ABSTRACT

Title of Dissertation:	IMPROVING IRRIGATION MANAGEMENT AND ROW COVER USE IN STRAWBERRY PRODUCTION IN THE MID-ATLANTIC REGION
	Bruk Eshetu Belayneh, Doctor of Philosophy, 2020
Dissertation directed by:	Professor John Lea-Cox Department of Plant Science and Landscape Architecture

Irrigation strategies that reduce water application and improve water use efficiency could be useful in strawberry production, to save water and reduce the environmental impact of nutrient leaching. Therefore, the effect of moisture availability on the physiology, growth, yield and fruit quality of strawberry (*Fragaria X ananassa*) was studied under field and greenhouse conditions by implementing deficit irrigation at decreasing matric potentials. Incremental drought stress significantly affected crop physiology, growth and yield, but not fruit quality. The results revealed both physiological and morphological adaptations of strawberries to incremental drought stress that are typical of isohydric plants. Since reduced irrigation applications led to proportional yield losses, there was no significant improvement in the irrigation water use efficiency/water productivity of the crop. Economic analysis showed that the loss of

revenue as a result of reduced yields was of a much higher magnitude than the savings associated with reduced irrigation application, making adoption of reduced irrigation strategies such as deficit irrigation unlikely. Nevertheless, results revealed that soil moisture measurement-based irrigation management can be used to improve current (excess irrigation) grower practices, without impacting revenue.

The effect of row covers on canopy and soil temperature, was studied in plasticulture strawberry production to more quantify their effects on crop phenology and frost mitigation. Row cover use increased the average temperature measured in the canopy and soil by 6.9 and 9.8%, respectively. Although this seems relatively insignificant, these temperature increases translated to an 84 and 122% increase in growing degree-day accumulation at the canopy and in the soil during a fall study period. In addition, increases in soil temperature were positively correlated with soil moisture. These results indicate the advantages that row covers can provide to growers, as a tool to enhance plant growth and for freeze and frost protection of plants. However, growers need to monitor environmental conditions at canopy level under row covers and in the ambient air in order to gain these benefits without negative consequences for yield.

IMPROVING IRRIGATION MANAGEMENT AND ROW COVER USE IN STRAWBERRY PRODUCTION IN THE MID-ATLANTIC REGION

by

Bruk Eshetu Belayneh

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Advisory Committee:
Dr. John Lea-Cox, Chair
Dr. Joseph Fiola
Dr. Erik Lichtenberg
Dr. Andrew Ristvey
Dr. Joseph Sullivan

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Chapter 1. Introduction

1.1. Agricultural Water Use

Water availability is the most critical limiting factor for agricultural production in many areas of the world including the United States (US). Considering the rapidly increasing world population and the need to double food production by 2050 (Parris, 2010), addressing issues related to the provision of adequate irrigation water is a critical issue for agriculture. In addition, the availability of fresh water for agriculture is likely to decrease in the future, due to increasing pressure from urbanization and population growth as well as increasing competition from other sectors such as industry.

Furthermore, continuing changes occurring in the global climate has led to modifications of the hydrologic cycle. This is affecting not only the amount of water received in many regions but also its distribution during the year. This has led to periodic droughts in areas that otherwise receive adequate precipitation throughout the year (for example the mid-Atlantic and Northeast region of the US), impacting agriculture and food production (Parris, 2010; Wolfe et al., 2017).

Implications of these changes in agricultural water availability are already apparent in the United States. The western US (for example California) has been in various states of drought for a long period of time, limiting water availability and severely impacting agricultural production in a region which heavily relies on year-round irrigation water availability (USDA, 2016). The effects of climate change on the other hand are perhaps most exemplified in the Northeast and mid-Atlantic region of the US, where periodic droughts and temperature shifts can impact agricultural production in a region with an otherwise adequate precipitation (Wolfe et al., 2017).

1.2. Strawberry Production in the US

Strawberry (*Fragaria X ananassa*) is an economically important crop, with the US producing 20% of the world strawberry supply and the industry valued above $2.5 billion (USDA, 2017). Year to year production of the crop and sustainability of the industry in general is heavily reliant on the adequate availability of irrigation water. This is especially true as 90% of the total US strawberry crop is produced in California (USDA, 2018), illustrating how vulnerable this crop is to water scarcity. Other major strawberry growing regions of the world are also facing water availability issues, with the Huelva region of Spain being a prime example due to its location close to the Doñana National Park, a wetland with the maximum European environmental protection, and increasing scrutiny and application of water withdrawal restrictions (Lozano et al., 2016).

