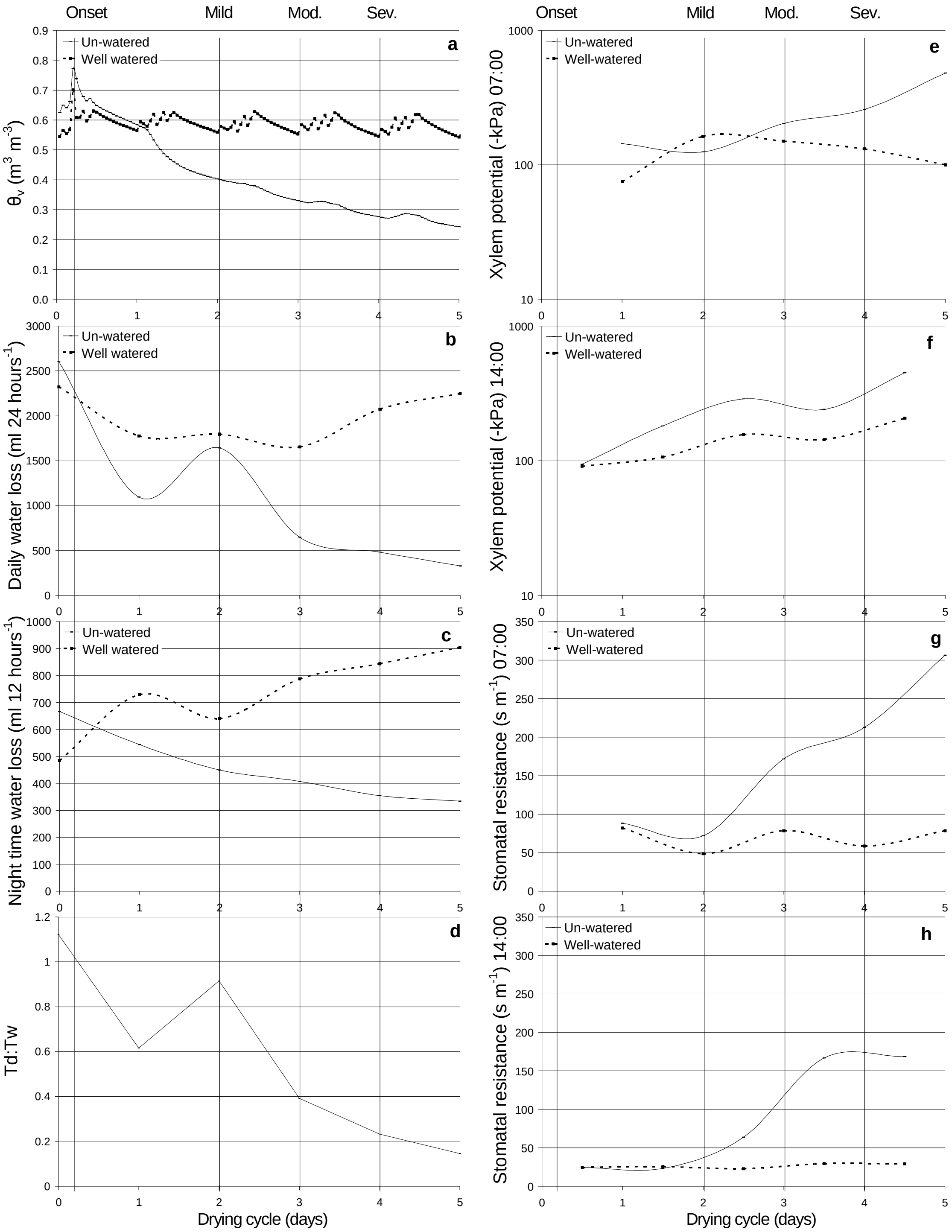

Figure 3.1.1 Development of water stress of cucumber plants during the drying cycle induced in the small bags (9 L): a) Diurnal change in volumetric water content ($m^3\ m^{-3}$); b) Daily water loss (ml 24 $hours^{-1}$); c) Night time water loss (ml 12 $hours^{-1}$); d) Actual transpiration (T_d) over potential transpiration (T_w); e) Xylem potential (-kPa) measured at dawn (07:00); f) Xylem potential (-kPa) measured at midday (14:00); g) Stomatal resistance ($s\ m^{-1}$) measured at dawn (07:00); and h) Stomatal resistance ($s\ m^{-1}$) measured at midday (14:00). The different stages of plant water stress are indicated by vertical lines on the graphs, viz. onset of water stress (Onset), mild (Mild), moderate (Mod.) and severe (Sev.) water stress.

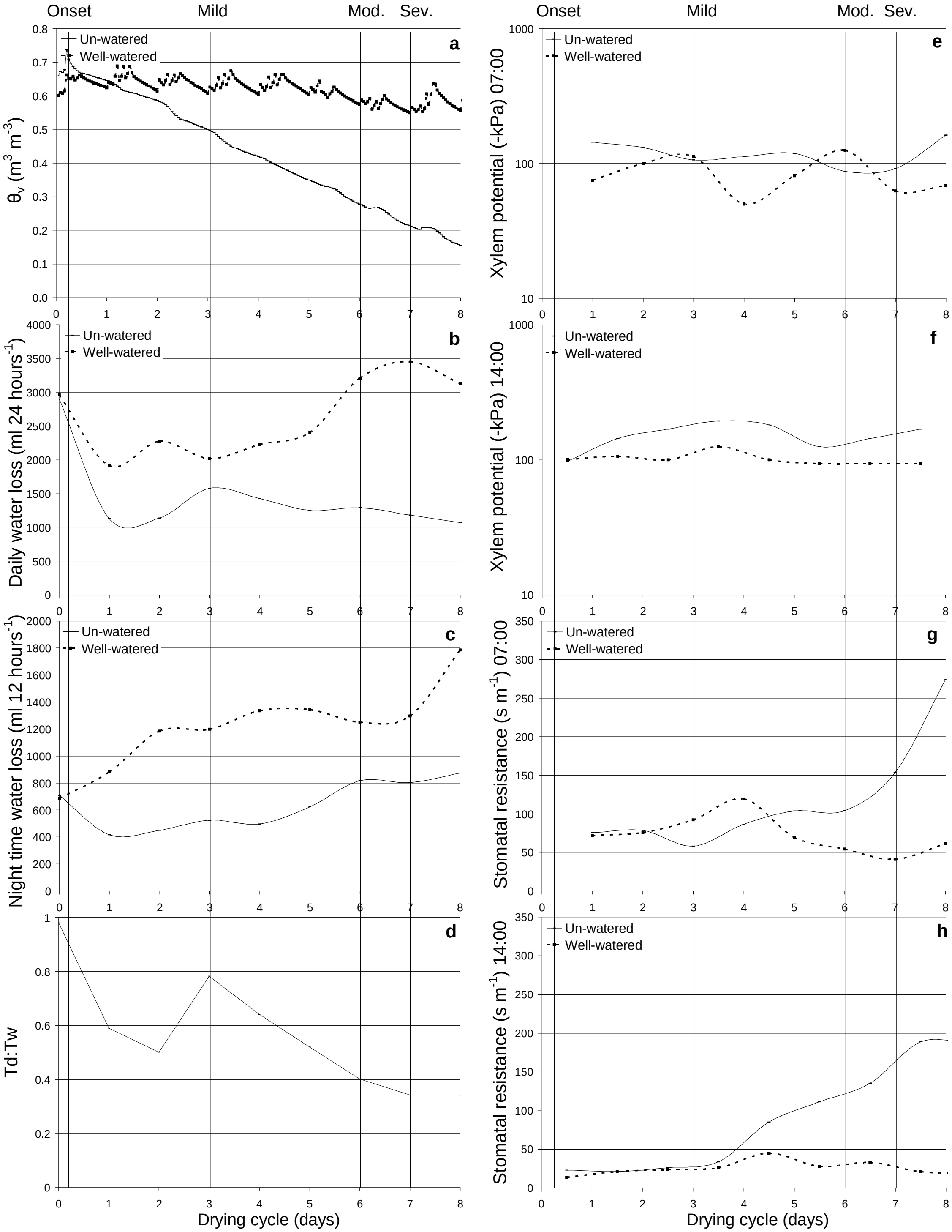

Figure 3.1.2 Development of water stress of cucumber plants during the drying cycle induced in the large bags (20 L): a) Diurnal change in volumetric water content (m^3 m^{-3}); b) Daily water loss (ml 24 $hours^{-1}$); c) Night time water loss (ml 12 $hours^{-1}$); d) Actual transpiration (T_d) over potential transpiration (T_w); e) Xylem potential (-kPa) measured at dawn (07:00); f) Xylem potential (-kPa) measured at midday (14:00); g) Stomatal resistance (s m^{-1}) measured at dawn (07:00); and h) Stomatal resistance (s m^{-1}) measured at midday (14:00). The different stages of plant water stress are indicated by vertical lines on the graphs, *viz*. onset of water stress (Onset), mild (Mild), moderate (Mod.) and severe (Sev.) water stress.

The plant maintained turgor for the greatest part of the drying cycle in spite of the previous results which indicated water shortage in the medium and decreased water loss by the plant. Since the plants were allowed to grow indeterminately throughout the experiment, it became obvious that plants from unwatered treatments gradually ceased growth compared to plants from well-watered treatments as the experiment progressed. Visual symptoms correlated with turgidity and the observation of softer leaves was only made as wilting became visible. After visible wilting, the cucumber plants deteriorated rapidly and reached severe wilting within one day; irrespective of bag size (Figure 3.1.3 illustrates leaves of plants in the large bags).

Day 2 Day 3 Day 4 Day 5 Day 6 Day 7 Day 8

Figure 3.1.3 Development of visual water stress symptoms on the leaves of cucumber plants grown in large bags, where the first visual symptoms were observed on Day 6, while irreversible wilting occurred on Day 7.

Inconsistent measurements of xylem potential for plants in the large bags measured at dawn (Figure 3.1.2e) were probably due to experimental error. Failure to completely seal off the deep indentations on the petioles, probably lead to gas leakage which resulted in poor measurement of the xylem potential (Hsiao, 1990). In spite of the measurement problems, xylem potential indicated plant water stress (as compared to the well-watered treatments) for the plants in the small bags at both dawn and midday (Figure 3.1.1e, f) as well as at midday for plants in the large bags (Figure 3.1.2f).

Stomatal resistance increased rapidly from similar points where recovery was observed in daily water loss and T_d:T_w (Figure 3.1.1g, h, 3.1.2g, h). Lower values of stomatal resistance of the unwatered plants at midday (compared to dawn) may be the result of the aerial environment (e.g. humidity) on measurements as suggested by Hsiao (1990). These results may indicate that stomatal opening, like xylem potential, is only a confirmation of water stress and not sensitive enough to timely indicate plant water stress for managing irrigation.

3.1.3.2 Identification and classification of different stages of plant water stress

The development of water stress as observed from the medium as well as the plant water status can be further characterised into four different stages of water stress as indicated by the vertical lines on Figure 3.1.1 and Figure 3.1.2, *viz*. onset of water stress (Onset), mild water stress (Mild), moderate water stress (Mod.) and severe water stress (Sev.).

The onset of water stress was identified as the point where the water was turned off. Water content ($m^3\ m^{-3}$) and water loss (ml) started to decrease relative to the well-watered treatments soon after the onset of water stress (Figure 3.1.1a-c, 3.1.2a-c). After the recovery and conditioning period, water content and -loss and T_d:T_w declined continuously (Figure 3.1.1a-d, 3.1.2a-d). The start of this gradual decline was identified as the onset of mild water stress, since no further recovery (regaining of turgidity) of the plant occurred. For both bag sizes this point is supported by the increase in stomatal resistance for plants of unwatered treatments compared to that of well-watered treatments (Figure 3.1.1g, h, 3.1.2g, h). From the previous results, clear evidence revealed that the cucumber plants already started to experience water stress regardless of the lack of visual wilting at this identified stage. This was in contrast to Hensley’s (1984) observation that mild water stress, referred to as first material stress by the author, in leaves of maize and wheat occurred only when water stress symptoms became visible. This may be explained by the differences in crop sensitivity to water deficits, as well as the extensive root zone of field crops where roots differentiate over multiple soil layers compared to the limited root zone of greenhouse crops with roots concentrated throughout the entire medium. The roots of field crops therefore have a non-uniform uptake of water in contrast to a more uniform water uptake of greenhouse crops which depletes the root zone quicker and more completely, resulting in water stress before visual wilting sets in. Plant available water contents were significantly higher in the large bags compared to the small bags at the critical point of mild water stress (Table 3.1.1). This was identified as the direct result of bag size as well as differences in root concentration between different bag sizes. Volumetric water content, T_d:T_w, and stomatal resistance measured at noon at mild water stress were not significantly different ($P = 0.05$) between bag sizes (Table 3.1.1). However, volumetric water content at mild water stress varied significantly between the small and large bags at a 10%

probability level. At this stage, T_d:T_w and volumetric water content values seem to be the best indicators of mild water stress for cucumber plants grown in small and large bags.

Table 3.1.1 Comparison of various physical points between well-watered (reference) treatments, onset of water stress, mild water stress, moderate water stress, severe water stress and irreversible water stress for greenhouse cucumbers grown in small and large bags in a coir medium.

	Reference	Onset	Mild	Moderate	Severe
Days after drying cycle started:					
Small bags	-	0	2	3	4
Large bags	-	0	3	6	7
Volumetric water content (m^3 m^{-3}):					
Small bags	0.588a	0.679a	0.400a	0.327a	0.275a
Large bags	0.620a	0.687a	0.497a	0.276a	0.211a
Plant available water content (%):					
Small bags	93a	126a	26a	0a	-19a
Large bags	104a	124a	67b	0a	-20a
Daily water loss (ml 24 $hours^{-1}$):					
Small bags	1982a	2713a	1634a	655a	484a
Large bags	2393b	2849a	1547a	1284b	1166b
T_d:T_w:					
Small bags	1.00a	1.16a	0.91a	0.40a	0.23a
Large bags	1.00a	0.96b	0.77a	0.40a	0.34a
Stomatal resistance (s m^{-1}):					
Small bags	26.4a	24.6a	43.6a	115.3a	167.7a
Large bags	25.7a	21.5a	30.2a	123.5a	162.2a

Means within each stress level and for different measurement groups followed by the same letter are not significantly different at P=0.05

After the onset of mild stress was identified, a breaking point approach (as described by Starr & Paltineanu, 1998) was followed to identify various points for the curves of daily water loss and T_d:T_w where the slope of each of the curves changed significantly. The identified breaking points were on day 3 and 4 for the small bags and on day 6 and 7 for the large bags. The first breaking point of both bag sizes was confirmed by the first signs of visual wilting which was observed in the afternoon of day 3 and day 6 for plants grown in the small and large bags respectively. This stage was identified as moderate water stress. The second breaking point for both bag sizes correlated with irreversible wilting of about 75% of the total leaves of all plants in the afternoon, while the slopes flattened from this point onwards and differences became negligible. This stage was identified as severe water stress.

Daily water loss at moderate and severe water stress varied significantly between different bag sizes, probably due to differences in the total water holding capacity (L bag^{-1}) and root concentrations. Values of volumetric water content, plant available water content, T_d:T_w and stomatal resistance at noon did not vary significantly between different bag sizes for moderate and severe water stress (Table 3.1.1). Due to measurement errors of xylem potential, stomatal resistance was a much better indicator of the development of water stress in the plant.

The results set criteria for the identification of different stages of water stress for greenhouse crops, although the values of the used indicators will vary between crops. Firstly, mild water stress was identified as the point from where the T_d:T_w does not recover under continuous drying of the medium. Next, the first breaking point after recovery, together with visual wilting, indicated moderate crop water stress, while severe water stress was identified as the point where changes in the slope of T_d:T_w becomes negligible and about 75% of all plants are irreversibly wilted.

3.1.3.3 Implication for irrigation management

The response of greenhouse cucumber plants to the drying cycle with regard to plant water relations indicated possible luxury uptake of water with the standard irrigation method for sawdust and shavings in South African greenhouses. This implicates that greenhouse cucumbers grown in coir and irrigated according to the standard irrigation method of 6-8 irrigation events per day, are over-irrigated. The recovery of cucumber plants to a more conservative uptake of water when the drying cycle was started possibly indicates the point to which water may be allowed to be depleted in coir before the next irrigation event. For both bag sizes this point was identified at mild water stress, two and three days after the previous irrigation event for the small and large bags, respectively. Although it is simpler to schedule irrigation according to fixed intervals such as days, this is not recommended since other factors like climate may influence water uptake and availability. It is therefore recommended that irrigation is scheduled to start at mild water stress which can be identified for small and large bags through the results in this paper. Soil water sensors or tensiometers may be used to monitor the change in volumetric water content of the medium to the physical point of mild water stress where irrigation is triggered. Soil water sensors such as the EC-10 and EC-20 capacitance sensors can be calibrated accurately with a simple but scientifically sound procedure to predict the volumetric water content of coir (Van der Westhuizen & Van Rensburg, 2009, Chapter 2.1). An accurate laboratory-determined retention curve developed for coir may be used to convert volumetric water content values to matric suction values, should tensiometers be the preferred method of scheduling (Figure 3.1.4). The ratio of T_d:T_w and stomatal resistance may be valuable to confirm mild water stress. The benefits of increased irrigation intervals include reduced water and fertilizer use, but may also prove beneficial as load shedding of electricity becomes more common. It should be stressed that this recommendation is based purely on plant water relations and further experiments will also consider the impact of reduced irrigation events on yield and fruit quality.

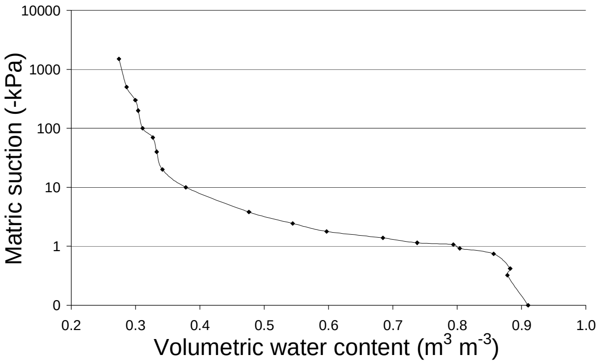

Figure 3.1.4 Water retention characteristics of coir for the conversion of volumetric water content (m^3 m^{-3}) to matric suction (-kPa) for irrigation scheduling with a tensiometer.

3.1.4 Conclusion

Greenhouse cucumber plants grown in coir are mostly over-irrigated when irrigation is scheduled according to the standard method used in South African greenhouses for sawdust and shavings. The results indicated luxury uptake which will probably not be required for maximum yield. After the onset of water stress, cucumber plants experienced a shock condition to which they responded with severely restricted water loss, but adapted and recovered to a more conservative water uptake. However, when the drying cycle continued, the plants started to gradually restrict water uptake, with the start of this gradual reduction identified as mild water stress. The observation of visual wilting supplied good evidence for the identification of moderate water stress, while breaking points for daily water loss and T_d:T_w proved to be the best indicator for identifying moderate and severe crop water stress. Measurements of xylem potential were inconsistent and are only recommended as a supportive indicator of plant water stress. Stomatal resistance recorded at 12:00 proved to be a good measure to confirm moderate and severe water stress. Water was more or less equally available to the plant up to a critical point identified as mild water stress, whereafter it decreased rapidly. Based on the plant response it is recommended to allow water depletion to the point of mild water stress before the next irrigation event is started. It is again stressed that this recommendation is based purely on plant water relations, and possible effects on yield and fruit quality were not considered and will be addressed in follow on Chapters. Soil water sensors calibrated for coir or tensiometers set to volumetric water content from the laboratory-determined retention curve, may be used to trigger irrigation at mild water stress.

The characterisation of water stress for greenhouse cucumbers grown in coir identified boundaries for different stages of water stress, which can be monitored by equipment that measures volumetric water content or matric suction. Further experimentation to determine the effect of the different identified stages of water stress on plant growth and yield as well as water use efficiency will indicate if reduced irrigation frequency in coir can maintain yield and improve irrigation efficiency in South African greenhouses. These will also be useful indicators of the ability of greenhouse cucumbers, especially those grown in small bags, to prevent large yield losses if irrigation should fail due to unforeseen situations such as power failures.

3.1.5 References

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3.2 Characterising plant water stress of greenhouse tomatoes (*Lycopersicon esculentum* Mill.)

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The standard irrigation method for greenhouse crop production in sawdust and shavings in South Africa consists of a fixed irrigation frequency of eight irrigation events over the daylight period, while the volume applied is increased throughout the growing period to maintain a drainage percentage of approximately 20% to prevent the build-up of salts. Considering that coir can hold up to 700% of its mass in water, greenhouse crops are mostly over-irrigated when scheduling occurs according to this standard method. This presumably results in luxury uptake because plants receive more water than is probably required for maximum yield or fruit quality. There is therefore a need to improve irrigation scheduling techniques in order to decrease water loss from drain-to-waste greenhouse crop production in coir in South Africa. The objectives of this study were to describe the development of plant water stress and plant response during a drying cycle of greenhouse tomatoes grown in coir for two bag sizes, to identify different stages of plant water stress and set criteria for the identification of these stages, and to determine the implication for irrigation management. From this study, mild water stress was identified as the point from where the T_d:T_w (transpiration ratio where T_d = transpiration of unwatered and T_w = transpiration of well-watered plants) does not recover under continuous drying of the medium. Visual wilting as well as the first breaking point

after mild water stress indicated moderate crop water stress. Severe water stress was identified as the point where changes in the slope of T_d:T_w over time becomes negligible and about 75% of all plants are irreversibly wilted. It is recommended to allow water depletion to the point of mild water stress, before irrigation is started, although this is based purely on plant response without considering yield. Irrigation may be triggered at volumetric water content levels of mild water stress for both bag sizes through soil water sensors calibrated for coir, or tensiometers of which matric suction is converted to volumetric water content from an accurate laboratory-determined retention curve.

Keywords: Capacitance sensors, coir, drying cycle, greenhouse tomato, water stress

3.2.1 Introduction

Coir is increasing in popularity as medium for greenhouse crops world wide (Verhagen, 1999; Noguera *et al.*, 2000). The medium has a total porosity of approximately 92%-96% (Kang *et al.,* 2004) and relatively high easily- available water content of about 35% (Prasad, 1997). Additionally, it can hold up to 700% of its mass in water, improving water use efficiency when irrigation is scheduled correctly. However, lack of knowledge on irrigation of greenhouse crops grown in coir, severely hampers the productivity of the medium, with some South African producers returning to sawdust and shavings, or production in the soil. Considering the relatively high cost of most substrates, an incorrect approach to irrigation scheduling for the medium, will result in failure to achieve improved yield, fruit quality (Böhme *et al.*, 2001; Halmann & Kobryń, 2003) and water use efficiency (Rincón *et al.*, 2005). This in return reduces drainage of fertigated water and thereby reduces the cost of nutrient loss to the producer and the environment. Continuous soil water monitoring is an increasingly common practice, used by Kennedy Irrigation Consultants (Personal communication, J. Kennedy, 2009, www.ech$_2$o.co.za) and Griekwaland-Wes Co-operative (Personal communication, J. Bothma, 2009, Douglas), for example, to apply irrigation in the summer rainfall field crop production areas of South Africa. However, to accomplish the same magnitude of success for greenhouse production in coir, it is critical to characterize the medium's water retention characteristics and ability to supply water.