Strawberry production typically requires large use of water and nutrients, both for crop establishment during the fall and to obtain high yield and quality fruit during spring. Over-irrigation and high rainfall events can lead to harmful environmental impacts such as the leaching of fertilizers and other agrochemicals from production areas, resulting in the pollution of surface and ground water. Over-utilization of groundwater for crop irrigation can also lead to aquifer depletion and salt water intrusion (California Department of Water Resources, 2014) as well as land subsidence (Aurit et al., 2013). To mitigate these harmful impacts on the environment, national and state level regulations are increasingly being put in place. In Maryland for example, nutrient management regulations limit the amount of both organic and inorganic nutrient (particularly nitrogen and phosphorus) applications that are applied by any agricultural operation, to reduce nutrients entering surface waters and the Chesapeake Bay (Lea-Cox and Ross, 2001).

These combined challenges of water availability and environmental issues that the US strawberry industry faces require better management practices, if an economically and environmentally sustainable industry is to be achieved. We need to research new irrigation strategies and technologies for growers, aimed at reducing water losses and improving water use efficiency (Lea-Cox et al., 2013). Nutrient leaching from the root zone of strawberry production fields, which could be significant in regions with sandy soils as in states like Maryland and Florida, should also be minimized to increase the sustainability of the production system (Stevens et al., 2009) and increase profitability (Stevens et al., 2007; 2011). For strawberry growers, meeting environmental guidelines means they are following regulations and reducing their liability, leading to more efficient utilization of their resources for a profitable and sustainable operation.

1.3. Strawberry Plasticulture

Strawberry plasticulture refers to the annual hill training system in which bare-root transplants or rooted plugs are planted in late summer or early fall in fumigated raised beds , covered with black plastic mulch (Poling, 1993). Planting is done typically in double rows, resulting in high densities of approximately 17,400 plants/acre (43,000 plants/ha) (Poling, 1993). Harvest usually occurs 7-8 months after planting, making it an efficient system compared to the matted row production system where fruit is only produced more than a year (13-14 months) after planting (Poling, 1993). The plasticulture system is the predominant strawberry production system in the main production regions of the US (California, Florida, North Carolina), and is increasingly being adopted in the mid-Atlantic region where a significant number of growers practice the traditional matted row production system (Poling, 2015; Samtani et al., 2019).

The plasticulture system can be highly productive if adapted cultivars that are disease free are used, weather risks are well managed, and recommended cultural practices are followed (Poling, 2015). Among the various advantages, the plasticulture system is suited for implementation of drip irrigation, enabling efficient water usage. This also allows integration of water and nutrient management as soluble fertilizers can be used to deliver nutrients with irrigation water. Nutrient application is localized as drip tubes are installed in the row within few inches of plant roots, minimizing the likelihood of leaching and thereby increasing nutrient use efficiency.

In the plasticulture system, frequent irrigations are required for proper plant establishment in the fall, a critical growth stage for the plant. Further large quantities of water and nutrients are applied by growers later in the spring, in order to maximize yield, fruit mass, and fruit quality (Poling, 2015). This creates a potential for over application of irrigation water that can lead to inefficient water utilization and environmental pollution through nutrient leaching. Hence, proper irrigation management in the plasticulture system needs to be given emphasis in order to address the water scarcity and environmental impact issues associated with strawberry production. Improved irrigation management in the system will increase water use efficiency (WUE) and could greatly benefit the balance of freshwater sources.

1.4. Irrigation Management in Strawberry Production

Efficient water use is important for an economically and environmentally sustainable strawberry industry. With good soil management, planting material choice, planting dates, fertilizer use and other recommended best management practices can all contribute to increased efficiency of water use (Poling, 2015). For a sustainable production of strawberries in the face of water limitations however, it is critical to both minimize water losses to maintain supply for the crop and to increase the crop’s use efficiency or productivity for water. Adopting practices and technologies that increase the proportion of water that is transpired by the crop, as opposed to those that lead to water losses through drainage, runoff etc., and increase the crop's capacity to produce biomass (assimilate CO_2) and yield per unit of water transpired is important (Wallace, 2000).