Characterization should be based on measurements of irrigation, drainage, change in medium water content and evapotranspiration of the medium during a drying cycle compared to well-watered conditions. Irrigation and drainage are easily measured within a closed glasshouse environment; evaporation from the medium surface is eliminated by covering the surface area, and the change in medium water content is determined through measurement with in situ calibrated capacitance sensors. The transpiration flux of water vapour into the atmosphere from the plant foliage depends on the availability of water in the root zone and therefore transpiration can be accurately attained from the hydrological balance.

In normal irrigated production, plant water uptake is the result of water loss through transpiration which allows the plant to assimilate carbon dioxide. Daily water loss causes a reduction in leaf water potential (Ψ_L), which in turn results in a potential gradient between the medium and the plant for water absorption from the medium and transport to the leaves (Hsiao, 1990). Ψ_L is therefore always lower than medium water potential (Ψ_M) during the day as long as there is transpiration (Hsiao, 1990), while during night-time, water is redistributed due to the potential gradient that develops between areas in the medium, with and without roots, as well as between the medium and the plant leaves and roots (Loomis & Connor, 1996).

Excessively low Ψ_L can be caused by medium drying, high transpiration, high medium hydraulic resistance, or high plant hydraulic resistances, or a combination of these factors (Hsiao, 1990). Therefore, when irrigation water is withheld for an indeterminate period, Ψ_L and root water potential (Ψ_R) will initially equilibrate to meet Ψ_M at dusk, but as the medium dries out, Ψ_L and Ψ_R diurnal equilibration becomes progressively later, until finally these potentials can not recover to meet Ψ_M (Loomis & Connor, 1996). At this stage the water supply in the medium is not sufficient to meet loss by transpiration, with the result that the water potential of the leaves and shoots are depressed, causing a depression in plant water status or turgor loss, which may cause the stomata to close (Hsiao *et al.*, 1976a; Marshall & Holmes, 1988). Closure of stomata varies within the plant canopy with higher leaves intercepting more radiation and thus transpiring more, while higher leaves are also farthest from the roots, and therefore have greater Ψ_L and close stomata at higher water potential than lower leaves (Hsiao *et al.*, 1976a). Stomatal closure increases leaf hydraulic resistance (R_L) (s m^{-1}) and reduces leaf function and growth, while measurements of R_L describes the nature of the plants' response to water shortage (Loomis & Connor, 1996). Tomato plants exhibit both leaf and root osmotic adjustment to water deficit stress, allowing the crop to survive or remain productive under conditions of water shortage. Tomato stomata are highly sensitive to evaporative demand (Hsiao, 1990), and they can control the leaf water status in such a way, that plant water status is maintained over a wide range of medium water contents (Jones, 1990). Osmotic potential is lowered in response to water stress, and thereby turgor is maintained. The lower osmotic potential may enable stomatal adjustment so that stomata remain open, as Ψ_L decreases. This characteristic of tomatoes further allows the crop to maintain a favourable water status particularly in the roots and also maintains growth during water stress periods (Wullschleger & Oosterhuis, 1991). Therefore significant differences in stomatal resistance only occur at severe water shortages (Grange & Hand, 1987), while closure of the stomata needs to be considerable and stomatal resistance quite high, to exert a significant effect on transpiration (Hsiao, 1990). Jones (1990) confirmed the importance of R_L and added plant responses such as visual wilting/rolling or leaf orientation, which reduce interception and radiation for photosynthesis (Hsiao *et al.*, 1976b), and changes in growth rate or plant dimensions as indicators of water stress, to improve crop water status under water stress. Plant water status is however not a very sensitive indicator of water stress (Jones, 1990). Apical meristems are relatively isolated from water shortage, with the result that leaf initiation is the last process affected by water stress. Leaf primordia may accumulate on the meristem under severe water stress and continue cell division and expansion, when assimilate supply and turgor are once more suitable.

Medium-plant predawn water potential disequilibrium can occur even earlier, if night-time transpiration is substantial (Caird *et al.*, 2007a). As during the day, night-time water loss depends on leaf conductance and the vapour pressure deficit (VPD) between leaves and the air, as well as canopy structure and atmospheric mixing. According to Caird *et al.* (2007b), night-time transpiration rates of tomato plants under ambient glasshouse conditions are 9%-30% and much higher than for the field grown tomato crops, which only indicated a maximum of 10%. Leaf conductance during night-time can be attributed to the following factors: i) Photoperiod length and light intensity can affect the speed and degree to which stomata close in the dark, e.g., incomplete closure resulted from short-day photoperiods in Crysanthemum, while high light intensity during the day or longer photoperiods, resulted in faster stomatal closure in roses, although closure was not complete (Caird *et al.*, 2007a). ii) Conditions that allow high photosynthetic rates during daytime, can also result in high night-time conductance, e.g., leaf-to-air VPD and air movement are important determinants of the magnitude of water loss, with partially open tomato stomata causing substantial water loss throughout the night (Caird *et al.*, 2007b). iii) Plants may pre-open stomata before dawn in an effort to increase their photosynthetic carbon gain. This may be especially advantageous in water-limited environments, because of higher potential for early morning carbon gain when temperatures and VPD are lower (Caird *et al.*, 2007a). In contrast, Donovan *et al.* (2003) argued that substantial night-time water loss, due to low water availability and/or high night-time VPD, decreases predawn water status of plants, which will lead to the loss of limited water resource without carbon gain and may shorten the period of photosynthetic carbon gain (Rawson & Clarke, 1988), thus reducing overall plant water use efficiency. Potential reduction in crop productivity could result from reduced plant water status, compared with non-night-time transpiring plants (Caird *et al.*, 2007b). The objectives of this study were i) to describe the development of plant water stress and plant reaction during a drying cycle of greenhouse tomatoes grown in coir, ii) to identify different stages of plant water stress as well as criteria for the identification of these stages, and iii) to describe the implication thereof on irrigation management.

3.2.2 Material and methods

3.2.2.1 Location and cropping details

The experiment was conducted in a 48 m^2 temperature-controlled glasshouse at the University of the Free State, in the Free State province of South Africa (26º11’20” E, 29º06’33” S, 1409 m altitude). Tomato (*Lycopersicon esculentum* Mill.) seed of the cultivar Espadilha were sown on 9 April 2008 in seedling trays. Seedlings were transplanted to 9 L and 20 L bags filled with coir at a mean density of 1.8 plants m^{-2} on 15 May 2008. All coir used in the experiment (30 x 5 kg blocks) was processed before the bags were filled to minimise variation in bulk density between bags. Compressed coir blocks were soaked in water, excess water was drained and the coir was spread out on plastic sheeting and mixed to ensure uniform distribution of coir dust and fibres in all bags. The medium was flushed within the bags using municipal water of EC 0.2 mS cm^{-1} until the EC of the drain water was equal to that of the input water. Plants were fertigated through a drip irrigation system with a balanced nutrient solution of EC 2.0 mS cm^{-1} (Maree, 1993), which was prepared from feeding municipal water with an EC of <0.2 mS cm^{-1}.

3.2.2.2 Treatments and experimental design

Plant response to irrigation treatments were evaluated in two bag sizes. Planted bags were organised in eight single rows which were divided into two blocks, resulting in four single rows of 12 plants per bag size, *viz.*, 9 L and 20 L. The tomato plants were grown to full maturity, reaching the horizontal trellising wire 2 m above the bag surface and in full production, in accordance to local practice, before the irrigation treatments were applied randomly in each bag size block. Before the irrigation treatments started, all plants were irrigated according to the standard irrigation method used in South African greenhouses, which consists of a fixed irrigation frequency of eight irrigation events over the daylight period. The volume applied was increased throughout the growing period to maintain a drainage percentage of approximately 20% to prevent a build-up of salts. The irrigation treatments which started on 23 August 2008, consisted of an unwatered treatment with no irrigation, to create a drying cycle and induce water stress, and a well-watered control treatment which was irrigated as described. The drying cycle lasted about five days for the small bags and eight days for the large bags, whereafter the experiment was terminated.

3.2.2.3 Measurements

Echo 10 and Echo 20 capacitance water sensors (Decagon Devices, Inc.) were installed vertically in the 9 L and 20 L bags, respectively. A 7 cm distance between the sensor, emitter and plant was constant for all treatments and replications (Thompson *et al.*, 2006). A data logger (model CR1000, Campbell Scientific Africa) recorded water content measurements of the sensors (in mV) every 20 minutes. The millivolt readings were converted to volumetric water content values (m^3 m^{-3}) through in situ determined calibrations as described by Van der Westhuizen and Van Rensburg (2009, Chapter 2.1). The exposed surface area of the medium was covered with cardboard to prevent evaporation losses. Transpiration (T) was determined from the water balance equation: $T = I – D – \Delta\theta$; where I = irrigation (m^3), D = drainage (m^3) and $\Delta\theta$ is the change in water content (m^3) as measured through the previously mentioned calibrated sensors. Irrigation and drainage volumes of four plants per irrigation treatment and medium volume, were measured once a day. Water potential of mature leaves, located at the top of the canopy, was measured daily at dawn and midday with a Scholander pressure chamber. Leaves were not removed entirely, but rather a section of about one by five centimetres were cut from the leaves and measurements were taken within one minute after each section was cut, to prevent serious changes in leaf water status. Four sections were measured per irrigation treatment and bag size. Removal of sections of the leaves was spread over replications (single plants) so that the same plant was only used again, after three measurement events. One leaf allowed for the removal of approximately four sections, therefore a maximum of two leaves per plant was used for the duration of the experiment. Stomatal resistance (s m^{-1}) was measured with a steady state diffusion porometer (model SC-1, Decagon Devices, Inc.), as indicator of plant water stress, on four plants per irrigation treatment and bag size. Stomatal resistance was measured daily at dawn and midday. Well-watered treatments were used as reference data for comparison with unwatered treatments, thereby nullifying the need for weather data outside of the greenhouse.

3.2.2.4 Methods used to identify different stages of crop water stress

Various approaches identified in a previous experiment (Van der Westhuizen *et al.*, 2009, Chapter 3.1) were used to determine the different stages of crop water stress, during a continuous drying cycle. The first approach was based on the transpiration ratio (T_d:T_w; where T_d = Transpiration unwatered (ET_a) and T_w = transpiration well-watered/reference transpiration (ET_p)), where water stress increases as the ratio nears zero and differences between measurements becomes negligible (Botha *et al.*, 1983; Loomis & Connor, 1996). Secondly, the breaking point approach identifies a point where the medium displays a critical change in water content or a breaking point (Starr & Paltineanu, 1998). The third approach was according to Ψ_L (kPa) (Hsiao, 1990) and R_L (s m^{-1}) (Loomis & Connor, 1996), as well as visual symptoms of wilting. Magnitude of crop water stress was increased as the Ψ_L and R_L of unwatered plants increased, relative to that of well-watered plants. The criteria were as follows: i) Mild water stress was identified as the point from where the T_d:T_w does not recover under continuous drying of the medium. ii) Visual wilting indicated moderate crop water stress. iii) Severe water stress was identified as the point where changes in the slope of T_d:T_w becomes negligible and about 75% of all plants are irreversibly wilted.

After the identification of the different stages of crop water stress, plant available water content was determined and introduced as indicator of the various stages of water stress. This was done in an effort to create a universal indicator which will overcome differences between systems, e.g., different bag sizes. Plant available water content was determined as the water content between the drained upper limit (DUL) and the lower limit of water availability. DUL was determined in the laboratory using three samples packed to a density of 0.1 g cm^{-3} in 876 cm^3 columns. Samples were first saturated under vacuum pressure (-50 kPa), before being transferred to a wet sand bath where they drained for three days. Mass were recorded and expressed in a volumetric format. The lower limit was determined during the experiment as a point in the drying cycle when all plants suffered wilting. Millivolt readings at these points were used to express the lower limit for each bag size on a volumetric basis.

3.2.2.5 Statistical analyses

A one way analysis of variance (ANOVA) was performed on the volumetric water content, plant available water content, daily water loss, T_d:T_w, leaf water potential and stomatal conductance results of the different bag sizes, for the different water stress levels. P-values were used to compare means at a 5% probability level, using STATISTICA version 8.0 (StatSoft Inc., 2004).

3.2.3 Results and discussion

3.2.3.1 Development of plant water stress and plant response

The change in volumetric water content for the well-watered and unwatered treatments over the entire drying cycle are presented in Figure 3.2.1a and Figure 3.2.2a, for the small and large bags, respectively. Water contents of well-watered treatments ranged from 0.640 $m^3\ m^{-3}$ to 0.751 $m^3\ m^{-3}$ for the small bags and 0.642 $m^3\ m^{-3}$ to 0.704 $m^3\ m^{-3}$ for the large bags throughout the drying cycle. The water content of both bags ranged above the laboratory-determined DUL for coir, *viz*., 0.607 $m^3\ m^{-3}$, indicating that there was no water shortage in the well-watered plots, but also indicating that the standard irrigation strategy, used for greenhouse crops grown in sawdust and shavings, over-irrigates coir. This was supported by expressing the total amount of drainage as a percentage of the total irrigation application over the experimental period, which resulted in unproductive water losses of 18% and 36% for the small and large bags, respectively. In contrast, the complete lack of irrigation in the unwatered treatments caused a steady decline of the volumetric water content over time in both bag sizes and the plants were forced to rely on the coir reservoir to supply water to meet the daily requirements. The unwatered treatment characterised the development of crop water stress during a drying cycle (Figure 3.2.1a-h, 3.2.2a-h). The drying cycle lasted five days for the small bags and nine days for the large bags. Trends of all data were similar for the small and large bags and therefore some of the results will be discussed without special reference to individual bag sizes, although both are implicated.

Two different phases of daily water loss were observed for the unwatered treatments, namely an initial reduction in water loss, followed by a continuous decline in water loss by the plants without any further recovery (Figure 3.2.1b, 3.2.2b). The plants, therefore, experienced a shock condition from the onset of water stress and restricted water loss severely, although they recovered quickly to more conservative values of water loss during the first phase. This may be the result of luxurious uptake in response to the high frequency irrigation scheduling. It is uncertain if the luxurious uptake is required for optimal plant growth and production and if water use efficiency can be improved by irrigating at a target value, similar to the conditioned state. This will be evaluated in the near future. Reduced night-time water losses were observed for the unwatered treatments, compared to the well-watered treatments for the small bags, but not for the large bags (Figure 3.2.1c, 3.2.2c). The difference between water loss for well-watered and unwatered treatments in the small bags, increased towards the end of the experiment. No such trend was found for the large bags, which may be explained by the observation by Caird *et al.* (2007a), that plants may pre-open their stomata before dawn in an effort to increase their photosynthetic carbon gain, especially in water-limited environments, because of the higher potential for early morning carbon gain, when temperatures and VPD are lower. However, this may be debatable if the contrasting argument by Donovan *et al.* (2003) is considered which states that substantial night-time water loss, due to low water availability and/or high night-time VPD, decreases predawn water status of plants. This will lead to the loss of limited water resource without carbon gain (Caird *et al.*, 2007b) and may shorten the period of photosynthetic carbon gain (Rawson & Clarke, 1988), thus reducing overall plant water use efficiency. Measurements of stomatal conductance were taken during the night (data not shown) in the glasshouse and confirmed some stomatal activity. However, the stomatal conductance during the night could also have been the result of street lights in the vicinity of the glasshouse.

The relationship between T_d and T_w also decreased rapidly early in the drying cycle, but also recovered partially as the plant conditioned itself to the changed water levels in the medium (Figure 3.2.1d, 3.2.2d). Thereafter, a constant reduction in T_d:T_w occurred, as the plant approached permanent wilting.

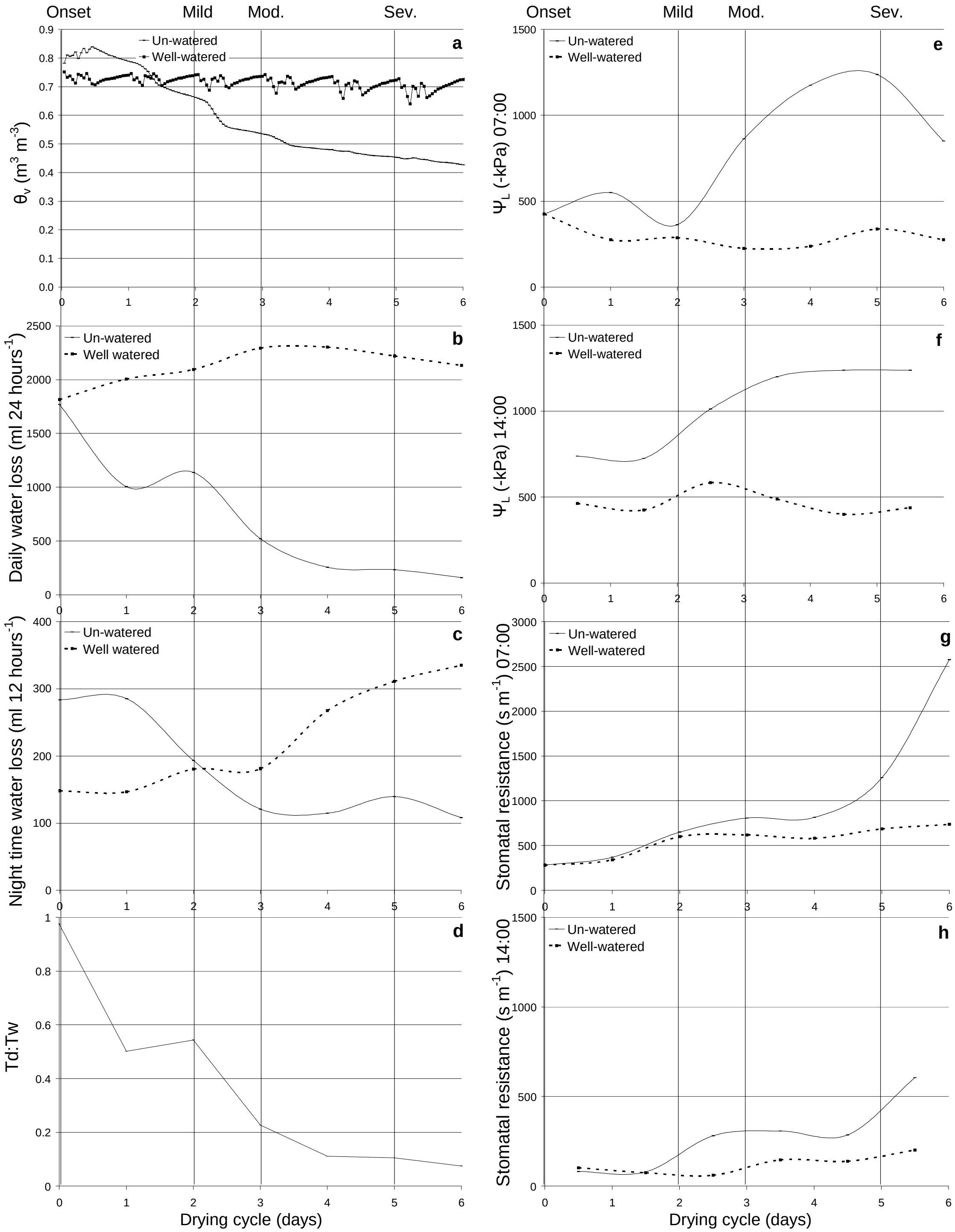

Figure 3.2.1 Development of water stress of tomato plants during the drying cycle induced in the small bags (9 L): a) Diurnal change in volumetric water content ($m^3\ m^{-3}$); b) Daily water loss (ml 24 hours^{-1}); c) Night-time water loss (ml 12 hours^{-1}); d) Actual transpiration (T_d) over potential transpiration (T_w); e) Xylem potential (-kPa) measured at dawn (07:00); f) Xylem potential (-kPa) measured at midday (14:00); g) Stomatal resistance (s m^{-1}) measured at dawn (07:00); and h) Stomatal resistance (s m^{-1}) measured at midday (14:00). The different stages of plant water stress are indicated by vertical lines on the graphs, *viz*. onset of water stress (Onset), mild (Mild), moderate (Mod.) and severe (Sev.) water stress.

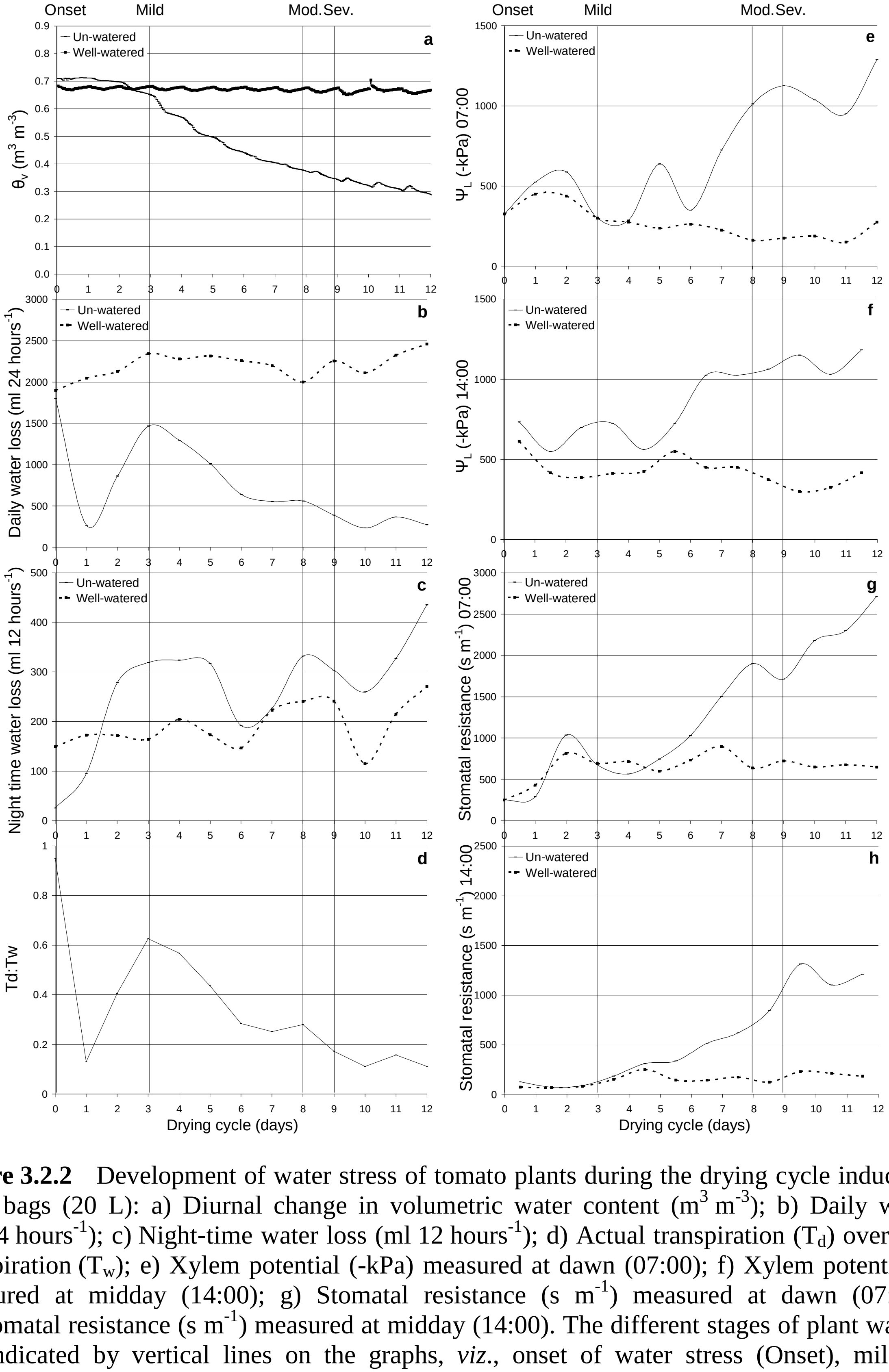

Figure 3.2.2 Development of water stress of tomato plants during the drying cycle induced in the large bags (20 L): a) Diurnal change in volumetric water content (m^3 m^{-3}); b) Daily water loss (ml 24 hours^{-1}); c) Night-time water loss (ml 12 hours^{-1}); d) Actual transpiration (T_d) over potential transpiration (T_w); e) Xylem potential (-kPa) measured at dawn (07:00); f) Xylem potential (-kPa) measured at midday (14:00); g) Stomatal resistance (s m^{-1}) measured at dawn (07:00); and h) Stomatal resistance (s m^{-1}) measured at midday (14:00). The different stages of plant water stress are indicated by vertical lines on the graphs, *viz.*, onset of water stress (Onset), mild (Mild), moderate (Mod.) and severe (Sev.) water stress.