1.4.1. Improving Irrigation Efficiency

Inefficient irrigation systems are usually the primary source of water loss that needs to be addressed to improve irrigation management. While the drip irrigation system used with strawberry plasticulture is an efficient system in minimizing water losses, a significant number of growers in the Midwest, Northeast and mid-Atlantic region using the matted row production system (Samtani et al, 2019) depend on sprinkler irrigation that is inherently inefficient. In states like Florida (ranked second in terms of strawberry production and acreage in the US) on the other hand, significant water losses occur through sprinkler irrigation during establishment of fresh dug bare-root plants (Santos et al. 2012; Dash et al, 2017; Samtani et al., 2019). Uniform irrigation management is imperative in these situations in order to minimize water and fertilizer losses. Selection of appropriate planting materials and use of continuous and intermittent low-volume sprinklers in the sprinkler irrigation systems is one alternative strategy that can save significant amounts of water (Santos et al, 2012).

1.4.2. Improving Crop Water Productivity

Crop water productivity (CWP) can be defined as the yield or biomass/dry matter produced per unit of water transpired by a given crop. It is an important concept in irrigated agriculture that is synonymously used with WUE. The uptake of carbon dioxide from the atmosphere by plants during photosynthesis leads to an inevitable loss of water by transpiration, because the pathway that permits the entrance of carbon dioxide through the stomata also permits the loss of water vapor (Turner and Burch, 1983). Improving the CWP or WUE of strawberries is an alternative that needs to be given emphasis as major strawberry producing regions of the world (for example California in the US and the Huelva region in Spain) are under continuous water shortages and environmental issues (USDA, 2016; Lozano et al., 2016).

There is an important distinction between CWP and WUE however. WUE values for cultivated crops are often generated by considering the yield or biomass obtained and the water volume applied, through both irrigation and precipitation. WUE values assume that all of the water applied has been transpired by the plant without accounting for other processes taking place in the soil, such as drainage and runoff (Fernandez et al., 2019). CWP values on the other hand are generated by considering only the water volume that is transpired by the crop as all water losses (including drainage) are accounted. While WUE of crops can be determined with field experiments, CWP values are usually obtained from experiments in controlled environments. For the sake of simplicity, the term CWP has been used throughout this dissertation, with WUE used whenever appropriate.

For most cultivated crops, very high yields are typically obtained from well-irrigated fields under no water limitation. However, higher CWP typically occur with reduced water applications. This is because water deficits in plants that are non-severe can increase CWP as a result of stomatal closure (Rekika et al., 1998). If water deficits are severe enough to decrease photosynthesis from metabolic causes, i.e., non-stomatal limitations, overall decreases in CWP can occur (Lawlor, 2002; Tambussi et al., 2007). This increase of CWP under non-severe drought conditions can be used as irrigation management strategy whereby a deficit, i.e., below the full water requirement of the crop, is imposed on crops (Tambussi et al., 2007).

1.4.3. Deficit Irrigation as an Advanced Irrigation Technique

Deficit Irrigation (DI) is a strategy under which crops are deliberately allowed to sustain some degree of drought stress and yield reduction (Pereira et al., 2002). Implementation of DI therefore involves decreasing moisture availability in the root zone in order to induce the crop's inherent response to drought conditions with the goal of increasing the instantaneous CWP (Davies et al., 2002). The water savings associated with such regulated deficit irrigation scenarios are attributed to reductions in stomatal conductance which occurs as a result of the plant roots encountering drying soil, and precedes any change in leaf water potential (Webber et al., 2006). While the stomata control both the rates of transpiration and CO_2 entry into the cell, some evidence suggests that initially the reduction in stomatal conductance is greater than the concurrent reduction in carbon assimilation (Webber et al., 2006).

DI as an irrigation technique is commonly practiced in horticultural crop production. With implementation at the right stage of plant growth, DI can improve WUE and fruit quality. Chaves et al. (2007) reported increased WUE and concentrations of berry skin anthocyanins and total phenols in grapevines under partial root-zone drying with only half of the water applied in full irrigation. Similarly, Velez et al. (2007) reported non-significant differences in yield, average fruit weight and number of fruits per tree for citrus plants that received 15% less irrigation compared to control trees, resulting in improved WUE for the deficit irrigation treatments. Similar increases in WUE under deficit irrigation have been reported in pears (Lopez et al., 2011) and peaches (Girona et al., 2005).

High strawberry yields are obtained from heavily irrigated and fertilized fields, with reduced water applications resulting in growth reductions and yield losses. In a study involving reduced water application to strawberry plants through partial root-zone drying and deficit irrigation techniques, leaf water potential, leaf area, fresh berry yield, and berry weight decreased for strawberry plants that received 60% of the water supplied to fully-irrigated strawberries (Liu et al., 2007). WUE, however, was increased by 40% for both reduced irrigation strategies. Yuan et al. (2004) reported increased plant biomass, fruit size and marketable yields when irrigation application to drip-irrigated strawberries was increased from 0.75 to 1 and 1.25 times the surface evaporation measured with a standard 200 mm pan. However, the plants that received the smallest amount of irrigation water (0.75 times surface evaporation) had the highest WUE as compared to plants that received 1 and 1.25 times the surface evaporation. Similarly, Grant et al. (2010) reported that strawberry plants that received only 70% of the water applied for the control irrigation regime (based on daily evapotranspiration) had increased WUE and root to shoot dry mass ratio with decreased leaf water potential, transpiration rate and leaf area.

Duration of actual drought stress is an important factor when implementing deficit irrigation. However, there is lack of information on consistent and quantifiable drought stress and its effect on the morphological and physiological development, yield and yield components, and fruit quality of strawberry plants. For long term sustainability and profitability of the US strawberry industry, reduced irrigation techniques/strategies that can lead to improved CWP of the major strawberry cultivars needs to be investigated. Identifying deficit irrigation strategies that can reduce water and fertilizer inputs without significantly reducing yield could greatly benefit strawberry producers.

In additions to the effect on plant growth and yield, DI has effect on the concentrations of beneficial compounds and hence fruit quality in strawberries. Terry et al. (2007) showed increased levels of monosaccharides (fructose and glucose), sugars, acids, antioxidants (phenolics) in the strawberry cultivar *Elsanta* grown under deficit irrigation. Additionally, Bordonaba and Terry (2010) also reported increased dry matter and concentration of sugars and acids for the strawberry cultivars *Sonata* and *Symphony* grown under deficit irrigation conditions. Significant increases in the concentration of beneficial compounds and improved fruit quality associated with DI could partially compensate yield losses to maintain profitability to growers.

The proportion of strawberry yield losses associated with reduced irrigation application is an important factor in determining whether improved CWP is economically profitable for strawberry producers. DI can be implemented to determine soil moisture conditions that lead to improved CWP of the crop, in order to save water and reduce the environmental impact of overwatering and nutrient leaching. In addition to these benefits however, economic analysis should also consider lost revenue as a result of reduced yields before a DI scenario can be recommended for strawberry growers.

1.5. Determining Plant Water Requirements

To implement DI, the water requirement of strawberry plants growing under a specified condition needs to first be determined. Plant water requirements are typically determined by measuring parameters that are indicators of the plant water demand. Among these, evapotranspiration measurements and soil water status measurements are two widely used approaches that have been implemented for various crops.

1.5.1. Evapotranspiration-based Approaches

Evapotranspiration-based approaches estimates plant water requirement for a given period based on the prevailing environmental conditions, modified by a crop coefficient (Kc). Initially, evapotranspiration from a reference surface (called Reference Evapotranspiration, ETo) is calculated from four environmental variables (solar radiation, air temperature, relative humidity and wind speed). The most widely used method to calculate crop evapotranspiration (ETc) is defined by the Penman-Monteith equation (Allen et al., 1998). Kc values incorporate four main characteristics of the crop that distinguish it from the reference surface, i.e., crop height, reflectance, canopy resistance and evaporation from soil, which are specific for the crop species and phenological stage of growth (Allen et al., 1998). Kc values are typically derived from scientific experiments and tabulated values for many cultivated crops are available. The crop evapotranspiration (ETc) is the product of the reference evapotranspiration (ETo) and crop coefficient (Kc).

Irrigation management using evapotranspiration approaches can be implemented with relatively low cost due to advances in environmental data collection, analysis and integration (Lea-Cox et al., 2013; van Iersel et al., 2013). However, these approaches estimate plant water demand indirectly and are not suitable for real-time irrigation management. Nevertheless, irrigation management based on evapotranspiration-based approaches has the potential to save water and improve efficiencies, especially in the traditional matted row production system where growers typically use sprinkler irrigation system. As evapotranspiration-based approaches use past water requirements of a crop to predict future water applications, they are not suited for application in the plasticulture production system where growing plants have a limited soil volume to get water from. In addition, lack of uniform plant cover in the system (for example, alternating plant production beds and empty rows) and the use of plastic mulch on beds make the proper accounting of evapotranspiration in plasticulture difficult.