Regular monitoring of the response of the tomato plants to water stress symptoms resulted in the observation of soft leaves, approximately 0.5 and 3.5 days, before wilting was visible for plants in the small and large bags, respectively (Table 3.2.1). The observation of softer leaves was made after the plant experienced mild water stress. This indicates that mild water stress may be the limit to which water can be depleted, before it affects the turgidity of the tomato plant. After visible wilting, the tomato plants deteriorated rapidly and reached severe wilting shortly after visual wilting (Figure 3.2.3).

Leaf water potential as well as stomatal resistance indicated plant water stress of the unwatered, compared to the well-watered treatments for plants in the small and large bags at both dawn and midday (Figure 3.2.1e, f, 3.2.2e, f). Both Ψ_L and R_L increased rapidly from similar points, where recovery was observed in daily water loss and T_d:T_w. From these results, it seems that stomatal opening and leaf water potential are good indicators of tomato plant water stress, although measurements should be taken at a fixed time daily, to increase sensitivity of the predictions of water stress.

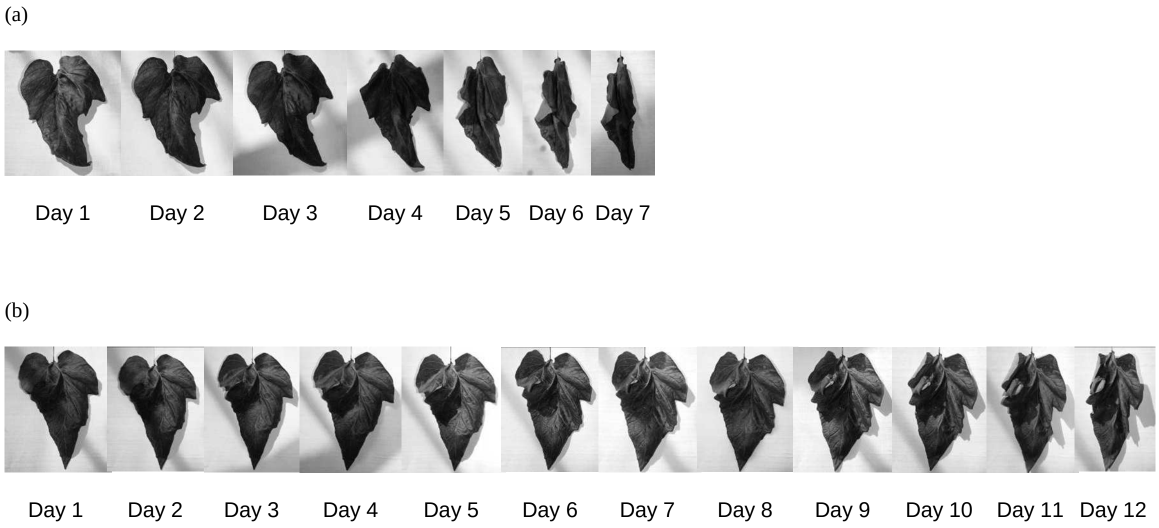

Figure 3.2.3 Development of visual water stress symptoms of tomato plants grown in a) 9 L and b) 20 L bags.

Table 3.2.1 Diagnostic symptoms of water stress in greenhouse tomatoes, after the onset of two drying cycles in small and large bags filled with coir, respectively.

Day	Time	Small bags	Large bags
2	14:00	No visual signs of wilting Some leaves from dry plots feel softer compared to wet plots	No visual signs of wilting
3	07:00	First signs of wilting	
4	07:00	All plants from dry plots are wilted, some severely	
	14:00	All plants from dry plots are moderately to severely wilted	No visual signs of wilting Some leaves from dry plots feel softer compared to wet plots
5	07:00	Bottom 75% of all plants from dry plots are severely wilted	
	14:00	Top 25% of all plants from dry plots also suffer visual wilting	
6	07:00	Top 25% of all plants from dry plots suffer severe wilting	Leaves of all plants from dry plots are softer than those from wet plots
	14:00	Leaves are becoming brittle from the bottom of all plants from the dry plots	
7	07:00	Plants beyond recovery and removed from greenhouse	
8	07:00		First signs of wilting on bottom 20-50% of some plants from dry plots
	14:00		Most plants from dry plots show visual symptoms in bottom leaves
9	07:00		Most plants from dry plots are wilted
	14:00		Bottom 75% of all plants from dry plots are severely wilted
13	07:00		Plants beyond recovery and removed from greenhouse

3.2.3.2 Different stages of plant water stress

Four different stages of plant water stress was characterized as the drying cycles progressed and are indicated by the vertical lines on Figure 3.2.1 and Figure 3.2.2. These are expressed as the onset of water stress (Onset), mild water stress (Mild), moderate water stress (Mod.) and severe water stress (Sev.).

Since the drying cycle was started by the discontinuation of irrigation, this point was identified as the onset of water stress. This point triggered the decrease in water content ($m^3\ m^{-3}$) and water loss (ml) of the unwatered treatments, relative to the well-watered treatments to the point of recovery (Figure 3.2.1a-c, 3.2.2a-c). Since the water content, water loss and T_d:T_w gradually declined after recovery, this point was identified as the onset of mild water stress (Figure 3.2.1a-d, 3.2.2a-d). This point is supported by the increase in leaf water potential and stomatal resistance for plants of unwatered treatments, compared to that of well-watered treatments for both bag sizes (Figure 3.2.1e-h, 3.2.2e-h). From the results, it is obvious that the tomato plants already started to experience water stress regardless of the lack of visual wilting at the onset of mild water stress. This is supported by the findings of Araki *et al.* (2000), which indicated that leaf water potentials for well-watered tomato plants are approximately equal to -600 kPa, while that of water-stressed plants can decrease to -1400 kPa, under severe water stress.

Volumetric water content, plant available water content, daily water use, T_d:T_w, and leaf water potential measured at noon at mild water stress, was not significantly different ($P = 0.05$) between bag sizes (Table 3.2.2). It seems that these values are the best indicators of mild water stress for tomato plants grown in small and large bags. Stomatal resistance at mild water stress varied significantly between the small and large bags. This may probably be ascribed to the great variation in R_L between replicate plants in the small and large bags, respectively (data of individual replicates not shown). This may indicate that stomatal resistance is too variable to use as an indicator of mild water stress, although it may be useful to confirm stress.

The breaking point approach described by Starr and Paltineanu (1998), was followed to identify various points for the curves of daily water loss and T_d:T_w, starting from the newly identified point of mild water stress, to the end of the drying cycle. Two points were identified where the slope of each of the curves changed significantly on day 3 and 4, for the small bags and on day 8 and 9, for the large bags. The first signs of visual wilting coincided with the first breaking point on day 3 and 8, for plants grown in the small and large bags, respectively (Figure 3.2.3). This stage was identified as moderate water stress. Irreversible wilting of about 75% of all leaves on all plants occurred in the afternoon of day 4 and 9, for the small and large bags respectively, and this stage was identified as severe water stress (Table 3.2.1).

Table 3.2.2 Comparison of various physical points between well-watered (reference) treatments, onset of water stress, mild water stress, moderate water stress, severe water stress and irreversible water stress for greenhouse tomatoes grown in small and large bags in a coir medium.

	Reference	Onset	Mild	Moderate	Severe
Days after drying cycle started:					
Small bags	-	0	2	3	5
Large bags	-	0	3	8	9
Volumetric water content (m^3 m^{-3}):					
Small bags	0.733a	0.786a	0.533a	0.480a	0.452a
Large bags	0.786a	0.713a	0.568a	0.342b	0.320b
Plant available water content (%):					
Small bags	226a	272a	50a	0a	-24a
Large bags	168a	147a	88a	0a	-9b
Daily water loss (ml 24 $hours^{-1}$):					
Small bags	2116a	1754a	1154a	528a	269a
Large bags	2087a	1802a	1465a	556a	399a
T_d:T_w:					
Small bags	1.00a	0.96a	0.54a	0.24a	0.12a
Large bags	1.00a	1.08a	0.63a	0.27a	0.18a
Leaf water potential (-kPa):					
Small bags	470a	738a	725a	1013a	1238a
Large bags	433a	733a	700a	1025a	1063a
Stomatal resistance (s m^{-1}):					
Small bags	87.7a	81.4a	280.5a	391.4a	638.0a
Large bags	81.5a	126.0a	183.8b	852.7b	1184.7a

Means within each stress level and for different measurement groups followed by the same letter are not significantly different at P=0.05

Volumetric water content at moderate water stress varied significantly between different bag sizes. Values of plant available water content, daily water use, T_d:T_w and leaf water potential at noon, did not vary significantly ($P = 0.05$) between different bag sizes for moderate water stress (Table 3.2.2). At severe water stress, volumetric water content and plant available water content, varied significantly between bag sizes ($P = 0.05$), while daily water loss, T_d:T_w and stomatal resistance varied significantly at $P = 0.10$. Great variation in volumetric water content, plant available water and daily water use between bag sizes at moderate and severe water stress, is probably due to differences in the water holding capacity and root concentrations. Great variation in stomatal resistance at moderate and severe water stress, between replicated plants, again indicated that this is not a reliable method for monitoring the development of crop water stress, although it may be useful to confirm water stress.

3.2.3.3 Implication for irrigation management

Greenhouse tomato plants responded similarly to greenhouse cucumber plants, to the drying cycle induced by the unwatered treatment. The result was again luxury uptake of water, when plants are irrigated according to the standard irrigation method, for sawdust and shavings in South African greenhouses. Greenhouse tomatoes grown in coir and irrigated according to the standard irrigation method of 6 to 8 irrigation events per day, are therefore over-irrigated. The adaptation of tomato plants to the initial drying period possibly indicates the point to which water may be allowed to be depleted in coir, before the next irrigation event. This point was identified at mild water stress, two and three days after the previous irrigation event, at 0.533 m^3 m^{-3} for the small bags and 0.568 m^3 m^{-3} for the large bags. Similar threshold values of plant available water content for irrigation scheduling were observed by Thompson *et al.* (2007), at 49%-70% and 52%-81% for winter and spring tomato, respectively, while the variation was due to the method used to determine drained upper limit (DUL) and permanent wilting point (PWP). Lower values were observed by the authors for DUL and PWP values determined in the laboratory by pressure plate (30 kPa-1500 kPa), while higher values were observed using values of DUL and PWP determined in situ, although the PWP value used, was determined for a pepper crop. Scheduling of irrigation according to fixed intervals such as days, is not recommended, since other factors like climate may influence water uptake and availability. In order to schedule irrigation to start at a targeted water content depletion level such as mild water stress, the volumetric water content of the medium must be monitored continuously. Therefore irrigation can be controlled by the use of soil water sensors or tensiometers. The volumetric water content can easily be predicted by soil water sensors such as the EC-10 and EC-20 capacitance sensors, which can be calibrated accurately for coir with a simple, but scientifically sound procedure (Van der Westhuizen & Van Rensburg, 2009, Chapter 2.1). Tensiometers can also be used for scheduling to a targeted water content depletion level, by converting matric suction values to volumetric water content values, through an accurate laboratory-determined retention curve developed for coir (Figure 3.2.4). The use of water content depletion levels to schedule irrigation will increase the irrigation intervals, which may in turn reduce the water and fertilizer use, while it may also prove beneficial, as load shedding of electricity becomes more common.

The possible water depletion level identified as mild water stress for the scheduling of irrigation in coir, is purely based on plant water relations. Further experiments will consider the impact of the reduced irrigation events on yield and fruit quality.

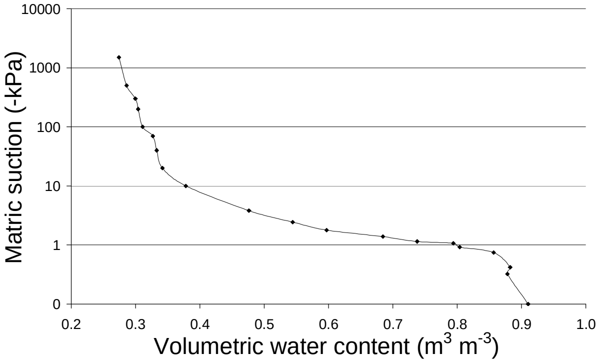

Figure 3.2.4 Water retention characteristics of coir for the conversion of volumetric water content (m^3 m^{-3}) to matric suction (-kPa) for irrigation scheduling with a tensiometer.

3.2.4 Conclusion

From this study, luxurious water uptake is evident for greenhouse tomato plants grown in coir, and irrigated according to the standard method for sawdust and shavings in South African greenhouses, although the effect on yield remains uncertain. As irrigation was discontinued in the unwatered treatments, the tomato plants severely restricted water loss, although it recovered to a point where water uptake was more conservative. This point of recovery was identified as mild water stress. Continuation of the drying cycle further restricted water uptake, without recovery. Breaking points for daily water loss and T_d:T_w identified moderate and severe crop water stress, which coincided firstly, with visual wilting and secondly, with a point where the slope of T_d:T_w becomes negligible and about 75% of all plants are irreversibly wilted. Although leaf water potential and stomatal resistance increased from the point of mild water stress, there were no distinct boundaries between the different stages of crop water stress. Both methods are therefore only recommended as a supportive indicator of plant water stress.

The recommendation to allow water depletion to the point of mild water stress before irrigation is started, is based purely on plant response without considering yield. Irrigation may be triggered at volumetric water content levels at mild water stress for both bag sizes, through soil water sensors calibrated for coir or tensiometers, of which matric suction is converted to volumetric water content from the laboratory-determined retention curve.

From the current study, volumetric water content boundaries for different stages of water stress, was identified for greenhouse tomatoes grown in coir. The effect of the different identified stages of water stress on plant growth and yield, as well as water use efficiency will be tested in future experiments to ensure verification of the finding that reduced irrigation frequency in coir can maintain yield and improve irrigation efficiency in South African greenhouses. Yield data will further indicate if greenhouse tomatoes, especially those grown in small bags, can resist large yield losses, if irrigation should fail due to unforeseen situations, such as power failures.

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Chapter 4

4.1 Effect of pre-determined water depletion levels on the water balance components, yield and water use efficiency of greenhouse cucumbers (*Cucumis sativus*) in coir

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Sawdust and shavings are becoming scarcer and more expensive and some greenhouse producers have started to experiment with coir as growth medium. Difficulty to schedule irrigation is however a big obstacle and producers may not achieve similar yields compared to sawdust and shavings. This may be the result of over-irrigation as producers use the standard irrigation method which consists of a fixed number of irrigations per day for sawdust and shavings. The objectives of this study were to assess the use of capacitance sensors for irrigation management with regard to bag size and target depletion levels, and determine the effect of this management option on sensor performance, water balance components, yield and water use efficiency of greenhouse cucumber plants (*Cucumis sativus).* The results of this study indicated that irrigation can be successfully and accurately managed to pre-determined water content levels in both the 9 L and 20 L bag sizes. However, it is recommended that the EC-10 and EC-20 capacitance sensors are also calibrated between the drained upper limit and saturation and that multiple sensors should be used to eliminate faulty measurements. It is also suggested that irrigation should be managed to an upper level where it is turned off instead of fixed volume application. Scheduling to the pre-determined level identified between mild water stress and the drained upper limit in both bag sizes, decreased the irrigation and drainage to between 42–58% and 12–24% for the small and large bags, respectively, while maintaining or even improving yield compared to the standard irrigation treatment. This increased the transpiration and irrigation water use efficiency significantly, indicating that the standard irrigation method restrict yield through over-irrigation. Further experiments should comprise of several depletion levels between mild water stress and the drained upper limit for individual bag sizes to identify the optimum depletion level for irrigation scheduling of greenhouse cucumbers.

Keywords: Capacitance sensors, coir, greenhouse cucumbers, water depletion, water use efficiency, yield

4.1.1 Introduction

Cucumber plants grow vigorously and therefore require plenty of water (Mao *et al*., 2003; Suojala-Ahlfors & Salo, 2005). Cucumber plants subjected to water stress levels of -600 kPa yield less compared to plants subjected to higher water potentials (Suojala-Ahlfors & Salo, 2005). Suojala-Ahlfors and Salo (2005) recommend irrigation scheduling based on soil water content measured by tensiometers to an optimal threshold for starting irrigation between -15 and -30 kPa for sand and sandy clay soils. Scheduling within soil water content boundaries can be achieved through the use of soil water sensors. Zotarelli *et al*. (2009) observed that the appropriate use of sensor based irrigation systems can allow producers to sustain profitable yield while reducing irrigation application for tomatoes grown in a sandy soil. However, when crops are grown in soil, rooting depth, field capacities, wilting point, sensor calibration and sensor accuracy across the relevant range of water contents are issues of uncertainty, which impede the scheduling of irrigation to a recommended fixed threshold value of plant available water content with soil water sensors (Thompson *et al.*, 2007).

Efficient use of water by a crop and irrigation system is essential to improve irrigation especially in arid and semiarid regions. To complicate the situation, different crops and even cultivars of the same crop may vary in their response to water deficit, especially during sensitive growth stages.

Crop water use efficiency (WUE_{ET}, g L^{-1}) as defined by Bennie *et al*. (1988) limits the WUE_{ET} to the total amount of marketable produce per volume of water lost through evapotranspiration; thereby they simplified the comparison between greenhouse crops since the marketable fruit is the desired product and not total biomass. Irrigation efficiency (WUE_I, g L^{-1}) reflects on the marketable produce per volume water applied through the irrigation system, while the water added is subject to unproductive water losses, e.g. evaporation, runoff and drainage (Hillel, 1987).

Variable results exist for WUE_{ET} and WUE_I under deficit and well-watered conditions for the cucumber crop grown in soil, which is probably dependent on the severity and timing of water stress. Kaya *et al*. (2005) found an increase in WUE_{ET} under deficit irrigation scheduled to 75% of A-pan evaporation every three days, regardless of a greatly reduced fruit yield. They observed mean WUE_{ET} values for field cucumbers of 3.7 g L^{-1} without mulch and 5.3 g L^{-1} for deficit irrigation with mulch. Mao *et al*. (2003) observed the best WUE_{ET} and WUE_I of 56.6 and 48.7 g L^{-1} over the total production season when deficit irrigation in the form of a fixed frequency every 18-20 days, was applied for greenhouse cucumbers in soil. Şimşek *et al*. (2005) confirmed improved WUE_I but not WUE_{ET} for open field cucumbers under deficit irrigation which were started at 50% of available soil water. The mean WUE_I over two years were 8.6 g L^{-1} for well-watered plants compared to 14.3 g L^{-1} for the deficit treatment, while WUE_{ET} for the well-watered treatment was 8.6 g L^{-1} compared to 8.0 g L^{-1} for the deficit treatment. According to Şimşek *et al*. (2005), over-irrigation had the lowest WUE_{ET} and WUE_I of 6.8 g L^{-1} and 6.6 g L^{-1}, respectively. The results from over-irrigation observed by Şimşek *et al*. (2005) suggest that cucumber plants are sensitive to excessive watering and significant water and yield losses can occur. They proposed a polynomial relationship between irrigation and marketable fruit yield for a cucumber crop. Mao *et al*. (2003), Yuan *et al*. (2006) and Tüzel *et al*. (2009) observed good linear relationships between yield and irrigation water amount. The authors did however not consider the effects of over-irrigation and therefore the use of the linear equations involves a lot of uncertainty. The objectives of this study were i) to assess the irrigation management options with regard to bag size and target depletion levels of a cucumber crop grown in coir, and ii) to determine the effect of these management options on the water balance components, yield and water use efficiency.

4.1.2 Material and methods

4.1.2.1 Location and cropping details

The experiment was conducted on fresh market cucumber (*Cucumis sativus*) of the cultivar Airbus in a 48 m^2 temperature-controlled glasshouse at the University of the Free State in the Free State province of South Africa (26º11’20” E, 29º06’33” S, 1409 m altitude). Cucumber seed were sown on 15 January 2009 and transplanted at a mean density of 2 plants m^{-2} on 23 January 2009. Seedlings were transplanted to 9 L and 20 L bags filled with coir, with drainage holes at the bottom of all bags to prevent the build-up of a water table. All coir used in the experiment (30 x 5 kg blocks) was processed before the bags were filled to minimise variation in bulk density between bags. Municipal water with an electrical conductivity (EC) of below 0.2 mS cm^{-1} was used to flush the coir of excess salts. Plants were fertigated through a drip irrigation system with a balanced nutrient solution of EC 1.8 mS cm^{-1} (Maree, 1992). The cucumber plants were topped when they reached the horizontal trellising wire approximately 2 m above the bag surface and the experiment was only terminated once all the fruit on all the plants were harvested.