1.5.2. Soil Water Status-based Approaches

Soil water status measurements in the root-zone of plants provide more direct information on plant water status. As plant roots interact with soil water in the vadose zone in real-time, irrigation can be applied to meet plant water demands in real-time. Soil water status measurements also allow implementation of fine-tuned irrigation strategies such as DI, in order to identify the soil moisture conditions that can result in improved water use efficiencies. As opposed to evapotranspiration-based approaches, soil water status measurement-based approaches are well suited for application in plasticulture strawberry production.

1.5.3. Soil Parameters of Importance for Irrigation Management

Important properties of soil water arise due to the forces of cohesion and adhesion holding water in soils, with surface tension, capillarity and osmotic pressure also playing a significant role (Lal and Shukla, 2004). Soil water content and soil water potential are the two main variables of interest for understanding plant water requirements, and hence irrigation management. Respectively, they represent the relative amount of water contained in a unit mass or volume of soil and the energy state of water in the soil (Hillel, 1980), and have a relationship that is unique for a given soil or substrate that is given by the moisture characteristics curve/ moisture retention curve. Unsaturated hydraulic conductivity is another parameter that is relevant to irrigation management as it determines how fast water moves in soil and hence processes such as drainage, water infiltration and evaporation. An understanding of these parameters through measurements on the field and characterization in laboratory procedures is critical for understanding plant water requirements and successful irrigation management, especially when implementing fine-tuned irrigation strategies such as DI.

Soil water content is a physical measure of the amount of water that exists in the soil, on a mass or volume basis. It is usually expressed as percentage by volume or mass basis, after water is evaporated from soil by heating at 105 ^{o}C to a constant weight (Lal and Shukla, 2004). However, expression of soil water content in the form of depth, i.e., as the depth of water contained per total soil depth for a given area, is common and useful when working with soil profiles (Hillel, 1980). Soil water content affects many soil properties including consistency, plasticity, strength, compactability, penetrability, stickiness, and trafficability (Hillel, 1980).

Soil water content by itself is not sufficient to describe the status of water in soil, as it does not necessarily describe the availability of the water to plants nor indicates how the water moves within the soil profile (Lal and Shukla, 2004). The only information provided by water content is the relative amount of water in the soil. Soil water possesses potential energy because it can move in response to certain forces within the soil. This potential energy is primarily responsible for determining the state and movement of water in soil (Hillel, 1980). Soil water moves from where the potential energy is higher to where it is lower in pursuit of thermodynamic equilibrium (Thien, 1983).

Therefore, water movement in soils and its availability to plants is a function of the soil water potential. The total soil water potential is the sum potential resulting from various forces acting on soil water and is expressed by the relationship given in Equation 1.1 below (Hillel, 1980). Among the components of soil water potential, the soil matric potential (MP) that is a function of soil texture and structure is the predominant force. It is the force that attracts and binds water as films on the soil or plant solids and as capillary water in small openings (Thien, 1983). Plant water uptake through roots is mostly affected by the soil MP.

$$\psi_t = \psi_g + \psi_m + \psi_o + \psi_p + \cdots \qquad \text{(Equation1.1)}$$

Where ψ_t = total soil water potential

ψ_g = gravitational potential

ψ_m= matric potential

ψ_o = osmotic potential

ψ_p = external pressure potential

There is a unique relationship between soil water content and soil MP for any given soil, a relationship that is given by the soil moisture characteristics curve (also called soil moisture retention curve). This relationship is usually derived by procedures that are based on laboratory instruments (for example sand box apparatus and pressure plates), resulting in a set of discrete data pairs. Mathematical functions are then used to smooth the measured data and to interpolate between the measured data points. The unimodal constrained van Genuchten (1980) model (Equation 1.2) is the most widely used expression to describe water retention in vadose zone hydrology. It fits retention data with a unimodal shape, a gradual air entry, and an asymptotic approximation of finite residual water content (Pertassek et al., 2011).

$$\theta = \theta_r + (\theta_s - \theta_r)\left(\frac{1}{1+(\alpha|h|)^n}\right)^m \qquad \text{(Equation 1.2)}$$

Where, θ = volumetric moisture content ($m^3.m^{-3}$)

θ_r= residual volumetric moisture content ($m^3.m^{-3}$)

θ_s= volumetric moisture content at saturation ($m^3.m^{-3}$)

h = matric potential expressed in cm H_2O

α = shape parameter related to inverse of the air-entry

n = shape parameter controlling bending of curve

m = additional shape parameter, with the restriction $m = 1 - \frac{1}{n}$

Porous media with heterogeneous pore structures (soils and soilless substrates) cannot be adequately described by the usually used (such as van Genuchten) retention models (Durner 1994). For a bimodal pore structure, Durner (1994) proposed a function by overlapping two individual van Genuchten equations. The resulting function is given in Equation 1.3 (Priesack and Durner, 2006).

$$\theta = \theta_r + \left(\theta_s - \theta_r\right)\sum_{i=1}^{2} wi\left[\frac{1}{1+(\alpha i|h|)^{ni}}\right]^{1-\frac{1}{ni}} \qquad \text{(Equation 1.3)}$$

Where the additional parameter w_i represents the weights of the partial functions w1 and w2, and has the restriction $0 < w_i < 1$ and w1+w2 =1.

The portion of soil water that plants can use is called plant available water (PAW). According to Thien (1983), this water must be within the tension range from which plant roots are capable of exerting an extractive force greater than the opposite binding forces represented by the total soil water potential. Therefore, PAW always comes from the same potential range regardless of the soil type and condition. The upper and lower limit of this range is generally estimated to be -10 to -33 kPa and -1500 kPa, and is referred as the field capacity (FC) and permanent wilting point (PWP), respectively.

FC refers to the water contained in a soil following free drainage by gravity. Several attempts to correlate FC and MP proved unsatisfactory due to failure to take into account the dynamic properties of the whole soil profile (Hillel, 1980). Although FC does not correspond to a fixed MP value however, it is roughly estimated to be at -10 kPa (sandy soils) and -33 kPa (clayey soils). PWP is the moisture content in a soil at which plants can no longer sustain turgor even when placed in a saturated condition subsequently (Hillel, 1980; Thien, 1983), and is commonly thought to be moisture retained at MP of -1500 kPa. However, the exact PWP is a dynamic value determined by specific plant and soil characteristics (Thien, 1983).

The readily available water (RAW) is the portion of the available water that can be extracted from the root zone without suffering drought stress (Hillel, 1980; Allen et al., 1998). As the soil water content decreases, the water becomes more strongly bound to the soil matrix and is more difficult to extract. Although PWP is traditionally considered to be the lower limit of moisture availability, crop water uptake is reduced before this point is reached in soils (Allen et al., 1998).

The actual amount of water contained within a given soil water potential range depends on specific soil properties (Thien, 1983). Sandy soils present very little total surface area for water absorption and thus only small amounts of available water are present in such soils, whereas clay soils have much greater specific surface areas which require large amounts of water to satisfy the attractive forces of the soil matrix (Hillel, 1980; Thien, 1983).

Hydraulic conductivity is another key parameter that is important for understanding water movement, modeling flow processes and deciding water management in soils (Zhuang et al., 2001). It is defined as the ratio of flux (q) - the volume of water passing through a unit cross sectional area (perpendicular to the flow) per unit time - to the hydraulic gradient (Hillel, 1980). Flux is proportional to the hydraulic gradient, with the proportionality factor K designated as hydraulic conductivity and given by Darcy's Law (Hillel, 1980) in Equation 1.4 as:

$$q = K \frac{\Delta H}{L} \qquad \text{(Equation1.4)}$$

Where, q = flux (ms^{-1}),

K = hydraulic conductivity (ms^{-1}),

$\frac{\Delta H}{L}$ = the hydraulic head gradient (mm^{-1})

While the hydraulic conductivity of a saturated soil is constant, the hydraulic conductivity of a soil for unsaturated flow is determined by degree of unsaturation (Hillel, 1980; Thien, 1983). Since the gravitational force is not strong enough to overcome the attraction of water molecules to the soil solids, the matric forces are more important than gravitational force (Hillel, 1980). Thus, unsaturated flow is most of the time slow due to the high resistance to flow.