4.1.2.2 Treatments and experimental design

The response of cucumber plants to irrigation scheduled to pre-determined water depletion levels were evaluated in two bag sizes. Planted bags were organised in eight single rows which were divided into two blocks, resulting in four single rows of 12 plants per bag size *viz*. 9 L and 20 L. The outer rows and plants on the ends of rows were excluded from the experimental plot. The cucumber plants were irrigated according to the standard irrigation method used in South African greenhouses, which consists of a fixed irrigation frequency of eight irrigation events over the daylight period, for two weeks after transplanting before the irrigation treatments were applied randomly in each bag size block. The irrigation treatments started on 6 February 2009 and included a control irrigation treatment namely the standard irrigation method and three irrigation treatments scheduled to start irrigation at pre-determined water depletion levels identified in a previous study by Van der Westhuizen *et al*. (2009, Chapter 3.1). This comprised depletion to a level identified between the water contents recorded for the standard irrigation method and mild water stress (BSM), mild water stress (Mild) and moderate water stress (Mod). The depletion levels were at approximately 0.585 m^3 m^{-3} for BSM, 0.452 m^3 m^{-3} for Mild and 0.335 m^3 m^{-3} for Mod in the small bags, and 0.565 m^3 m^{-3} for BSM, 0.421 m^3 m^{-3} for Mild and 0.253 m^3 m^{-3} for Mod in the large bags.

Irrigation volumes were determined as the difference between the laboratory determined drained upper limit (DUL) of 0.607 m^3 m^{-3} and the depletion level, plus 20% to maintain a drainage percentage of approximately 20% to ensure that the drainage water EC never increased by more than 50% of the applied nutrient solution EC (Combrink, 2005). Different irrigation treatments were applied for the duration of the experiment until all fruit from all plants were harvested; whereafter the experiment was terminated on 27 March 2009.

4.1.2.3 Measurements

Echo 10 and Echo 20 capacitance sensors (Decagon Devices, Inc.) were installed vertically in the 9 L and 20 L bags respectively. A 7 cm distance between the sensor, emitter and plant was constant for all treatments and replications as recommended by Thompson *et al.* (2006). A data logger (model CR1000, Campbell Scientific Africa) recorded soil water content measurements of the sensors (in mV) every 20 minutes. The millivolt readings were converted to volumetric water content values (m^3 m^{-3}) through in situ calibrations as described by Van der Westhuizen and Van Rensburg (2009, Chapter 2.1). The exposed surface area of the medium was covered with cardboard to reduce evaporation losses. Transpiration (T) was determined from the water balance equation: $T = I - D - \Delta\theta$; where I = irrigation (m^3), D = drainage (m^3) and $\Delta\theta$ is the change in water content (m^3) as measured through the mentioned calibrated sensors in this study. Irrigation and drainage amounts of two random plants per irrigation treatment and bag size, was measured daily. Fruit was harvested twice a week and marketable yield with regard to fruit number and fruit yield was recorded per plant for all irrigation treatments. Transpiration water use efficiency (WUE_T) and irrigation water use efficiency (WUE_I) were calculated per square meter as gram fresh marketable yield per litre water transpired or applied.

4.1.2.4 Statistical analyses

Factorial analysis of variance (ANOVA) was performed on the total fruit number, total fruit fresh yield, total WUE_T and total WUE_I with bag size and irrigation treatments as factors. P-values were used to compare means at a 5% probability level, using STATISTICA version 8.0 (StatSoft Inc., 2004).

4.1.3 Results and discussion

4.1.3.1 Sensor performance in controlling irrigation to pre-determined depletion levels

The changes in volumetric water content for the various irrigation treatments over the entire production season for greenhouse cucumbers are presented in Figure 4.1.1 for the small bags and Figure 4.1.2 for the large bags. The results for the individual bag sizes are discussed separately, since water depletion was dissimilar between bag sizes.

In the small bags, a gradual increase in volumetric water content occurred for the standard irrigation treatment over the first 6 weeks of the experiment, whereafter it remained approximately constant for the duration of the production season (Figure 4.1.1a). The volumetric water content observed in the bags of the standard irrigation treatment continuously exceeded the laboratory determined DUL of 0.607 $m^3\ m^{-3}$.

Scheduling to the pre-determined depletion levels in the small bags were very accurate in this study, with irrigation starting at or close to 0.585, 0.452 and 0.335 $m^3\ m^{-3}$ for the BSM, mild and moderate stress irrigation treatments, respectively (Figure 4.1.1b-d). The upper level also remained constant within treatments, although it differed between treatments which may indicate that the DUL varied between treatments. From these figures it is also clear that the number of irrigation cycles decreased as the depletion level increased. In the small bags, the number of irrigation cycles for the standard irrigation treatment amounts to 342, compared to 19, 11 and 8 cycles for the BSM, mild and moderate irrigation treatments, respectively, over the total production season (Table 4.1.1).

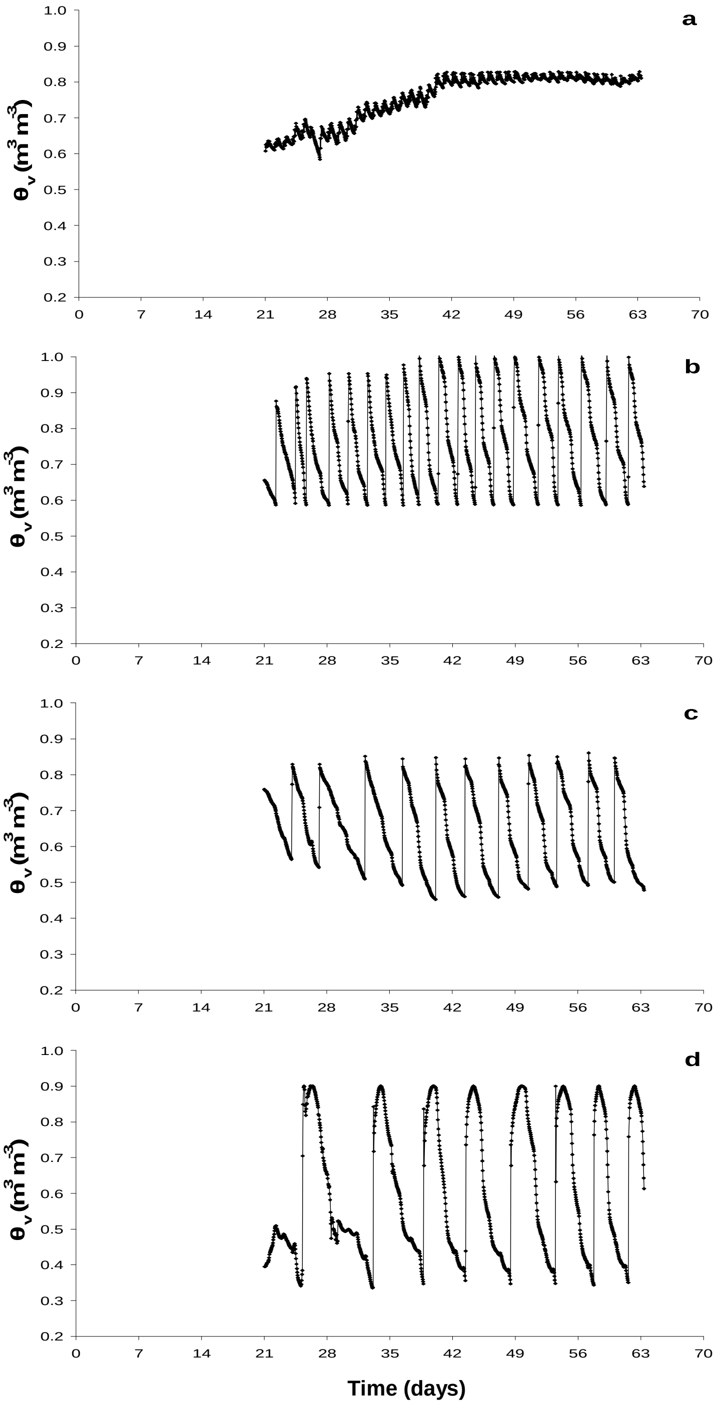

Figure 4.1.1 Volumetric water content (θ_V) of coir in the 9 L bags for the standard (a), between standard and mild (b), mild (c) and moderate (d) stress irrigation treatments over the duration of the cucumber production season.

Table 4.1.1 Weekly and total number of irrigation cycles (C) and water balance components, *viz.* irrigation (I), drainage (D), transpiration (T) and drainage percentage (DP), for different irrigation treatments for greenhouse cucumbers grown in small bags.

	Standard					Between Standard and Mild					Mild					Moderate				
Week	C	I	D	T	DP	C	I	D	T	DP	C	I	D	T	DP	C	I	D	T	DP
	No.	L m^{-2}			%	No.	L m^{-2}			%	No.	L m^{-2}			%	No.	L m^{-2}			%
3	56	34	9	24	28	3	15	0	16	0	2	15	2	13	11	1	9	1	3	10
4	56	41	11	29	26	4	31	2	25	5	1	9	1	11	11	1	10	0	8	2
5	56	44	13	30	29	3	28	3	28	10	2	19	3	17	13	1	11	1	16	5
6	56	58	16	41	28	4	41	7	30	16	2	22	3	19	15	2	23	2	14	8
7	56	59	17	42	28	2	21	4	24	17	2	23	4	19	18	1	12	1	16	8
8	56	51	15	36	29	3	32	4	25	13	2	23	3	21	15	2	24	3	16	11
9	6	5	2	4	29	0	0	0	2	0	0	0	0	0	0	0	0	0	4	0
Total	**342**	**292**	**83**	**206**	**28**	**19**	**168**	**20**	**150**	**11**	**11**	**111**	**16**	**100**	**15**	**8**	**89**	**8**	**77**	**8**

In the large bags, the volumetric water content for the standard irrigation treatment increased steadily over the first 6 weeks of the experiment and increased slightly from approximately week 8 until the experiment was terminated. Again the volumetric water content for the entire production season remained above the laboratory determined DUL (Figure 4.1.2a).

Figure 4.1.2b-d presents depletion to 0.565, 0.421 and 0.253 $m^3 m^{-3}$ for the BSM, mild and severe irrigation treatments, respectively, which was again at or close to the pre-determined depletion levels for the large bags. The upper limit of re-fill remained constant for all treatments, but again varied between treatments, possibly indicating differences in the DUL between bags or the influence of the crop on the DUL. As the depletion level increased, the number of irrigation cycles over 7 weeks was reduced from 342 for the standard irrigation treatment to 14, 9 and only 2 cycles for the BSM, mild and moderate irrigation treatments (Table 4.1.2).

Since the volumetric water content constantly exceeded the laboratory determined DUL for the standard irrigation treatment in both bag sizes, it is suggested that over-irrigation occurred for the total duration of the production season. Re-fill of all the depletion level treatments also resulted in water contents well above the laboratory determined DUL. It is therefore possible that these treatments also may have been over-irrigated and that it will be important to determine the crop modified upper level in future studies as suggested by Hattingh (1993). It could also be possible that the estimation of the volumetric water content above 0.700 is not very accurate since sensors were not calibrated between 0.700 and 0.910 $m^3 m^{-3}$ at saturation. The irrigation management may therefore be improved by calibrating sensors between 0.700 and 0.910 $m^3 m^{-3}$ and by stopping irrigation at a pre-determined upper level instead of applying fixed irrigation volumes.

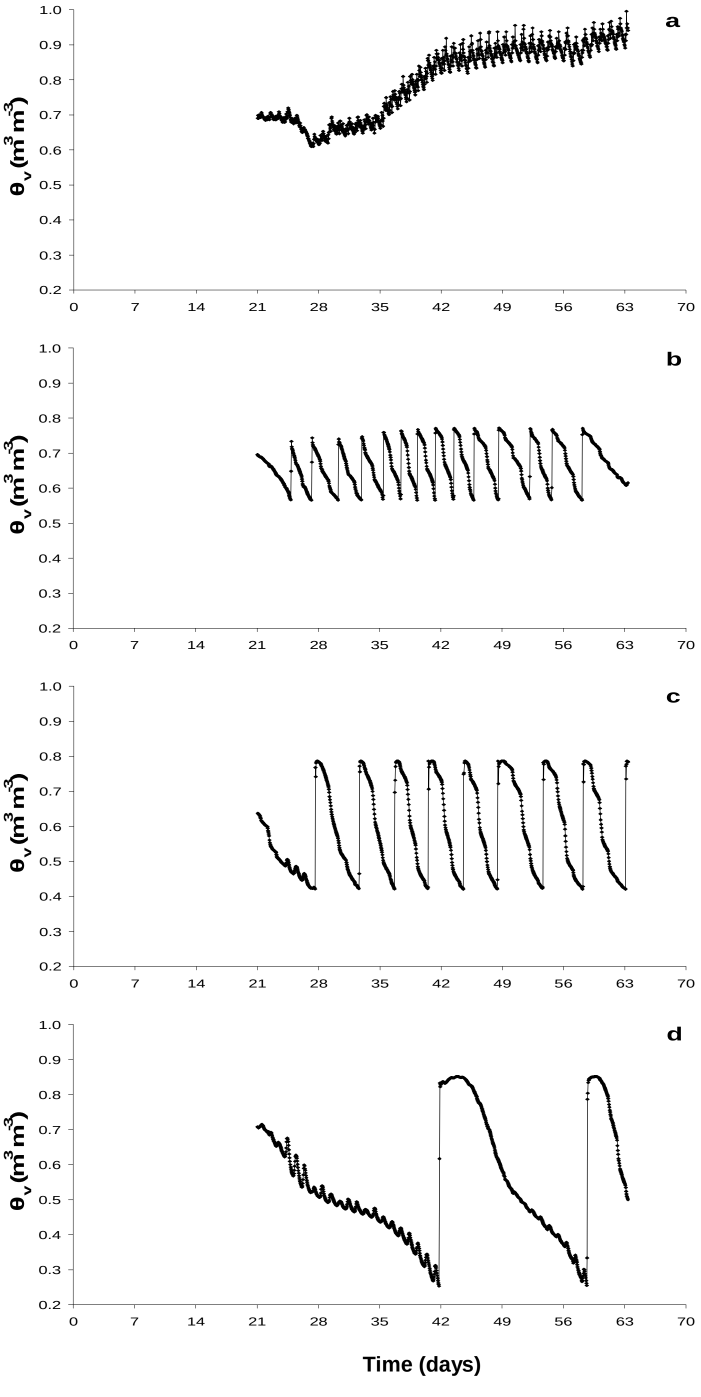

Figure 4.1.2 Volumetric water content (θ_V) of coir in the 20 L bags for the standard (a), between standard and mild (b), mild (c) and moderate (d) irrigation treatments over the duration of the cucumber production season.

Table 4.1.2 Weekly and total number of irrigation cycles (C) and water balance components, viz. irrigation (I), drainage (D), transpiration (T) and drainage percentage (DP), for different irrigation treatments for greenhouse cucumbers grown in large bags.

	Standard					Between Standard and Mild					Mild					Moderate				
Week	C	I	D	T	DP	C	I	D	T	DP	C	I	D	T	DP	C	I	D	T	DP
	No.	L m^{-2}			%	No.	L m^{-2}			%	No.	L m^{-2}			%	No.	L m^{-2}			%
3	56	40	10	33	24	2	19	0	19	0	1	15	0	9	2	0	0	0	7	0
4	56	57	10	45	18	2	21	0	25	1	1	16	1	23	9	0	0	0	3	0
5	56	72	14	52	20	4	48	4	39	8	2	34	3	25	9	1	20	2	3	12
6	56	80	17	62	21	3	43	4	39	9	2	38	3	33	7	0	0	0	9	0
7	56	82	22	60	27	2	29	3	28	9	1	19	1	24	6	0	0	0	8	0
8	56	76	22	53	29	1	15	1	18	6	1	19	1	25	6	1	21	3	11	15
9	6	8	2	5	23	0	0	0	0	0	1	19	1	5	6	0	0	0	2	0
Total	**342**	**415**	**97**	**310**	**23**	**14**	**175**	**12**	**168**	**7**	**9**	**160**	**10**	**144**	**7**	**2**	**41**	**5**	**43**	**13**

4.1.3.2 Water balance components

Weekly and total values of the water balance components for the different irrigation treatments are presented in Table 4.1.1 for the small bags and Table 4.1.2 for the large bags.

Irrigation of the small and large bags for the standard treatment over the entire experiment was 292 L m^{-2} and 415 L m^{-2}, respectively (Table 4.1.1, 4.1.2). Total irrigation for the BSM, mild and moderate irrigation treatments, expressed as a percentage of that of the standard treatment, was 58, 38, 31% for the small bags and 42, 39, 10% for the large bags, respectively.

The mean drainage percentage for the standard irrigation treatment over the entire production season was 83 L m^{-2} or 28% of the total irrigation for the small bags and 97 L m^{-2} or 23% of the total irrigation for the large bags. Total drainage for the BSM, mild and moderate irrigation treatments as a percentage of the standard treatment's drainage was 24, 19, 10% for the small bags and 12, 10, 5% for the large bags, respectively. It was assumed that the build-up of salts in the growth medium was not detrimental to the plants, because the drainage EC remained close to the irrigation water EC for the duration of the experiment.

Total transpiration of the standard treatment amounted to 206 L m^{-2} in the small bags and 310 L m^{-2} in the large bags. Transpiration decreased almost linearly in both bags over the treatments, *viz.* 73, 49 and 37% of the standard transpiration in the small bags and 54, 47 and 14% of the standard transpiration in the large bags.

4.1.3.3 Yield

Harvesting started in week six for both bag sizes and all irrigation treatments, except the moderate treatment for the large bags which was only harvested once in week nine (Figure 4.1.3, 4.1.4). Marketable yield peaked in week eight for the standard and BSM irrigation treatments with yields of 4.5 and 4.1 kg m^{-2} for the small bags and 4.6 and 5.7 kg m^{-2} for the large bags, respectively. Marketable yield from the mild irrigation treatment for the large bags also peaked in week eight with a yield of 2.5 kg m^{-2}. Marketable yield for the mild and moderate irrigation treatments in the small bags peaked only in week nine with yields of 2.6 and 2.2 kg m^{-2}. In large bags marketable yields for the moderate treatment also peaked during week nine with yields of 0.5 kg m^{-2}. The later peaking of yield for the mild treatment in the small bags and moderate treatments in the large bags was induced by the greater exposure to water stress, especially in the small bags where the water reservoir is very small. According to Suojala-Ahlfors and Salo (2005), reduced vegetative growth of

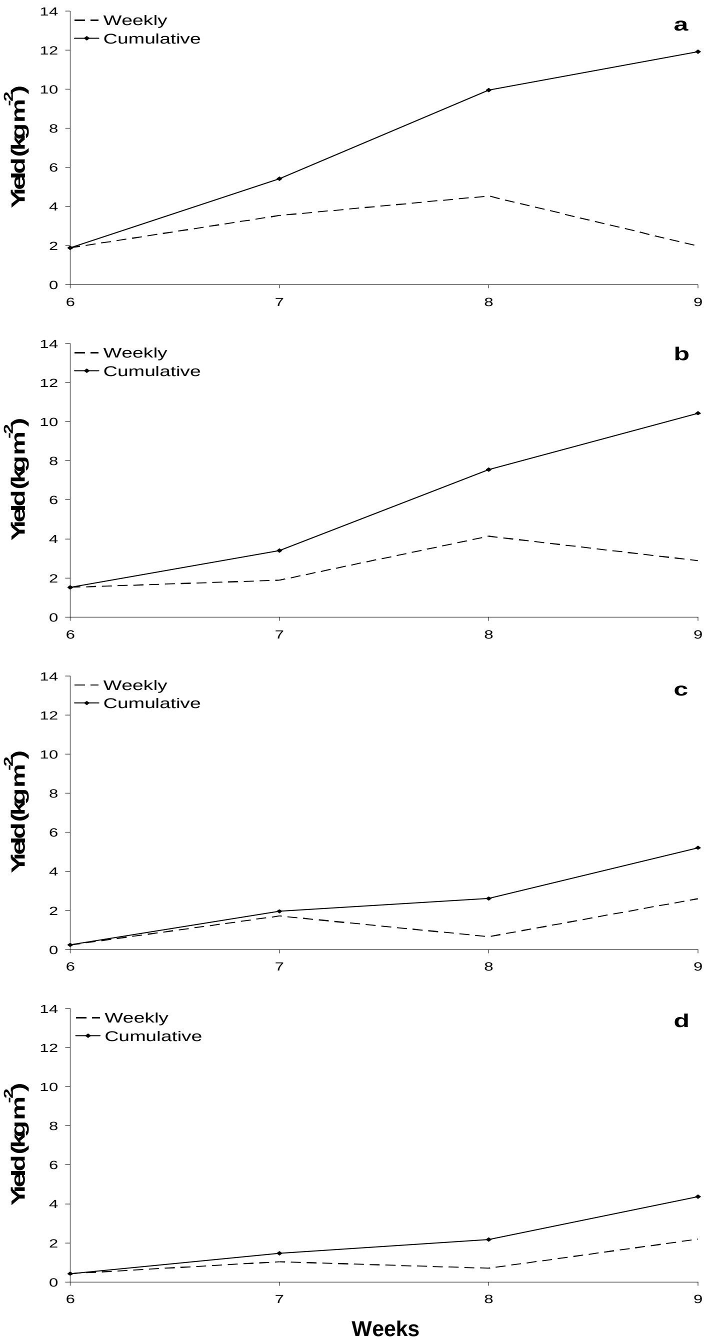

Figure 4.1.3 Marketable yield (kg m^{-2}) of cucumber plants in the 9 L bags for the standard (a), between standard and mild (b), mild (c) and moderate (d) irrigation treatments during the harvesting period.

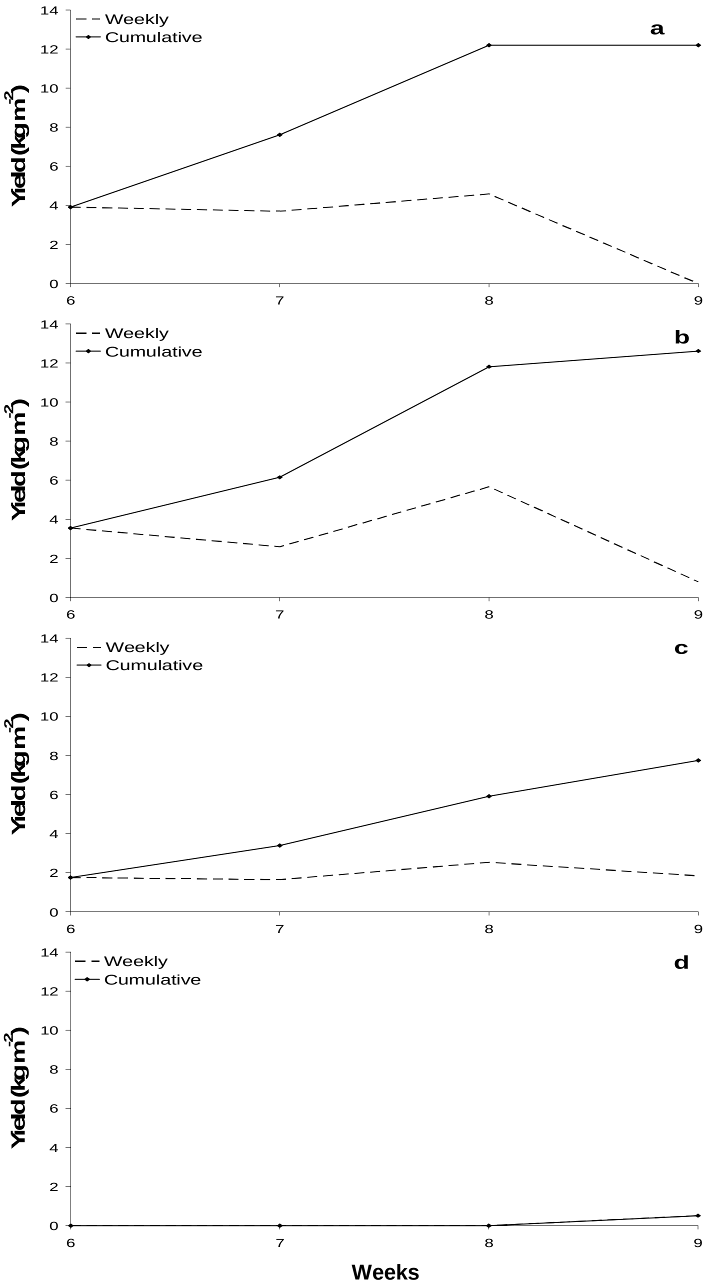

Figure 4.1.4 Marketable yield (kg m^{-2}) of cucumber plants in the 20 L bags for the standard (a), between standard and mild (b), mild (c) and moderate (d) irrigation treatments during the harvesting period.

pickling cucumbers due to water stress decreases fruit growth and increase competition between plant organs. The result is continued growth of larger fruit under water stress while that of small fruit are severely inhibited (Ortega & Kretchman, 1982), although the yield quality is maintained (Suojala-Ahlfors & Salo, 2005). This is confirmed by Kaya *et al*. (2005) who observed that continued irrigation deficit causes flowers and small fruit to drop while yields are significantly reduced. Mao *et al*. (2003), Yuan *et al*. (2006) and Tüzel *et al*. (2009) also correlated deficit irrigation with lower fresh yields when compared to well-watered plants.