The unsaturated hydraulic conductivity K - as a function of water content θ [K(θ)] and the hydraulic gradient h [K(h)] - is an important parameter to understand water flow in soils. The model of Mualem (Mualem, 1976) that is based on the constrained van Genuchten (1980) model is a well-known equation for unsaturated hydraulic conductivity [K(θ) or K(h)] determination and is given, respectively, in Equation 1.5 and 1.6 as:

$$K(\theta) = K_s \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^l \left[1 - \left(1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{\frac{1}{m}}\right)^m\right]^2 \qquad \text{Equation1.5}$$

$$K(h) = K_s \ \frac{\{1 - (\alpha|h|)^{n-1}[1 + (\alpha|h|)^n]^{-m}\}^2}{[1 + (\alpha|h|)^n]^{ml}} \qquad \text{Equation1.6}$$

Where, K_s = saturated hydraulic conductivity ($m^3.m^{-3}$)

θ = volumetric moisture content ($m^3.m^{-3}$)

θ_r= residual volumetric moisture content ($m^3.m^{-3}$)

θ_s= volumetric moisture content at saturation ($m^3.m^{-3}$)

h = matric potential expressed in cm H_2O

α *and* n = shape parameters related to the curve

m = additional shape parameter, with the restriction $m = 1 - \frac{1}{n}$

l = tortuosity parameter (often set to 0.5)

1.5.4. Soilless Substrates

Soilless substrates are currently being widely used as growing medium in the production of horticultural crops, including strawberries. The demand to increase global food production in the coming decades will increase their utilization in the horticulture industry. Soilless substrates are generally made up of low bulk density (mostly organic or synthetic) materials and provide a number of advantages as a medium of growth compared to mineral soils such as high water and nutrient retention capacity, high aeration, low mechanical impedance and a suitable environment for root proliferation and biomass growth (Caron et al., 2015).

Most soilless substrates are made up of organic materials and decompose over time. Physical properties such as particle size, bulk density and air-filled porosity depend on the initial composition of the substrates but can change as substrates undergo decomposition and shrink (Caron et al., 2015). This change in physical properties of substrates with time affects water holding capacity, moisture retention properties, i.e. available water, and hydraulic functions. Therefore, characterization of physical properties of substrates as well as the measurement of parameters important to irrigation management need to be given due consideration. Physical properties of substrates are also affected by the shapes and sizes of containers they are used with. Methods employed to characterize physical properties need to account for this dynamic nature.

1.5.5. Irrigation Management Based on Soil/Substrate Parameters

Soil/substrate parameters can be effectively used for improved irrigation management of horticultural crops including strawberries. Recent advances in wireless sensor networks (WSN) has made possible the use of various sensors to measure soil moisture status, as well as provide the near real-time data to growers as usable information for use in their decision making process (Lea-Cox et al., 2013). More advanced software used with WSNs (Kohanbash et al., 2013) automate irrigation based on sensed values or models, avoiding the subjectivity of irrigation managers and growers and advancing capabilities.

Soil/substrate water status measurements can help with the two important questions involved in making irrigation decisions, (1) when to irrigate and (2) how long to irrigate. van Iersel et al. (2013) outlines two approaches that can be used in this process. The simplest approach involves using a user-defined threshold (set-point) value for the soil moisture status and initiating irrigation whenever a particular sensor reading drops below the set-point. Advanced approaches range from averaging readings from multiple sensors to using more complex crop water use models to control irrigation events. The duration of irrigation in both scenarios is usually a time period that is set by the user in the software. As an alternative, the sensing/return of the soil/substrate moisture to a certain user-defined value can be used.

Use of sensors for soil/substrate water status measurements and effective irrigation management requires an understanding of general sensing principles (van Iersel et al., 2013). Knowledge of the accuracy (how close measured value is to true value), precision (how similar measured values for a given property in a static state are), and resolution (the smallest change in the measured property that can be detected by the sensor) of sensors used for irrigation management is critical. As sensor manufacture specifications often do not distinguish differences between these parameters that are critical, it is important to optimize the value of information obtained from sensors in other ways. These include conducting custom calibration for all sensor-soil/substrate pairs, allocating enough sensors to fully characterize any given parameter based on the measurement area, and determining the appropriate measurement intervals for the variables of interest (van Iersel et al., 2013).

1.6. Row Cover Use in Strawberry Production

1.6.1. Cold Protection

Strawberry producers in the mid-Atlantic region frequently experience significant losses due to frost and freeze damages to plants. Costs associated with frost/freeze protection are therefore a significant portion of overall production costs (Poling 1993).