A significant interaction for total marketable fruit yield between irrigation treatments and bag sizes showed that, in contrast to all other irrigation treatments, the moderate treatment produced significantly higher yields in small than in large bags (Table 4.1.3). There was no significant difference in the mean cumulative marketable fruit yield of the standard and BSM irrigation treatments for both bag sizes (Table 4.1.3). The cumulative marketable fruit yield amounted to 11.9 and 10.4 kg m^{-2} for the small bags and 12.2 and 12.6 kg m^{-2} for the large bags, for the standard and BSM irrigation treatment, respectively. This was significantly higher than the marketable fruit yields of 5.2 and 4.4 kg m^{-2} for the small bags and 7.8 and 0.5 kg m^{-2} for the large bags, for the mild and moderate treatments, respectively.

Table 4.1.3 Marketable and unmarketable fruit yield (kg m^{-2}) and fruit number per square meter of greenhouse cucumbers for different irrigation treatments, namely standard (Std), between standard and mild (BSM), mild (Mild) and moderate (Mod), in small and large bags.

	Fruit yield (kg m^{-2})				Fruit number			
	Std	BSM	Mild	Mod	Std	BSM	Mild	Mod
Marketable Yield:								
Small bags	11.9a	10.4a	5.2b	4.4b	21.6a	20.0a	10.4b	9.6b
Large bags	12.2a	12.6a	7.8b	0.5c	20.8a	21.2a	14.0b	1.2c
Unmarketable Yield:								
Small bags	2.1a	1.5a	2.2a	1.1a	4.4a	5.2a	8.0a	4.4a
Large bags	1.4a	0.6a	1.6a	1.7a	2.4a	1.6a	4.0a	6.0a

Means for each parameter followed by the same letter are not significantly different at P=0.05

Marketable fruit number showed similar significant differences between irrigation treatments and bag sizes as observed for marketable fruit yield (Table 4.1.3). Mean individual fruit size was not influenced significantly by irrigation treatment, except for fruit from the moderate treatment in the large bags which was significantly smaller compared to all other treatments (Data not shown). This possibly indicates that the cucumber plant acclimatised to water deficit by developing fewer fruit to full size while abscising progressively more of the smaller fruit and flowers as the depletion levels increased, as also observed by Kaya *et al*. (2005).

Unmarketable fruit yield and number was not significantly affected by irrigation treatments or bag sizes which confirmed the suggestion that the cucumber plant rather aborts flowers and small fruit when mild to moderate water stress is experienced.

The result possibly indicates that irrigation may be reduced to values of BSM for both bag sizes, without significantly influencing yield. It is recommended that further experiments should be conducted on additional depletion levels between the standard and mild values in order to find the optimum depletion level for each bag size.

4.1.3.4 Water use efficiency

A significant interaction between the different irrigation treatments and bag sizes, similar to marketable fruit yields, was found for WUE_I and WUE_T (Figure 4.1.5). This interaction also showed significant differences due to bag size for the moderate irrigation treatment, but not for other irrigation treatments. The WUE_I of 61.6 and 71.9 g L^{-1} for small and large bags of the BSM treatment was significantly higher compared to the 40.6 and 29.4 g L^{-1} for the small and large bags of the standard treatment. The WUE_I of the mild treatment for both bag sizes was slightly, but not significantly, higher compared to the standard treatment (Figure 4.1.5a). In general the WUE_I found in this study was higher compared to the 48.7 g L^{-1} observed by Mao *et al*. (2003) when deficit irrigation was applied, which may be explained by the greatly reduced irrigation frequency and better fruit quality in the greenhouse. Şimşek *et al*. (2005) also reported improved WUE_I under deficit irrigation (irrigation started after 50% of the plant available soil water was used). The high WUE_I of the BSM treatment in the current study is the direct result of decreased unproductive water losses through drainage water, while the yield was maintained compared to the standard irrigation treatment.

Although only significant for the large bags, the WUE_T of 69.4 and 75.6 g L^{-1} for small and large bags of the BSM treatment was higher compared to 57.7 and 39.4 g L^{-1} for the standard irrigation treatment (Figure 4.1.5b). Irrespective of bag size, the WUE_T of the mild treatment were not significantly different from that of any other treatment except the large bags of the moderate treatment which were significantly less than all other treatments (Figure 4.1.5b). Although slightly higher values of WUE_T was observed in the current study, it supported earlier results of Mao *et al*. (2003) that showed that WUE_T are improved by deficit irrigation. In contrast to this Şimşek *et al*. (2005) observed decreased values of WUE_T when more severe deficit irrigation treatments were applied where irrigation is started once 50% of plant available soil water is depleted. From a fresh yield perspective, this indicates and confirms results from the current study that the severity of water stress influences WUE_T.

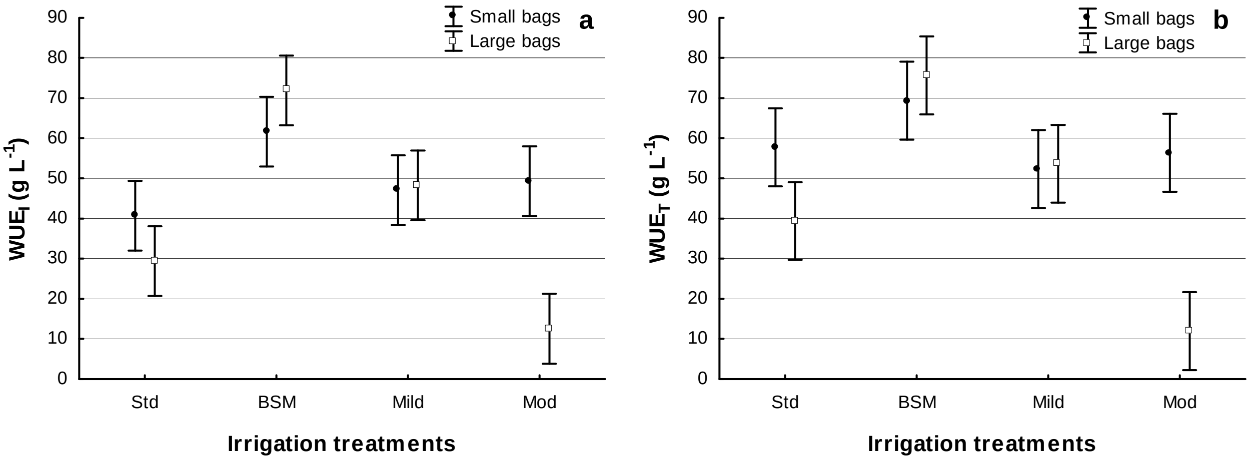

Figure 4.1.5 Water use efficiency of cucumber plants in the small and large bags based on a) irrigation (WUE_I; g L^{-1}) and b) transpiration (WUE_T; g L^{-1}), for all irrigation treatments, where Std = Standard; BSM = Between standard and mild; Mild = Mild; and Mod = Moderate irrigation treatments.

Both WUE_I and WUE_T clearly illustrates that the standard irrigation strategy leads to over-irrigation and luxurious growth, without an accommodating increase in yield. This is supported by results observed by Şimşek *et al*. (2005) which suggests that cucumber plants are sensitive to excessive watering and significant water and yield losses can occur.

4.1.4 Conclusion

The in situ calibrated EC-10 and EC-20 capacitance sensors managed irrigation successfully to the pre-determined water depletion levels. For the standard irrigation treatment, the volumetric water content constantly remained above the laboratory determined DUL for both bag sizes. Refilling of the bags from the depletion level treatments also indicated variation in the upper limit between treatments, although irrigation was determined as the difference between the laboratory determined DUL value and depletion level plus 20% for drainage. Both instances may indicate that the DUL is different for the coir filled bags in the greenhouse compared to the laboratory and/or that the calibration curves of the capacitance sensors are inaccurate for values exceeding 0.700 m^3 m^{-3}, which represents the upper limits to which the sensors were calibrated. It is possible that refilling caused over-irrigation of individual depletion level treatments. Irrigation management may therefore be improved by also calibrating sensors between 0.700 and 0.910 m^3 m^{-3} and by switching off irrigation at a pre-determined upper level instead of applying fixed irrigation volumes.

The use of depletion levels did reduce the applied irrigation and drainage without accumulation of salt in the growth medium, while scheduling to the BSM treatment maintained or even improved marketable fresh fruit yield and number in both bag sizes. This lead to improved water use efficiencies for the BSM treatment compared to all other treatments. It was also obvious that the standard irrigation method over-irrigates greenhouse cucumbers grown in coir. Further experiments on additional depletion levels between the standard and mild values can improve the estimation of the optimum depletion level for each bag size.

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4.2 Efficiency of pre-determined water depletion levels as a method to irrigate greenhouse tomatoes (*Lycopersicon esculentum* Mill.) grown in coir

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The lack of knowledge on the management of irrigation in coir inevitably leads to over-irrigation and luxurious growth of greenhouse crops. This becomes a problem when water is scarce or expensive and when similar yields can be achieved with less irrigation. The objectives of this study were to assess the use of capacitance sensors for irrigation management with regard to bag size and target depletion levels and to determine the effect of these management options on the sensor performance, water balance components, yield and water use efficiency. Results from this study indicated that irrigation can be successfully managed to pre-determined water depletion levels in both the 9 L and 20 L bag sizes, through the use of in situ calibrated capacitance sensors. However, various bag sizes require different irrigation management strategies, since the depletion of water varies between bag sizes. Less irrigation and drainage was achieved by scheduling to specified depletion levels, which is more cost efficient because less water and fertilizer are used, while less water and fertilizer drains to waste. Yield and water use efficiency results indicated that the depletion levels used in this study were too low, although the standard irrigation treatment resulted in luxury water use by the plants and inefficient irrigation. However, additional research is required to find the optimal depletion level for each bag size which will result in maximum water use efficiency. Capacitance sensors also needs to be calibrated for volumetric water content values between the drained upper limit (DUL) and saturation, as it was observed that the DUL of the bags varies from that determined in the laboratory. It is also recommended that producers use more than one sensor to monitor water content in the greenhouse as a precautionary measure to overcome the impact of a faulty sensor.

Keywords: Capacitance sensors, coir, greenhouse tomatoes, irrigation, water depletion, water use efficiency, yield

4.2.1 Introduction

Irrigation frequency for tomato crops varies between climatic regions, different soil types or growth mediums and different production environments e.g. open fields versus protective structures. Various authors have indicated boundaries for soil water content in which irrigation is optimal (Fares & Alva, 2000; Fares & Polyakov, 2006). This is required because water stress can cause large decreases in yield and percentage marketable fruits (Sammis & Wu, 1986), although a 50% allowable depletion of plant available water (PAW) through partial root drying, may have no effect on fruit quality with the exception of fruit size (Topcu *et al*., 2007).

Scheduling within soil water content boundaries can be achieved through the use of soil water sensors. According to Zotarelli *et al.* (2009) the use of time domain reflectometry (TDR) soil water sensors to schedule irrigation, increased marketable tomato yield by 10-26% compared to a time-based irrigation treatment, while also resulting in 15-51% reduction in applied irrigation. Therefore, the appropriate use of sensor based irrigation systems can allow producers to sustain profitable yield while reducing applied irrigation (Zotarelli *et al*., 2009). Thompson *et al*. (2007) cited some values of soil matric potentials for fresh market tomato, *viz.* -10 kPa in a fine sandy soil, -20 kPa in a clay loam soil, -30 kPa for loamy soils, -60 to -150 kPa for clay soils and -39 to -59 kPa for an artificial layered soil consisting of a 20 cm layer of sandy loam covered by a 10 cm layer of coarse river sand. The recommended FAO threshold value for available depletion is 60% of PAW for tomato under medium evaporative demand. Climate affects soil matric potential threshold values, with higher values recommended for higher evaporative conditions (Thompson *et al*., 2007). General problems with regard to scheduling irrigation in the soil to a recommended fixed threshold value of plant available water content with soil water sensors include issues related to rooting depth, measurement of field capacity and wilting point, sensor calibration and sensor accuracy across the relevant range of water contents (Thompson *et al*., 2007).

Efficient water use is a key characteristic of sustainable plant production in water-limited environments (Bhattarai & Midmore, 2007). According to Bennie *et al*. (1988), crop water use efficiency (WUE_{ET}, g L^{-1}) refers to the total amount of marketable produce per volume of water lost through evapotranspiration. Irrigation efficiency (WUE_I) reflects on the marketable produce per volume water applied through the irrigation system, and the water added is subject to unproductive water losses, e.g. evaporation, runoff and drainage.

Tomato plants maintained at field capacity receives and uses more water than those grown under water deficit conditions (Kirda *et al*., 2004; Bhattarai & Midmore, 2007). However, a water application greater than the maximum evapotranspiration achieved by the crop, eventually results in increased drainage and decreased water use efficiency (Sammis & Wu, 1986). This is supported by results of Kirda *et al*. (2004) and Topcu *et al*. (2007) for greenhouse tomato production in soil in Turkey, where partial root drying at 50% of the full irrigation indicated higher WUE_{ET} and WUE_I compared to the full irrigation treatment. Kirda *et al*. (2004) reported WUE_{ET} values of 29.6 and 45.9 g L^{-1} for full irrigation compared to 35.1 and 64.5 g L^{-1} for the partial root drying treatment, for spring and fall-planted tomatoes, respectively. The WUE_I was 32.2 and 45.1 g L^{-1} for the full irrigation treatment compared to 50.3 and 73.5 g L^{-1} for the partial root drying treatment, for spring and fall-planted tomatoes, respectively. For a spring planted tomato crop, Topcu *et al*. (2007) observed WUE_{ET} of 44.1 and 57.3 g L^{-1} for the full irrigation and partial root drying, respectively, while WUE_I was 46.4 and 70.8 g L^{-1} for the full irrigation and partial root drying, respectively. Kirda *et al*. (2004) found no significant differences in yield between the full irrigation treatment and partial root drying with 50% less irrigation water, although the yield was slightly higher for the full irrigation treatment. In contrast, Topcu *et al*. (2007) observed a significant increase in yield for the full irrigation treatment. The higher WUE observed by Topcu *et al*. (2007) for the spring planted tomato crop were ascribed to higher water stress experienced by the plants which caused a decrease in marketable yield (Sammis & Wu, 1986), although no measurements of the plant water status were taken. The objectives of this study were i) to assess the irrigation management options with regard to bag size and target depletion levels in coir, and ii) to determine the effect of these management options on the water balance components, yield and water use efficiency of greenhouse tomatoes.

4.2.2 Material and Methods

4.2.2.1 Location and cropping details

The experiment was conducted on fresh market tomato (*Lycopersicon esculentum* Mill.) of the cultivar Espadilha in a 48 m^2 temperature-controlled glasshouse at the University of the Free State in the Free State province of South Africa (26º11’20” E, 29º06’33” S, 1409 m altitude). Tomato seed were sown on 12 August 2008 and transplanted at a mean density of 2 plants m^{-2} on 20 September 2008. Seedlings were transplanted to 9 L and 20 L bags filled with coir. Drainage holes were punched into the bottom of all bags to prevent the build-up of a reservoir in the bag. All coir used in the experiment (30 x 5 kg blocks) was processed before the bags were filled to minimise variation in bulk density between bags. The medium was flushed within the bags using municipal water of electrical conductivity (EC) 0.2 mS cm^{-1} until the EC of the drain water was equal to that of the input water. Plants were fertigated through a drip irrigation system with a balanced nutrient solution of EC 1.8 mS cm^{-1} (Maree, 1993), which was prepared from feeding municipal water. The tomato plants were topped when they reached the horizontal trellising wire approximately 2 m above the bag surface and the experiment was only terminated once all the fruit on all the plants were harvested.

4.2.2.2 Treatments and experimental design

The efficiency of scheduling irrigation to pre-determined water depletion levels were evaluated in two bag sizes. Planted bags were organised in eight single rows which were divided into two blocks, resulting in four single rows of 12 plants per bag size *viz*. 9 L and 20 L. The outer rows and plants on the ends of rows were excluded from the experimental plot. The tomato plants were irrigated according to the standard irrigation method used in South African greenhouses, which consists of a fixed irrigation frequency of eight irrigation events over the daylight period for three weeks before the irrigation treatments were applied randomly in each bag size block. The irrigation management treatments which started on 9 October 2008 included a control irrigation treatment namely the standard irrigation method and three irrigation treatments scheduled to start irrigation at different water depletion levels. The water depletion levels used to schedule irrigation was identified in a previous study by Van der Westhuizen *et al*. (2009, Chapter 3.2). They consisted of depletion to a level identified between the water contents recorded for the standard irrigation method and mild water stress (BSM), mild water stress (Mild) and severe water stress (Sev). The depletion levels were at 0.633 $m^3 m^{-3}$ for BSM, 0.533 $m^3 m^{-3}$ for Mild and 0.452 $m^3 m^{-3}$ for Sev in the small bags, and 0.633 $m^3 m^{-3}$ for BSM, 0.568 $m^3 m^{-3}$ for Mild and 0.320 $m^3 m^{-3}$ for Sev in the large bags. Applied irrigation volumes were increased throughout the production period to maintain a drainage percentage between 20 and 30% for the standard irrigation treatment, while water was re-filled to the laboratory determined drained upper limit of 0.607 $m^3 m^{-3}$ plus 20% for the depletion level treatments to ensure drainage and prevent build up of salts. The drainage water EC never increased by more than 50% of the applied nutrient solution EC for the depletion level treatments, thus within limits as recommended by Combrink (2005). Different irrigation treatments were applied for the duration of the experiment until all fruit from all plants were harvested; whereafter the experiment was terminated on 12 January 2009.

4.2.2.3 Measurements

Echo 10 and Echo 20 capacitance sensors (Decagon Devices, Inc.) were installed vertically in the 9 L and 20 L bags, respectively. A 7 cm distance between the sensor, emitter and plant was constant for all treatments and replications as recommended by Thompson *et al.* (2006). A data logger (model CR1000, Campbell Scientific Africa) recorded soil water content measurements of the sensors in mV, hourly. The millivolt readings were converted to volumetric water content values ($m^3 m^{-3}$) using in situ calibrations as described by Van der Westhuizen & Van Rensburg (2009, Chapter 2.1). The exposed surface area of the medium was covered with cardboard to prevent evaporation losses. Transpiration (T) was determined from the water balance equation: $T = I - D - \Delta\theta$; where I = irrigation (m^3), D = drainage (m^3) and $\Delta\theta$ is the change in coir water content (m^3) as measured through the mentioned calibrated sensors in this study. Irrigation and drainage amounts of two random plants per irrigation treatment and bag size, was measured once a day. Fruit was harvested twice a week and marketable yield with regard to fruit number and fruit yield was recorded per truss per single plant for all irrigation treatments. Transpiration water use efficiency (WUE_T) and irrigation efficiency (WUE_I) was calculated per square meter as gram fresh marketable yield per litre water used.

4.2.2.4 Statistical analyses

Factorial analysis of variance (ANOVA) was performed on the total fruit number, total fruit fresh yield, total WUE_T and total WUE_I with bag size and irrigation treatments as factors. P-values were used to compare means at a 5% probability level, using STATISTICA version 8.0 (StatSoft Inc., 2004).

4.2.3 Results and discussion

4.2.3.1 Sensor performance in controlling irrigation to pre-determined depletion levels

The variation in volumetric water content in coir over time induced by the main irrigation treatments, namely a) the standard irrigation treatment that consists of 8 irrigation cycles per day, b) a pre-determined level allowing depletion to a point between the standard irrigation treatment and mild water stress (BSM), c) a pre-determined level allowing depletion to mild water stress (Mild), and d) a pre-determined level allowing depletion to severe water stress (Sev) before irrigation is started, are presented in Figure 4.2.1 and Figure 4.2.2 for the small and large bags, respectively. Water depletion varied between the two bag sizes, indicating that the bag size preferred by the producer will determine how the medium water depletion should be managed. Therefore the results for the individual bag sizes will be discussed separately.

The water content of the coir in the small bags remained constant within a narrow band of 0.720 and 0.835 $m^3\ m^{-3}$ for the standard irrigation treatment, except in the third week when it dropped to 0.487 $m^3\ m^{-3}$ as a result of power failure which prevented irrigation (Figure 4.2.1a). The water content of the standard irrigation treatment remained well above the laboratory determined drained upper limit, namely 0.607 $m^3\ m^{-3}$, for the duration of the production season.

The water depletion to the pre-determined water content levels for the small bags was very accurate for the BSM and severe irrigation treatments, in which irrigation was mostly started at the allowable depletion levels of 0.633 and 0.416 $m^3\ m^{-3}$, respectively (Figure 4.2.1b, d). Any diversions from these lower boundaries were mostly due to power failure or the stock nutrient solution that was depleted. The water content depletion was less accurate for the mild irrigation treatment, due to a faulty sensor, and therefore data from another replicated sensor for the same treatment was used (Figure 4.2.1c). There was a clear decrease in the number of irrigation cycles as the allowable depletion levels increased, as can be observed in Figure 4.2.1.

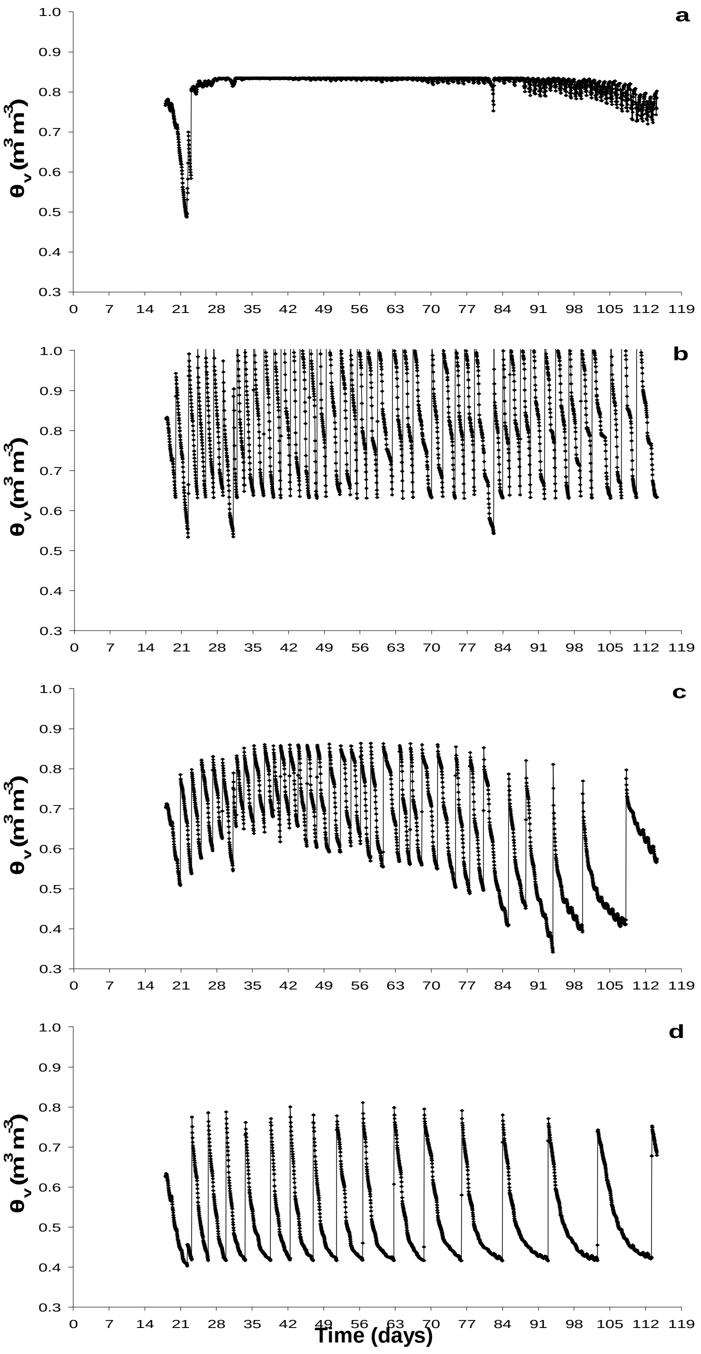

Figure 4.2.1 Volumetric water content (θ_V) of coir in the 9 L bags for the standard (a), between standard and mild (b), mild (c) and severe (d) irrigation treatments over the duration of the tomato production season.

The number of cycles per week was fixed at 56 for the standard irrigation treatment, but varied between weeks for all other treatments. The weekly variation is due to the change in water demand through the crop growth stages and climate. The standard irrigation method resulted in a total of 772 irrigation cycles over the tomato production season (weeks 3-16), while the BSM, mild and severe irrigation treatments resulted in only 44, 33 and 16 irrigation events within the same period (Table 4.2.1). The water content of the coir in the large bags irrigated with the standard irrigation treatment increased gradually from 0.617 to 0.864 m^3 m^{-3} over the first 12 weeks of the production season, which was also well above the laboratory determined drained upper limit (Figure 4.2.2). The last 4 weeks of the trial was characterised by a rapid increase in water content above 1.000 m^3 m^{-3}, which shows that the sensor had either become faulty or that the calibration curve used in converting mV into volumetric water content was out of range, i.e. exceeding 0.700 m^3 m^{-3}. However, the mean water contents between day 49 and 84 was used as the upper boundary for the last four weeks of the experiment. Scheduling according to depletion levels in the large bags resulted in accurate depletion of water to the pre-determined levels of BSM, mild and severe irrigation treatments at 0.633, 0.506 and 0.320 m^3 m^{-3}, respectively (Figure 4.2.2b-d). Deviation from the depletion level boundaries only occurred at the BSM treatment and this was the result of power failure within the third week of the production cycle (Figure 4.2.2b). The reduced amount of irrigation cycles as observed in Figure 4.2.2b-d are directly proportional to the larger amount of water available in the large bags for the crop as the depletion level increases. The number of irrigation cycles for the standard irrigation treatment was fixed at 56 irrigation events per week, but decreased considerably for the BSM, mild and severe irrigation treatments (Table 4.2.2). For the BSM treatment irrigations amounted to 2-3 times per week during the vegetative and early reproductive stages of the tomato crop, while it decreased toward late reproductive season. The number of irrigation cycles for the mild irrigation treatment peaked during the vegetative stage, while there was no trend for the severe irrigation treatment. In total the standard irrigation treatment resulted in 772 irrigation cycles during the production season, while the BSM, mild and severe irrigation treatments only irrigated 29, 15 and 5 times, respectively, during the production season (Table 4.2.2).

In both bag sizes, the volumetric water content of the coir regularly exceeded the laboratory determined DUL, and therefore sensors may not be calibrated sensitively enough to predict water content between DUL and saturation. This will become important for follow up experiments with depletion levels higher than that of BSM and therefore sensors will also need to be calibrated

Table 4.2.1 Weekly and total number of irrigation cycles (C) and water balance components, *viz.* irrigation (I), drainage (D), transpiration (T) and drainage percentage (DP), for different irrigation treatments for greenhouse tomatoes grown in small bags.

	Standard					Between Standard and Mild					Mild					Severe				
Week	C	I	D	T	DP	C	I	D	T	DP	C	I	D	T	DP	C	I	D	T	DP
	No.	L m^{-2}			%	No.	L m^{-2}			%	No.	L m^{-2}			%	No.	L m^{-2}			%
3	56	19	6	12	31	3	14	1	14	6	3	18	2	15	11	1	8	0	10	0
4	56	18	12	6	64	5	23	1	18	3	4	18	2	17	9	2	16	0	17	0
5	56	26	4	22	15	3	14	0	21	2	3	18	1	21	5	2	16	0	12	2
6	56	41	6	35	14	5	31	0	31	1	5	36	2	29	5	1	9	0	14	0
7	56	46	11	34	25	3	22	2	14	11	3	24	1	23	6	2	19	2	14	10
8	56	52	8	44	15	4	30	2	27	7	3	26	1	28	4	1	10	1	12	0
9	56	63	23	40	36	3	26	3	23	12	3	29	3	24	12	1	11	2	10	0
10	56	69	23	46	34	2	17	3	18	15	2	20	3	19	13	1	11	2	9	19
11	56	69	19	50	28	3	26	4	24	16	3	30	3	22	10	1	11	2	9	0
12	56	69	21	48	30	4	35	4	25	12	1	10	1	15	6	1	11	2	9	20
13	56	73	22	50	31	3	27	3	25	11	2	21	2	15	12	1	12	3	8	0
14	56	73	30	43	41	3	28	3	25	11	1	11	1	6	0	0	0	0	3	0
15	56	73	35	38	48	2	19	2	20	10	0	0	0	0	0	1	12	3	9	0
16	44	57	23	35	40	1	9	1	12	9	0	0	0	0	0	1	12	2	5	0
Total	**772**	**748**	**243**	**503**	**32**	**44**	**321**	**29**	**297**	**9**	**33**	**261**	**22**	**234**	**8**	**16**	**158**	**19**	**141**	**12**

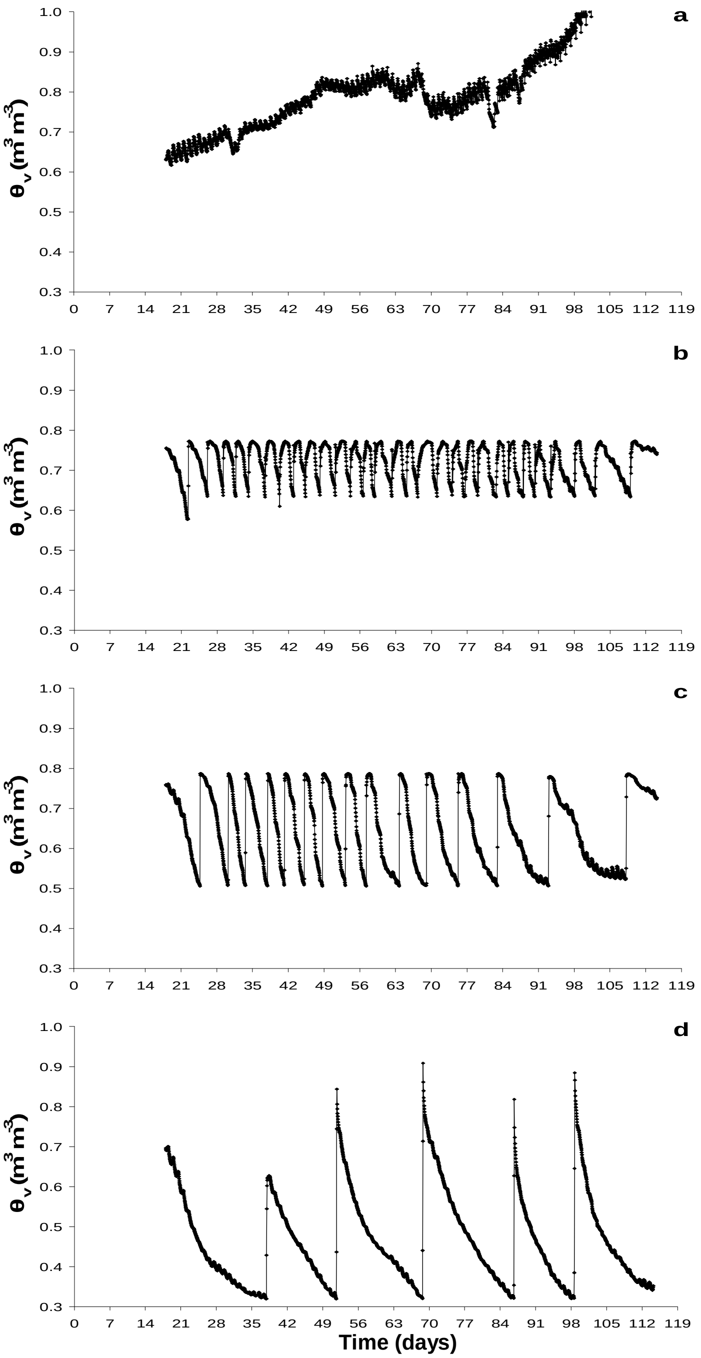

Figure 4.2.2 Volumetric water content (θ_V) of coir in the 20 L bags for the standard (a), between standard and mild (b), mild (c) and severe (d) irrigation treatments over the duration of the tomato production season.

Table 4.2.2 Weekly and total number of irrigation cycles (C) and water balance components, viz. irrigation (I), drainage (D), transpiration (T) and drainage percentage (DP), for different irrigation treatments for greenhouse tomatoes grown in large bags.

	Standard					Between Standard and Mild					Mild					Severe				
Week	C	I	D	T	DP	C	I	D	T	DP	C	I	D	T	DP	C	I	D	T	DP
	No.	L m^{-2}			%	No.	L m^{-2}			%	No.	L m^{-2}			%	No.	L m^{-2}			%
3	56	22	1	19	6	1	13	0	15	1	1	17	3	14	16	0	0	0	9	0
4	56	31	2	28	8	3	38	0	35	0	1	17	0	22	0	0	0	0	3	0
5	56	43	14	27	33	2	25	3	22	12	2	35	4	27	12	1	23	6	9	26
6	56	46	8	36	18	3	39	2	37	6	2	36	2	33	6	0	0	0	6	0
7	56	53	18	34	34	2	27	1	25	4	1	18	1	25	7	1	24	4	11	16
8	56	59	11	48	18	3	41	4	38	9	2	36	2	30	5	0	0	0	8	0
9	56	70	18	52	26	2	31	4	30	15	1	19	1	21	8	0	0	0	4	0
10	56	84	37	49	44	2	31	2	29	7	1	19	2	18	9	1	23	2	13	8
11	56	84	29	54	34	3	46	3	39	7	1	19	1	18	4	0	0	0	6	0
12	56	84	18	64	21	3	46	3	47	7	1	19	2	16	11	1	23	0	17	0
13	56	87	24	61	28	2	33	2	26	7	1	19	3	12	14	0	0	0	8	0
14	56	88	27	56	31	1	17	1	20	8	0	0	0	6	0	1	23	2	15	0
15	56	88	30	55	34	1	17	1	17	5	1	19	2	9	12	0	0	0	6	0
16	44	69	27	40	39	1	17	1	12	7	0	0	0	2	0	0	0	0	2	0
Total	**772**	**908**	**264**	**623**	**29**	**29**	**421**	**27**	**392**	**7**	**15**	**273**	**23**	**253**	**8**	**5**	**116**	**14**	**117**	**11**

between the laboratory determined DUL and saturation. The constant high volumetric water content of the standard irrigation treatment throughout the production season in the small and large bags possibly indicates over-irrigation of the growth medium through the use of the standard method of irrigation scheduling for sawdust and shavings in South Africa.

4.2.3.2 Water balance components

The effect of scheduling irrigation to different water depletion levels on the water balance components compared to the local standard method are presented in Tables 4.2.1 and 4.2.2 for the small and large bags, respectively.

Total applied irrigation water for the standard irrigation treatment was 746 and 908 L m^{-2} for the small and large bags, respectively (Table 4.2.1, 4.2.2). The application of allowable depletion levels reduced the total applied irrigation water in the small bags to 43, 35 and 21% and in the large bags to 46, 30 and 13% of that of the standard treatment for the BSM, mild and severe irrigation treatments, respectively.

The average drainage percentage over the entire production season for the standard irrigation treatment was 32% for the small bags and 29% for the large bags. The total drainage, expressed as a percentage of that of the standard treatment, of the BSM, mild and severe irrigation treatments were only 3.8, 2.9 and 3.0% for the small bags and 3.3, 2.5 and 1.4% for the large bags, respectively. Increased drainage volumes per irrigation event were the result of increased irrigation volumes, although the drainage percentages for the pre-determined levels remained low for both bag sizes (Table 4.2.1, 4.2.2).

For both bag sizes, depletion to the highest depletion level, namely BSM, resulted in irrigation quantities of less than 50% compared to the standard irrigation treatment, while some drainage was maintained and the drainage EC never exceeded 3 mS cm^{-1} (Data not shown). The fluctuation in drainage percentages for the depletion level treatments indicated that there existed some variation in refilling. This possibly shows that the DUL in the bags are different from that determined in the laboratory, although the reason for this is uncertain.

Total transpiration of the BSM irrigation treatment was 59 and 63% of the standard treatment for the small and large bags, respectively. The high total transpiration of the standard irrigation treatment may indicate luxury water use that may not be required for optimal yields. This assumption will be re-evaluated later in this paper when yields are also considered.

4.2.3.3 Yield

The start and peak of the harvesting period differed between irrigation treatments and bag sizes. Harvesting of fruit from plants in the small bags only started at week 10 for all irrigation treatments (Figure 4.2.3).

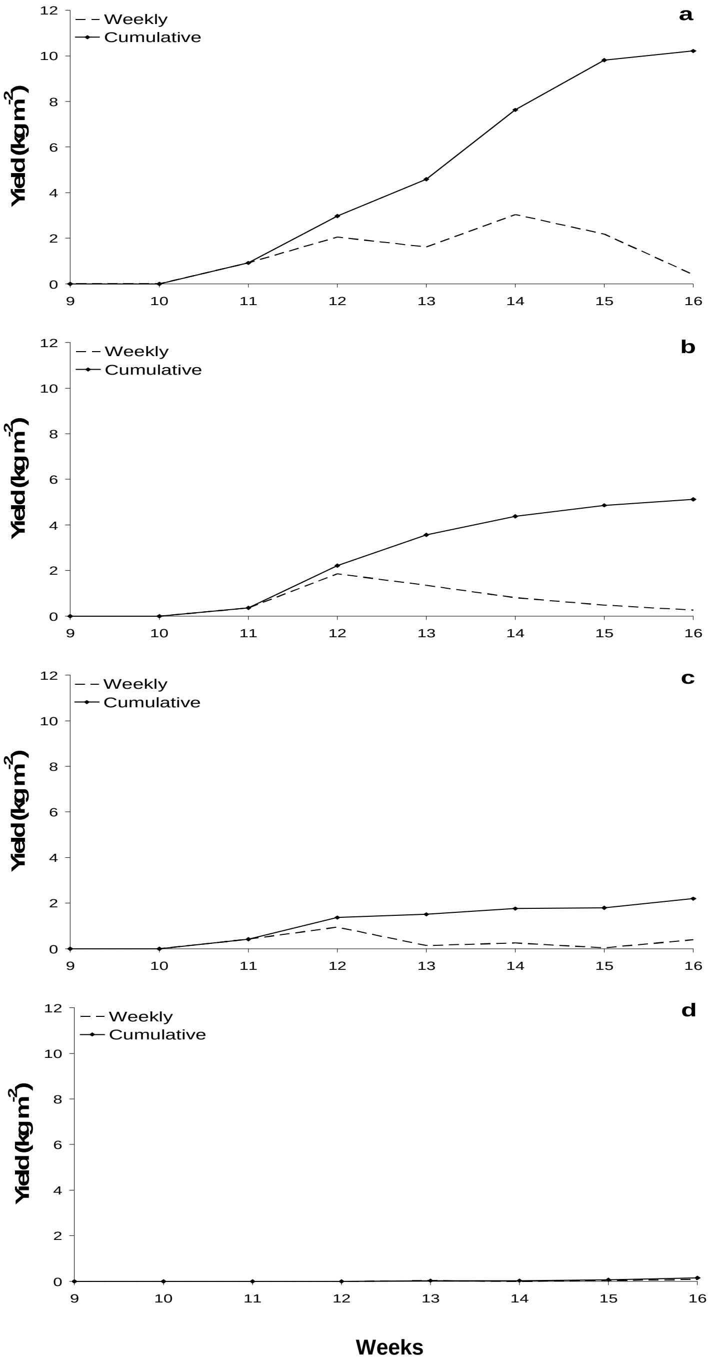

Figure 4.2.3 Marketable yield (kg m^{-2}) of tomato plants in the 9 L bags for the standard (a), between standard and mild (b), mild (c) and severe (d) irrigation treatments during the harvesting period.

Marketable yield of the standard irrigation treatment peaked at week 14 with 3.0 kg m^{-2} compared to week 12 for the BSM and mild irrigation treatments with only 1.4 and 0.9 kg m^{-2}, respectively.

Results presented in Figure 4.2.4 show that the harvesting of fruit from plants in the large bags started in week 9 for the BSM and mild irrigation treatments and in week 10 for the standard irrigation treatment. Marketable yield of the standard and BSM irrigation treatments peaked at week 14 with 3.0 and 2.6 kg m^{-2}, respectively, while yield of the plants from the mild irrigation treatment peaked in week 12. There was no peak for the severe irrigation treatment. The earlier ripening and peaking of fruit from plants from the drier mild irrigation treatments for both bag sizes, was attributed to faster development and ripening of fruit under water stressed conditions as explained by Wolf and Rudich (1988).

There was a significant interaction for total marketable yield between irrigation treatments and bag sizes (Table 4.2.3). Mean cumulative marketable yield of the standard irrigation treatment in the small bags was 10.2 kg m^{-2}, which was significantly higher than the respective mean total yields of 4.5, 2.2 and 0.1 kg m^{-2} achieved by plants from the BSM, mild and severe irrigation treatments. The mean cumulative marketable yield of the standard irrigation treatment in the large bags was 10.4 kg m^{-2}, which was not significantly higher than the mean total cumulative yield of 8.5 kg m^{-2} achieved by plants from the BSM irrigation treatment, but higher than that of the Mild and Sev treatments. Mean cumulative marketable yields for the standard, mild and severe irrigation treatments were similar in small compared to large bags, but BSM yielded significantly less in the small bags compared to the large bags (Table 4.2.3). This probably reflects on difficulty experienced in the selection of a depletion level between the mild and standard irrigation treatments between the bag sizes. The BSM depletion level was not identified in a previous trial like the other treatments. The problem should be resolved by adding depletion levels between the standard and mild irrigation treatments to identify points that are similar in physiological response between the different bag sizes. This was restricted in the current study due to too many depletion levels in the dry end and too few loggers and sensors.

Unmarketable yield was lowest for the standard and BSM irrigation treatments for both bag sizes, but increased as the depletion levels increased. The fresh yield of the unmarketable fruit did not vary significantly between the standard and BSM treatments for the respective bag sizes or between the small and large bags with regard to the standard irrigation treatment. However, the BSM, mild and severe treatments of the small bags yielded significantly more unmarketable fruit compared to the large bags (Table 4.2.3).

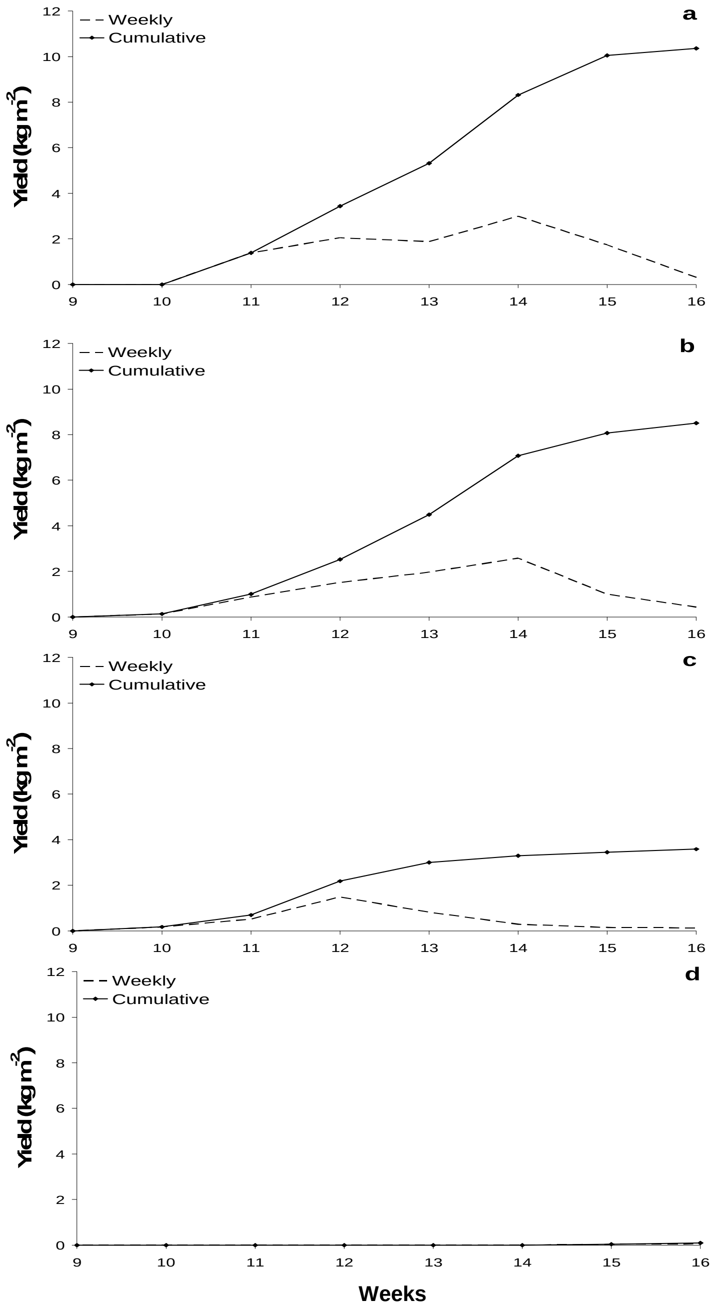

Figure 4.2.4 Marketable yield (kg m^{-2}) of tomato plants in the 20 L bags for the standard (a), between standard and mild (b), mild (c) and severe (d) irrigation treatments during the harvesting period.

Table 4.2.3 Marketable and unmarketable fruit yield (kg m^{-2}) and fruit number per square meter of greenhouse tomatoes for different irrigation treatments, namely standard (Std), between standard and mild (BSM), mild (Mild) and severe (Sev), in small and large bags.

	Fruit yield (kg m^{-2})				Fruit number			
	Std	BSM	Mild	Sev	Std	BSM	Mild	Sev
Marketable Yield:								
Small bags	10.2a	5.1bd	2.2cde	0.1ce	56a	41ac	20bc	4bd
Large bags	10.4a	8.5a	3.6d	0.1e	53a	54a	30c	2d
Unmarketable Yield:								
Small bags	0.9ac	1.5ad	3.5b	1.7ae	4a	13a	40bc	46bc
Large bags	0.8cde	0.3c	1.2cde	0.4cd	3a	2a	17ac	32c

Means for each parameter followed by the same letter are not significantly different at P=0.05

Marketable fruit number did not vary significantly between the standard and BSM irrigation treatment for both bag sizes (Table 4.2.3). This indicated that the difference in yield between these treatments was due to differences in individual fruit yield, as also observed by Nuruddin *et al*. (2003), Kirda *et al*. (2004), Gallardo *et al*. (2006) and Bhattarai & Midmore (2007), where fruit were smaller for the BSM treatment compared to the standard treatment for both bag sizes. Unmarketable fruit number was similar for the standard and BSM treatments for both bag sizes, but increased significantly for the mild treatment of the small bags and the severe treatment of both bag sizes. The incidence of blossom-end rot (BER) was higher under increasing water depletion levels and was the result of low Ca^{2+} status in the plant due to water stress or osmotic stress (Ho, 1999). It can, however, be prevented by sprays of Ca^{2+} to fruit at critical stages of fruit development (Ho, 1999).

4.2.3.4 Water use efficiency

For WUE_I and WUE_T, a significant interaction occurred between different irrigation treatments and bag sizes (Figure 4.2.5a, b). Significant differences in WUE_I and WUE_T between the severe and mild irrigation treatments can probably be explained by reduced marketable yields as the depletion levels were increased and the plants were subjected to more water stress (Sammis & Wu, 1986). According to literature, a reduction in yield can be attributed to the failure of pollination and fruit setting (Hsiao, 1982; Wolf & Rudich, 1988; Kirda *et al*., 2004), reduced translocation of assimilates to the fruit due to decreases in phloem and xylem sap fluxes, fruit respiration and leaf photosynthesis, while sap backflow through xylem and fruit shrinkage can also occur (Araki *et al.*, 2000). The reduced yield, WUE_I and WUE_T under water stressed conditions is therefore mainly attributed to the number of fruit and individual fruit yield (Nuruddin *et al.*, 2003; Kirda *et al.*, 2004; Gallardo *et al.*, 2006; Bhattarai & Midmore, 2007).

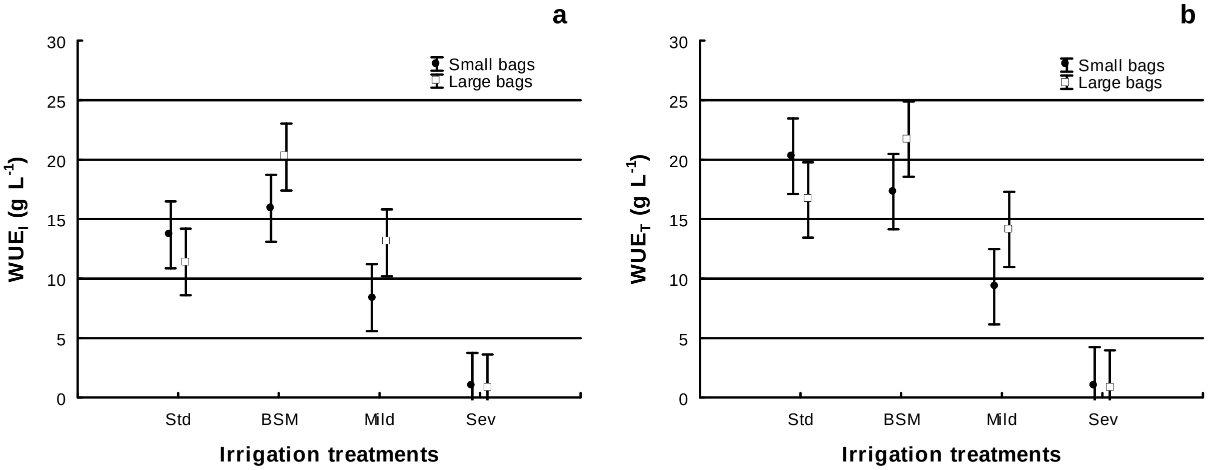

Figure 4.2.5 Water use efficiency of tomato plants in the small and large bags based on a) irrigation (WUE_I; g L^{-1}) and b) transpiration (WUE_T; g L^{-1}), for all irrigation treatments, where Std = Standard; BSM = Between standard and mild; Mild = Mild; and Sev = Severe irrigation treatments.

The yield advantage for both bag sizes decreased as the irrigation volumes or cumulative transpiration rates of the standard irrigation treatment that determine WUE_I and WUE_T, increased. The decline in yield advantage was, however, slower for the small bags compared to the large bags. From these results the conclusion can be drawn that optimal yield can probably be achieved with less frequent irrigation.

For both bag sizes, the WUE_I of 15.9 (small) and 20.2 (large) g L^{-1} for the BSM treatment was higher compared to 13.7 and 11.4 g L^{-1} for the small and large bags of the standard irrigation treatment, respectively. It was, however, only significantly higher for the large bags (Figure 4.2.5a). The increased values of WUE_I for the BSM treatment compared to the standard irrigation treatment can be ascribed to less water losses due to drainage, and thus improved irrigation management. The WUE_I was low compared to values observed by Kirda *et al.* (2004) and Topcu *et al.* (2007), which was 32.2 and 46.4 g L^{-1} for a full irrigation treatment consisting of tomato plants maintained at field capacity and 50.3 and 70.8 g L^{-1} at a partial root drying strategy where irrigation is managed to 50% of the full irrigation treatment. The higher accumulation of dry matter observed by Kirda *et al*. (2004) and Topcu *et al*. (2007) may possibly be attributed to lower mean temperatures throughout the production season in Turkey, which ranged between 15 and 25ºC, compared to local conditions of 16ºC minimum night time to 35ºC maximum daytime temperatures within the glasshouse.

As with WUE_I, the WUE_T was not significantly different between the standard and BSM treatments for both bag sizes. The highest WUE_T of 20 g L^{-1} for the standard irrigation treatment was obtained in the small bags and did not significantly differ from that of the BSM treatment (17 g L^{-1}) and may suggest that the turning point (maximum WUE_T without significant yield losses) will be somewhere between the BSM and standard irrigation treatment. For the large bags the WUE_T of 22 g L^{-1} for the BSM treatment was higher but not significantly different from the WUE_T of 17 g L^{-1} for the standard irrigation treatment (Figure 4.2.5b). The higher WUE_T for the BSM irrigation treatment possibly indicates luxury water use and transpiration of plants subjected to the standard irrigation treatment. Kirda *et al*. (2004) and Topcu *et al*. (2007) observed WUE_{ET} values of 29.6 and 44.1 g L^{-1} for tomato plants grown at field capacity (full irrigation) and 35.1 and 57.3 g L^{-1} when subjected to a partial root drying strategy where irrigation is managed to 50% of the full irrigation treatment. Bhattarai and Midmore (2007) also observed increased water use for tomato plants maintained at field capacity compared to deficit irrigation. Again, results of the current study were very low, and would have been even lower compared to results of Kirda *et al*. (2004) and Topcu *et al*. (2007) if these authors separated evaporation from transpiration. Since the vapour pressure deficit was not considered in any of the above results, climate may be the cause for these differences between studies. Lower values observed in the current study may also indicate disequilibrium between CO_2 and water uptake, because an increased water uptake does not necessarily result in increased carbon assimilation and therefore improved production. This should however be further investigated since the root mass and total biomass was not included for the determination of the WUE_T. Another limitation to WUE_T may be the availability of oxygen in the root zone, since the water content levels for the standard irrigation treatment was constantly above the laboratory determined drained upper limit and should have displaced part of the air space of the coir. The critical value of the oxygen deficiency rate is relatively high for tomato (25 $\mu g\ m^{-1}\ s^{-1}$) compared to other crops, e.g. 13 and 8 $\mu g\ m^{-1}\ s^{-1}$ for sugar beet and wheat, respectively (Gliński & Stępniewski, 1985). However, the oxygen levels were not measured in this study, and it is only speculated that this could be a factor, because the WUE_T of tomato plants is reduced in poorly aerated soils (Bhattarai *et al.*, 2006). Optimal yield may therefore be achieved at a much lower transpiration rate. These results for transpiration and irrigation indicate that there probably exists a point between the BSM and standard irrigation treatment where the water use efficiency will be at maximum. However, the lack of additional depletion levels above the BSM irrigation treatment prevented the exact determination of this point for the small and large bags, respectively.

4.2.4 Conclusion

Irrigation was successfully managed to pre-determined water depletion levels through the use of in situ calibrated EC-10 and EC-20 capacitance sensors. From the differences in depletion levels between the bag sizes, it is evident that various bag sizes require different irrigation management strategies. Irrigation and drainage was successfully reduced by scheduling to specified depletion levels. Irrigation of the BSM treatment was only 43 and 46% of that of the standard irrigation treatment for the small and large bags, respectively. Drainage was even lower at only 3.8 and 3.3% of that of the standard irrigation treatment for the small and large bags, respectively, without the reduced drainage amounts increasing the EC. This reduction is advantageous because less water and fertilizer are used, while less water and fertilizer drains to waste. The result is that production costs can be saved on fertilizer as well as water, which is especially beneficial to greenhouse producers who usually use expensive municipal water or who have to bridge periods of sub-surface/borehole water shortage with the use of expensive municipal water. Yield and water use efficiency results indicated that the depletion levels used in this study was too low, although the standard irrigation treatment resulted in luxury water use by the plants and inefficient irrigation compared to the BSM irrigation treatment. It may therefore be concluded that the standard irrigation method results in over-irrigation of tomatoes grown in coir, but that additional research is needed to find the optimal depletion level for each bag size between the BSM and standard irrigation treatment which will result in maximum water use efficiency. For this it will be necessary to calibrate the capacitance sensors for volumetric water content values between DUL and saturation, as it was observed that the DUL of the bags varied from that determined in the laboratory. It is also recommended that producers use more than one sensor to monitor water content in the greenhouse as a precautionary measure to overcome the impact of a faulty sensor. Monitoring of oxygen levels within the coir in future trials will also aid to explain differences in transpiration or crop water use efficiency between different depletion levels.

4.2.5 References

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Chapter 5

Comparing crop water stress of greenhouse cucumber and tomato plants under luxury water supply and cyclic water deficit conditions

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A crop's response to water stress varies greatly depending on its ability to acclimatise to water deficit conditions. The objectives of this study were firstly to determine if the water stress criteria developed for greenhouse cucumber and tomato plants, which was based on the relationship between the transpiration ratio and available depletion for conditions of luxury water supply, are sound for application in cyclic water deficits and secondly, to determine the relationship between available depletion and yield and evaluate the use of soil water sensors for irrigation scheduling. The relationship between transpiration data and available water depletion indicated that greenhouse cucumber and tomato plants subjected to luxury water supply experienced water stress earlier compared to plants subjected to cyclic water deficit conditions, irrespective of bag size. This was due to reduced transpiration by acclimatised greenhouse cucumber and tomato plants. The occurrence of mild crop water stress, based on transpiration, was variable for both crops in the small and large bags. The high irrigation frequency for small bags scheduled to pre-determined water depletion levels indicated that small bags are more dependent on the irrigation system than on water stored in the coir, while large bags rely more on the coir and less on the system. From the yield results, irrigation scheduling according to water depletion levels is not yet recommended for greenhouse tomato and cucumber plants grown in small bags, since the depletion levels used was too low (below 60%) and did not improve or maintain yield. However, the improved or maintained yields of the greenhouse cucumber and tomato plants in the large bags justified irrigation scheduling according to available water depletion levels through the use of soil water sensors. The lower depletion level for the large bags beyond which yield is reduced was estimated at 85% for tomatoes and 70% for cucumbers.

Keywords: Greenhouse cucumbers, Greenhouse tomatoes, Irrigation scheduling, Transpiration, Yield, Water depletion levels

5.1 Introduction

Coir is a relative new growth medium used in greenhouses with different water retention characteristics compared to other growth mediums used and therefore requires a different irrigation management strategy. There is however not many published guidelines for irrigation scheduling in this growth medium and greenhouse producers mostly rely on scheduling methods developed for other growth mediums. Van der Westhuizen *et al.* (2009a-b, Chapter 4) observed over-irrigation of greenhouse cucumber and tomato crops grown in coir which resulted in low crop water use efficiency compared to improved water use efficiency when irrigation was scheduled to water depletion levels and crops experienced cyclic water deficits. According to Turner and Begg (1981), a plant’s response to water deficit is modified by its ability to acclimatise to water shortage, while mechanisms of acclimation to water stress include changes in phenological development and physiology.

The effect of water deficit stress on plant phenology depends on the duration and intensity of the stress, as well as the timing relative to the development cycle of the plant (Desclaux & Roumet, 1996). Early water stress impairs early vegetative development and therefore has a continuous negative effect on growth and yield in corn (Jama & Ottman, 1993), while crop water stress in soybean lead to shortened reproductive phases and less time between crop phases (Desclaux & Roumet, 1996). According to Wolf and Rudich (1988), the level of soil water content influences the final dry mass of tomato fruit by influencing the length of the fruit development period and/or the rate of growth. Fruit developing early in the production cycle has a higher rate of dry mass accumulation compared to later developing fruit, due to a shortened growth period caused by reduced translocation of assimilates to the fruit and more rapid ripening under water deficit conditions (Wolf & Rudich, 1988). The result is reduced total and marketable fresh fruit yield under water stressed conditions, which can be mainly attributed to lower snumber of fruit and individual fruit yield (Nuruddin *et al.*, 2003; Kirda *et al.*, 2004; Gallardo *et al.*, 2006; Bhattarai & Midmore, 2007). The limitation of crop growth and yield or the acclimatisation of indeterminate greenhouse tomatoes and cucumbers to water deficit will therefore depend on the timing and severity of the stress imposed as suggested by Jama and Ottman (1993) and Desclaux and Roumet (1996).

According to Hsiao *et al*. (1976), a plant's ability to make physiological adjustment to water stress depends on the rate of water stress development, with more rapid development impairing this ability, while more gradual stress facilitates it. Therefore, physiological conditioning to water stress does not necessarily result in improved plant performance or yield (Jama & Ottman, 1993).

Water deficits are usually associated with a reduction in turgor and thereby in a reduction of the physiological processes in which turgor is involved, e.g. stomatal behaviour (Hsiao *et al.*, 1976). According to Kramer (1983), plants can respond to water deficit by delaying dehydration by maintaining relative high plant water potential, or by tolerating dehydration by continued functioning at lower plant water potentials. The maintenance of high plant water potential requires reduced transpiration by reducing stomatal conductivity, while the reduction of plant water potential requires active osmotic adjustment to maintain turgidity and support transpiration (Kramer, 1983). The maintenance of turgor potential when leaf water potential declines, which reduce the critical leaf water potential, is confirmed by Zhang and Archbold (1993), while Iannucci *et al*. (2000) observed that berseem clover acclimatised to water deficit through the maintenance of tissue hydration.

According to Turner and Begg (1981), all plants that actively transpire experience some degree of short term water deficit regardless of how well they are supplied with water. The available soil water potential sets the upper limit of recovery that is possible by the plant when it is not actively transpiring (Turner & Begg, 1981). For a longer period of water deficit, evaporative demand will start to progressively exceed water uptake from the root medium, regardless of several opportunities for the plant to recover. Plants subjected to continuous water stress reduce their transpiration rate relative to well-watered plants (Blum & Arkin, 1984). Riseman *et al*. (2001) exposed potted miniature roses to cyclic water deficits during the production season. They observed that the greatest physiological responses occurred following the first exposure to water deficit compared to well-watered plants, but that this had a conditioning effect on the plants which improved their response to subsequent water deficits. In contrast, Blum and Arkin (1984) observed that the transpiration rate of sorghum is unaffected by soil water unless it is reduced to 20% of available water or less. Below 20% available water, the transpiration of sorghum leaves were reduced probably due to a reduction in leaf area, although transpiration was not ceased completely and stomatal closure was not complete (Blum & Arkin, 1984). Because water deficit affects crop evapotranspiration (ET) and yield, it can be quantified by the rate of actual ET (ET_A) to maximum ET (ET_M) (Doorenbos *et al*., 1980). Fully irrigated crops will have a ET_A:ET_M of one, while the ratio will drop below one under water deficit conditions. Payero *et al*. (2006) observed that the ratio of transpiration of un-watered plants to that of well-watered plants, namely T_d:T_w, is a very stable water variable to relate crop yield to available soil water with a correlation coefficient of 0.90. The objectives of this study were: i) to determine if the water stress criteria developed for greenhouse cucumbers and tomatoes which was based on the relationship between the transpiration ratio (T_d:T_w) and available depletion for conditions of luxury water supply are sound for application in cyclic water deficits; and ii) to determine the relationship between available depletion and yield and evaluate the use of soil water sensors for irrigation scheduling.

5.2 Material and methods

Data used in this study was obtained from four separate experiments conducted in a 48 m^2 temperature-controlled glasshouse at the University of the Free State in the Free State province of South Africa (26º11’20” E, 29º06’33” S, 1409 m altitude). Fresh market cucumber (*Cucumis sativus*) of the cultivar Airbus and tomato (*Lycopersicon esculentum* Mill.) of the cultivar Espadilha were used in the experiments. In all experiments, seedlings were transplanted to 9 L and 20 L growing bags filled with coir and spaced at a mean density of 2 plants m^{-2}, while plants were topped when they reached the horizontal trellising wire approximately 2 m above the bag surface.

Different water stress treatments were applied during the four experiments. The first two experiments comprised a luxurious water supply and one drying cycle for greenhouse cucumber and tomato plants, respectively (Van der Westhuizen *et al*., 2009c-d, Chapter 3). In the last two experiments greenhouse cucumber and tomato plants were subjected to cyclic water deficit conditions (Van der Westhuizen *et al.*, 2009a-b, Chapter 4).

The first water stress treatment, the luxury stress treatment, comprised of keeping plants of both crops and for both bag sizes well-watered by irrigating eight times per day for the duration of the production season and withholding irrigation from half of the plants only in the mid reproductive stage, until they reached permanent wilting (Van der Westhuizen *et al.*, 2009c-d, Chapter 3). The second water stress treatment, the cyclic water deficit treatment, comprised of the acclimatisation of plants of both crops and for both bag sizes to different pre-determined water depletion levels (Van der Westhuizen *et al.*, 2009a-b, Chapter 4).

Some water stress criteria developed by Van der Westhuizen *et al.* (2009c-d, Chapter 3) for greenhouse cucumber and tomato plants grown in coir were used for comparison in this study. Firstly, mild water stress, *viz.* the point from where the transpiration ratio (T_d:T_w, where T_d = transpiration of dry or depletion level treatment and T_w = transpiration of well-watered treatment) does not recover under continuous drying of the medium as well as the lowest level to which irrigation may be scheduled based only on plant response, were used to compare transpiration ratios of cucumber and tomato plants between the two water stress treatments in small and large growing bags, respectively. Secondly, moderate water stress, identified as the lower level of plant available water content, and a modified drained upper limit (DUL_M) was used to determine the percentage water available for depletion at various data points, based on the volumetric water content of these points. This is referred to as available depletion which basically is the percentage of water in the medium that is easily available to the plant. A DUL_M was determined from the data of all four experiments (Van der Westhuizen *et al.*, 2009a-d, Chapter 3 & 4), as it was observed that water was constantly extracted above the laboratory determined drained upper limit for the well-watered and highest available depletion level treatments. The DUL_M was determined for each bag size as the combined mean water contents of the well-watered treatments over the previous four experiments. This resulted in a mean DUL_M value of 0.728 and 0.712 $m^3\ m^{-3}$ for the small and large bags, respectively.

Yield data from the experiments where irrigation was managed to pre-determined water depletion levels and plants acclimatised to the cyclic water deficit (Van der Westhuizen *et al.*, 2009a-b, Chapter 4), was used to determine the optimum level of available water depletion which will maintain yield in both bag sizes and for both crops. In order to compare yield between crops, it was converted to a relative value expressed as the ratio (Y_d:Y_w) between yield from the depletion level treatments (Y_d) and that from well-watered treatments (Y_w).

Regression lines of the relationship between the transpiration ratio and available depletion as well as yield and available depletion were compared by means of the *t*-test as described by Clewer and Scarisbrick (2001).

5.3 Results and discussion

5.3.1 Soundness of water stress criteria based on the transpiration ratio under luxury water supply

In previous experiments by Van der Westhuizen *et al.* (2009c-d, Chapter 3) the transpiration ratio was identified as the main criterium to determine available water content levels where mild water stress occurred for greenhouse tomato and cucumber crops. Based only on plant response to a drying cycle applied after well-watered conditions (luxury stress treatment), water content at mild water stress was identified as the lowest depletion level to which irrigation should be scheduled. The development of crop water stress for greenhouse tomato and cucumber crops subjected to cyclic water deficit conditions, based on the relationship between transpiration ratio and available water content determined from follow-up experiments by Van der Westhuizen *et al.* (2009a-b, Chapter 4), was similar compared to the luxury stress treatment. Statistical results for the slopes and intercepts of the linear relationship between transpiration ratio and available water depletion, presented in Table 5.1, were not significantly different between the two stress treatments for the tomato and cucumber crops within each bag size. Therefore, the linear regression lines of the different stress treatments were combined into one function per crop for each bag size (Figure 5.1).

From Figure 5.1 it is evident that both tomato and cucumber plants experience water stress immediately after irrigation is stopped, irrespective of bag size. This may be explained by the high leaf area index of greenhouse cucumbers and tomatoes, which may result in a large plant response to a small water deficit.

Table 5.1 Comparison of regression statistical parameters describing the development of water stress based on the relationship between the transpiration ratio (T_d:T_w) and available depletion between the luxury stress treatment and cyclic water deficit treatment (CWD) for greenhouse tomato and cucumber crops in small and large bags.

Crop	Treatment	Slope	Intercept	n	R^2
Tomatoes	*Small bags:*				
	Luxury	0.0078a	0.250a	4	0.958
	CWD	0.0061a	0.323a	4	0.937
	Large bags:				
	Luxury	0.0073a	0.236a	4	0.985
	CWD	0.0069a	0.145a	4	0.817
Cucumbers	*Small bags:*				
	Luxury	0.0061a	0.476a	4	0.661
	CWD	0.0055a	0.414a	4	0.976
	Large bags:				
	Luxury	0.0060a	0.425a	4	0.990
	CWD	0.0070a	0.183a	4	0.909

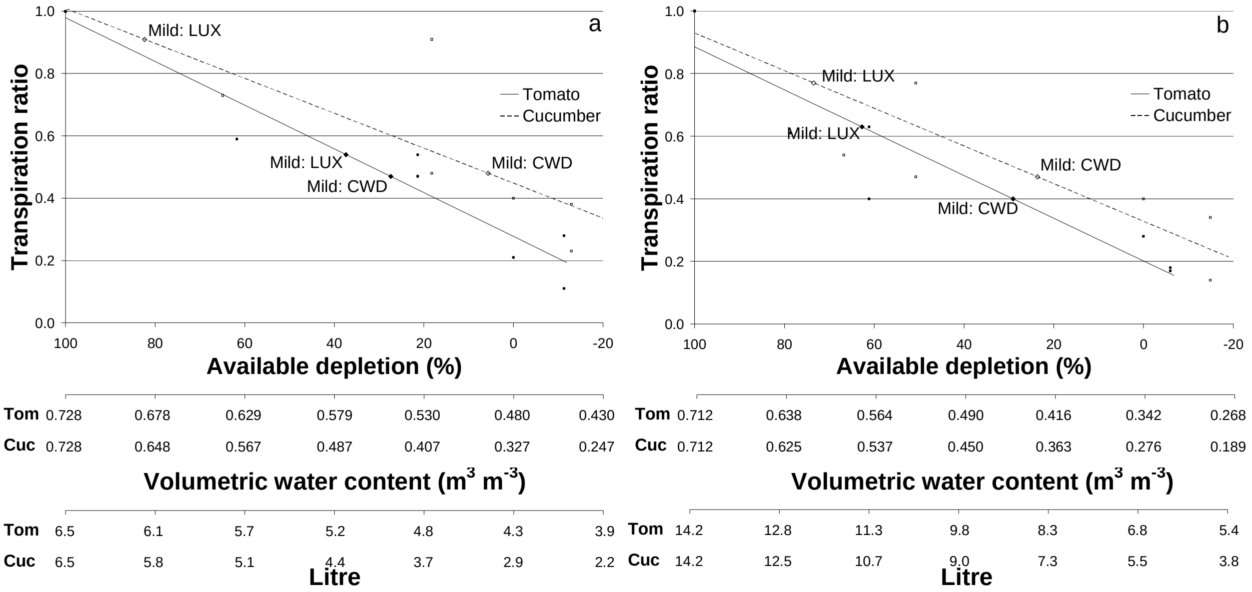

Figure 5.1 Linear regression of the relationship between the transpiration ratio (T_d:T_w) and available water depletion (%), volumetric water content (m^3 m^{-3}) and liters water content per bag for the combined luxury irrigation treatment (LUX) and cyclic water deficit treatment (CWD) for greenhouse tomato and cucumber plants in a) small bags and b) large bags.

Although the development of water stress was similar between the stress treatments, the transpiration ratio at which mild water stress occurred for each bag size and crop, varied. This variation between the two water stress treatments within each bag size and for individual crops was indicative of the difference in the intensity of water stress (Figure 5.1). Both tomato and cucumber plants subjected to the luxury stress treatment experienced water stress earlier compared to those which acclimatised to cyclic drying, irrespective of bag size. Mild water stress for cucumber and tomato plants subjected to the luxury stress treatment in the small bags occurred at transpiration ratios of 0.91 and 0.54, respectively (Van der Westhuizen *et al.*, 2009c-d, Chapter 3), compared to transpiration ratios of 0.48 and 0.47 for cucumber and tomato plants, respectively, which were conditioned to cyclic drying (Van der Westhuizen *et al.*, 2009a-b, Chapter 4). Similarly, cucumber and tomato plants in the large bags experienced mild water stress at transpiration ratios of 0.77 and 0.63, respectively, when subjected to the luxury stress treatment, compared to transpiration ratios of 0.47 and 0.40 for cucumber and tomato plants, respectively, which were conditioned to cyclic drying (Van der Westhuizen *et al.*, 2009a-b, Chapter 4). Therefore, in both bag sizes, cucumber and tomato plants experienced delayed water stress under the cyclic water deficit treatment because of reduced transpiration. As a result, greenhouse tomato and cucumber plants which are acclimatised to some degree of water stress, may deplete water to lower levels of available depletion with similar effects to the plant's response based on the water stress criteria, although transpiration will be reduced. This is contrasting to the results of Blum and Arkin (1984) who observed that the transpiration rate of sorghum was unaffected by available soil water above 20%, although a decrease in transpiration was observed by Payero *et al*. (2006) for corn.

The occurrence of mild water stress in greenhouse cucumber and tomato plants for the two different water stress treatments varied between bag sizes (Figure 5.1). It is expected that the water stored in the coir in the small bags are low compared to that of the large bags and therefore that plants should experience water stress earlier in the small bags. This was only true for cucumber plants subjected to the luxury stress treatment, with T_d:T_w ratios of 0.91 and 0.77 for the small and large bags, respectively, and tomato plants subjected to cyclic water deficits, with T_d:T_w ratios of 0.47 and 0.40 for the small and large bags, respectively. Cucumber plants subjected to cyclic water deficit experienced mild water stress at similar T_d:T_w ratios of 0.47 for the small bags and 0.48 for the large bags. The late observation of mild water stress of tomato plants subjected to the luxury stress treatment in the small bags is probably due to the high intensity of water stress experienced by this crop. This was not captured fully in the T_d:T_w ratio which was only calculated at 24 hour intervals, in order to prevent large errors in the T_d:T_w data which may result due to great variation in transpiration during the course of a 24 hour period.

However, plants in the small bags received a higher frequency irrigation compared to the large bags when scheduled to pre-determined water content levels. Therefore, cucumber and tomato plants grown in the small bags depend more on the irrigation system than on water stored in the coir (available depletion), while plants in the large bags rely relatively more on the coir to meet their daily crop water demand and less on the system.

5.3.2 Yield response to crop water stress and validity of soil water sensors for irrigation scheduling

The trend of relative yield of acclimatised crops to available depletion varied significantly between small and large bags for both tomatoes and cucumbers. From Figure 5.2 it was observed that relative yield of tomato plants were reduced more compared to cucumber plants at higher available water depletion levels for both bag sizes.

For both crops in the small bags, the lack of additional depletion levels between approximately 60 and 100% available depletion resulted in the unpredictability of the lowest depletion level that may be required to maintain yield (Figure 5.2a). From 60% available depletion both crops showed a slower linear decrease in yield with decreased levels of available depletion. The water reserve of the small bags is little in comparison to large bags and therefore the crops depend heavily on frequent application of water through the irrigation system. Further research is necessary for both cucumber and tomato crops grown in small bags to determine yield levels between 60 and 100% available depletion in order to evaluate the use of water depletion levels for irrigation management.

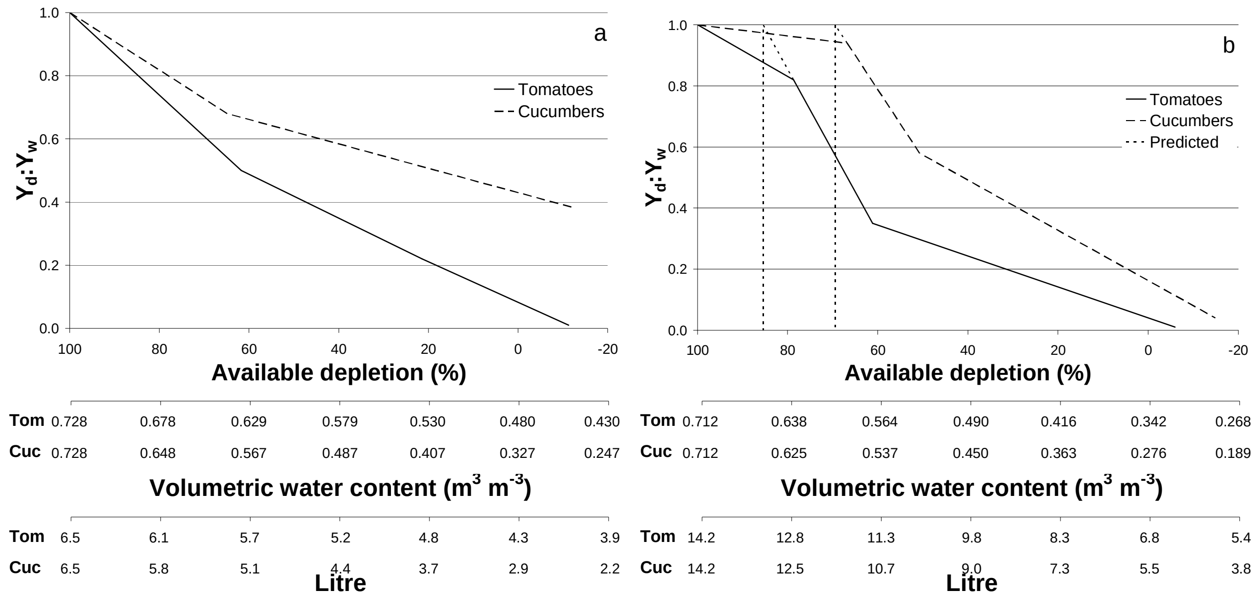

Figure 5.2 Relative yield (Y_d:Y_w) compared to available water depletion (%), volumetric water content (m^3 m^{-3}) and liters water content for greenhouse tomato (Tom) and cucumber (Cuc) plants in a) small bags and b) large bags.

Both tomato and cucumber plants in the large bags showed similar trends in relative yield as available depletion were reduced (Figure 5.2b). There were two clear breaking points for both crops between which relative yields decreased rapidly, *viz.* 79 and 61% available depletion for the tomatoes and 67 and 51% available depletion for the cucumbers. On either sides of this rapid decrease, yield decreased more slowly as available depletion was reduced. The generalized hypotheses quoted by Hillel (1998) states that water is equally available from the drained upper limit up to a critical point of available depletion beyond which availability decreases. Therefore, the optimal level of available water depletion for tomatoes and cucumbers in large bags may be predicted by extending the lines between the breaking points toward Y_d:Y_w = 1.0 as shown by the dotted lines on Figure 5.2b. This estimates the optimal level for available water depletion at 85% for tomatoes in large bags and 70% for cucumbers in large bags. This confirms previous results by Van der Westhuizen *et al*. (2009a-b, Chapter 4) that the standard irrigation method, which aims to maintain field water capacity or 100% available depletion, results in luxury water uptake by both greenhouse cucumber and tomato crops.

Compared to the transpiration ratio, optimal water management for maintaining yield is predicted from Figure 5.1 at 0.78 T_d:T_w for tomatoes and 0.75 T_d:T_w for cucumbers for the large bags. For tomatoes, this value was much higher than the 0.63 T_d:T_w of mild water stress for the luxury stress treatment, which was proposed as the lower depletion level to maintain yield, based only on plant response (Van der Westhuizen *et al.*, 2009c-d, Chapter 3). However, for cucumbers, this value was very similar to the 0.77 Td:Tw of mild water stress. Payero *et al*. (2006) observed a decreased transpiration ratio to the level of 0.59 T_d:T_w where yield of corn was not significantly reduced compared to a 1:1 ratio. The higher transpiration ratio required to maintain yield of the greenhouse crops compared to irrigated field corn is probably due to the indeterminate growth habit of greenhouse crops as well as plant factors such as the greater leaf area, leaf size and lesser leaf thickness of greenhouse crops.

From results of Van der Westhuizen *et al.* (2009a-b, Chapter 4), it was observed that the EC-10 and EC-20 capacitance sensors accurately scheduled irrigation to pre-determined water depletion levels in coir. Therefore, the optimal depletion levels identified in this study for greenhouse cucumber and tomato plants grown in coir should be achieved accurately through the use of these sensors in order to schedule irrigation in large bags. Until further research is conducted between 60 and 100% available water in small growing bags, irrigation scheduling according to water depletion levels is not recommended for small bags.

5.4 Conclusions

The development of crop water stress, based on the relationship between the transpiration ratio and available water content, for greenhouse cucumber and tomato plants did not vary significantly between the luxury stress treatment and cyclic water deficit treatment. Although the development did not differ between water stress treatments, the point of mild water stress was experienced earlier by both cucumber and tomato plants subjected to the luxury stress treatment compared to the cyclic water deficit treatment, irrespective of bag size. This clearly indicated that the response of both crops to water stress was delayed when they were acclimatised to cyclic water deficit, while transpiration was reduced compared to similar points of water stress for the luxury stress treatment.

The occurrence of water stress in greenhouse cucumber and tomato plants for the two different water stress treatments varied between bag sizes. Although no specific trend could be observed between the small and large bags, it was evident that the small bags are more dependent on the irrigation system than on water stored in the coir, due to the high irrigation frequency triggered by rapid water depletion. In contrast, plants in the large bags rely more on the coir to meet their daily water demand and less on the system. As a result, plants grown in large bags will be able to withstand water deficit if irrigation should fail due to unforeseen circumstances such as power failures.

From the yield results, irrigation scheduling according to water depletion levels is not yet recommended for greenhouse tomato and cucumber plants grown in small bags, since the depletion levels used did not improve or maintain yield. The buffer against water stress conditions in the small bags are too small for the depletion levels used, which may result in large yield losses over a small period of time, especially for greenhouse tomatoes. Until further research is conducted it is rather recommended to irrigate small bags to a fixed frequency and control irrigation quantity by monitoring of the drainage percentage. This frequency need not be eight times per day as for the standard irrigation method, but may probably be halved without the occurrence of mild water stress. Further research is necessary to determine if scheduling to water depletion levels with soil water sensors is the correct irrigation management strategy for production in coir in small bags (9 L).

The improved or maintained yields of the greenhouse cucumber and tomato crops may justify irrigation scheduling with soil water sensors to available water depletion levels for large growing bags. The lower level of plant available water capacity beyond which yield is reduced is estimated at 85% for tomatoes and 70% for cucumbers which amounts to transpiration ratios of 0.78 and 0.75 T_d:T_w for acclimatised tomato and cucumber crops, respectively.

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Chapter 6

Summary, application and recommendations

6.1 Summary

Hydroponic crops grown in coir in South African greenhouses are mostly over-irrigated, which waste limited irrigation water and fertilizer and reduce yields. As coir is a relative new growth medium and irrigation management guidelines limited and not readily available, the primary objective of this study was to evaluate an irrigation management strategy involving capacitance water content sensors for hydroponic tomato and cucumber plants grown in coir. Six experiments were conducted in a controlled climate chamber and glasshouse.

In the first experiment, a controlled climate chamber was used to evaluate a laboratory procedure for the calibration of EC-10 and EC-20 capacitance sensors in coir and evaluate the manufacturer's calibration equations for use in coir. The proposed laboratory calibration procedure was based on the principle of the continuous measurement of mass loss of a saturated coir sample during a drying cycle. The result was perfect calibration for sensor response against volumetric water content for all EC-10 and EC-20 sensors. Evaluation of the manufacturer's calibration equation indicated a poor accuracy of prediction which mostly underestimated the volumetric water content compared to the near perfect prediction of the coir specific laboratory calibration of individual sensors. The laboratory calibrations were between 27-42% and 33-43% more accurate than the manufacturer's calibration for the EC-10 and EC-20 sensors, respectively. While the proposed laboratory calibration procedure takes less time than some other calibration methods which also aspires high accuracy, it remains a time consuming method that may not be very usable in commercial production environments. In order to reduce the calibration time of these sensors, a rapid calibration procedure for EC-10 and EC-20 sensors was proposed to promote the commercial use of these sensors for irrigation management in coir. The proposed rapid procedure comprises of taking one sensor reading (mV) and one gravimetric sample (m^3 m^{-3}), both at drained upper limit, for each sensor installed under production conditions. An accurate general laboratory calibration equation for coir is used of which the x (mV) and y (m^3 m^{-3}) values are substituted by relative values of x (x_{Rel}) and y (y_{Rel}) which is determined from any given value of x or y divided by their corresponding values at drained upper limit, *viz.* x_{DUL} and y_{DUL}. The accuracy of prediction by the rapid calibration procedure for the plant available water content range was high for both EC-10 and EC-20 sensors, while the use of relative values of x and y for individual sensors compensated for variation between sensors.

The second set of experiments were conducted in a glasshouse and aimed to characterise the water retention and ability of coir to supply water to mature greenhouse tomato and cucumber crops. Growth medium water content was continuously monitored through the EC-10 and EC-20 capacitance sensors during a drying cycle and under well-watered conditions. Identified stages of water stress for both greenhouse cucumbers and tomatoes grown in coir comprised of: i) mild water stress as the point from where the T_d:T_w (transpiration ratio where T_d = transpiration of unwatered and T_w = transpiration of well-watered plants as determined using the water-balance equation) does not recover under continuous drying of the medium; ii) moderate water stress as the point were wilting became visible; and iii) severe water stress as the point where changes in the slope of T_d:T_w, plotted over time, becomes negligible and about 75% of all plants are irreversibly wilted. Based only on the plant's response to the drying cycle in both crops, it was recommended that water depletion can be allowed to the point of mild water stress which can be detected by soil water sensors.

In the third set of experiments, the identified stages of crop water stress were used to determine and apply depletion levels in coir and compare it to a well-watered treatment in glasshouse experiments for greenhouse cucumber and tomato plants. Sensor performance was evaluated and the efficiency of the pre-determined depletion levels, with regard to the water balance components, yield and water use efficiency for different bag sizes, was determined. From the results it was evident that irrigation was successfully managed to the pre-determined water depletion levels in coir through the use of in situ calibrated capacitance sensors for both cucumber and tomato plants. For both crops the depletion of water varied between bag sizes, indicating that various bag sizes require different irrigation management strategies. Scheduling to the highest pre-determined depletion levels reduced irrigation by 124 L m^{-2} in the small and 240 L m^{-2} in the large bags for cucumbers and 427 L m^{-2} in the small and 487 L m^{-2} in the large bags for tomato plants, compared to the well-watered treatments. Yields achieved by the greenhouse tomato plants in the large growing bags and cucumber plants in the small and large bags were maintained or improved when scheduled to the highest depletion level compared to the well-watered treatment. Yields were therefore not significantly reduced when irrigation were scheduled to 65, 67 and 79% of plant available water content for cucumbers in the small and large bags and tomatoes in the large bags, respectively. The combination of reduced irrigation and improved or maintained yields resulted in improved water use efficiencies (based on irrigation and transpiration) for the highest depletion level compared to the well-watered treatments. In all glasshouse experiments the well-watered treatment resulted in luxury water use by the plants.

Finally, a study was conducted in order to compare crop water stress of greenhouse cucumber and tomato plants under luxury water supply and cyclic water deficit conditions. The comparison was based on the transpiration ratio and yield, while the use of capacitance sensors was evaluated for irrigation scheduling in coir for both crops. Transpiration data indicated that cucumber and tomato plants subjected to luxury water supply experience water stress earlier than plants subjected to cyclic water deficit conditions, irrespective of bag size. Results indicated that irrigation scheduling according to water depletion levels is not yet recommended for greenhouse tomato and cucumber plants grown in small bags, until further research is conducted. However, the improved or maintained yields of the greenhouse cucumber and tomato plants in the large bags justified irrigation scheduling according to available water depletion levels through the use of soil water sensors. The lower depletion level for the large bags beyond which yield is reduced was estimated at 85% for tomatoes and 70% for cucumbers.

In conclusion, the study successfully addressed all specific objectives and it may be concluded that the use of capacitance sensors in large growing bags improves irrigation management of hydroponic cucumbers and tomatoes in coir through the exclusion of over-irrigation and improved water use efficiency.

6.2 Application and/or recommendations

6.2.1 Research

The laboratory calibration procedure proposed for the EC-10 and EC-20 capacitance sensors can be applied to various other soil water sensors and growth mediums or soil types to improve the accuracy of prediction of volumetric water content. It was evident from this study that water is extracted differently within a specific growth medium for different crops and root volumes.

The laboratory calibration procedure can be improved by starting calibration at saturation which can be achieved through the used of vacuum suction, as it was observed that the drained upper limit of the bags in the glasshouse varied from that determined in the laboratory. After this, additional research for both greenhouse tomatoes and cucumbers is required to find the optimal depletion level between saturation and the highest depletion level used in this study for each bag size which will result in maximum water use efficiency.

Further research is also required to determine an upper level to which irrigation should be managed in coir instead of a fixed volume application, which will further improve water use efficiency.

6.2.2 Irrigation management for greenhouse producers

It is evident from this study that the use of capacitance sensors in coir can improve irrigation management, yield and water use efficiency of greenhouse cucumbers and tomatoes. Since crop water stress are now characterised for greenhouse cucumbers and tomatoes grown in coir, laboratory calibration of sensors are not required and the rapid procedure proposed in this study provides a simple but scientifically sound method to calibrate sensors which is easy to apply to individual sensors in the field. It is, however, still recommended that producers use more than one sensor to manage irrigation in the greenhouse as a precautionary measure to overcome the impact of a faulty sensor.

It is recommended that the irrigation management strategy should be based on an available water depletion level determined from plants that were conditioned to a specific irrigation schedule throughout their growth period. General guidelines for depletion levels are proposed in this study for cucumber and tomato plants grown in large growing bags. For the large growing bags (20 L), it is recommended that the lowest depletion level of coir, without any yield penalty, is estimated at 85% for tomatoes and 70% of plant available water content for cucumbers. To determine these levels for application in large bags for a specific situation, the plant available water content may be calculated as the difference between the volumetric water content measured by the EC-20 capacitance sensors at drained upper limit and the lower level of plant available water content, *viz.* 0.276 m^3 m^{-3} for cucumbers and 0.342 m^3 m^{-3} for tomatoes. It is not recommended to schedule irrigation to water depletion levels in small growing bags (9 L) until the lower depletion level for coir, beyond which yield is reduced, is determined in further experiments. However, from the results in this study, which indicated 1-5 irrigation events per week for the highest depletion level treatment in the small bags, it can be speculated that an irrigation frequency of 2-4 cycles per day is more than sufficient to maintain or even improve yield of greenhouse tomato and cucumber crops grown in coir in the small bags under greenhouse conditions.