While cold injury that happens during overwintering can cause some damage on strawberry plants, frost/freeze conditions that occur during spring are more critical due to the advanced crop development stage. Various alternatives exist for frost/freeze protection in strawberry production.

Straw mulches have traditionally been used to reduce overwintering injuries to strawberry plants in the matted row production system. Although straw mulches slow down heat loss and desiccation in the plant canopy, they do not provide effective freeze protection to growing plants (Turner et al., 1992). The level of protection provided during frost events in the spring is further reduced as developing flower buds and fruits are much more sensitive to cold temperature. This is especially true for frost events that occur late in the spring, by which time straw mulches may have already been removed from fields. Use of straw mulches with strawberry plasticulture is not common; however mulches are sometimes applied between rows to avoid muddy conditions and provide ease of walking during harvest.

Sprinkler irrigation is a method of freeze/frost protection that is used in both matted row and plasticulture production system. It is a more effective method and is especially deployed during frost events at critical periods of crop development. It works based on latent heat of fusion of water (Perry, 1998) as energy is released when liquid water turns to ice, amounting to approximately 80 calories per 1 gram of water. The energy released to the environment keeps plant tissues near or above freezing. During sprinkler irrigation, liquid water also absorbs energy and change to gaseous form in a process called evaporative cooling. This evaporation process consumes a considerable amount of energy as opposed to latent heat of fusion, with 540 calories required to change 1 gram of water in to a gaseous form (Perry, 1998). The result of these two processes happening at the same time during freeze/frost events leads to application of large amount of water through sprinkler irrigation in order to get desired protection, up to 60,000 gal/acre of water per night (Hochmuth et al., 1993; Santos et al., 2011).

Therefore, sprinkler irrigation as a method of frost/freeze protection has environmental drawbacks. The huge amount of water pumped from ground wells can lead to drying of wells and land subsidence (Aurit et al., 2013), cause soil erosion and contaminate groundwater sources with leached agrochemicals. Other risks associated with sprinkler irrigation include the potential for electrical outages during frost protection which can lead to cold damage to plants and significant losses (Hochmuth et al., 1986). In addition, the level of effectiveness of sprinkler irrigation is significantly reduced during advective frost events that are characterized by cold fronts with gusty winds as it is difficult to maintain uniformity of application of water.

Row covers are fabric-like flexible plastic materials made from clear polyethylene, spun bonded polyester or spun bonded polypropylene (Wells, 1996). They are lightweight (0.3 to 1.75 $oz.yd^{-2}$) and fully or semi-transparent materials, allowing adequate light penetration for crop growth (Wells, 1996). Row covers have traditionally been used on single or multiple rows of plants to facilitate crop growth by increasing canopy temperature and to reduce wind damage to plants. The ability of row covers to retain heat under in plant canopies makes them useful for cold protection of plants in areas experiencing cold winters. While labor costs are associated with using row covers and could be significant, the drawbacks associated with sprinkler irrigation makes them a useful alternative for frost/freeze protection (Hochmuth et al., 1986).

While sprinkler irrigation is a more effective method, row covers are being widely utilized by strawberry growers for frost/freeze protection of established plants during winter (Hochmuth et al., 1993). A combination of the two methods however has been reported to be more effective in providing full protection to plants from frost/freeze damage under various environmental conditions (Poling et al., 1991; Turner et al., 1992).

1.6.2. Row Covers for Plant Growth Management

More recently, row covers are being utilized by strawberry growers to aid plant growth and development during the fall, enabling earlier harvests and improved yields (Gent, 1990; Poling et al., 1991). This has also led to their use as intervention strategies for late planting and unfavorable growth conditions during fall (Pattinson et al., 2013). Row covers provide benefits to plants by maintaining heat in the canopy (Hochmuth et al., 1986; Poling, 1991). However, the temperature improvements under row covers vary based on prevailing environmental conditions (Poling et al., 1991; Turner et al., 1992).

The temperature moderation provided by row covers could be critical during frost events where slightly higher temperatures in the plant canopy below the cover could be critical to the survival of plants (Poling, 1991). By retaining heat, row covers could also moderate temperatures in the soil profile which is important for variety of biochemical and physiological process taking place in the soil. Knowledge of the levels of soil temperature moderation provided by row cover use is important and could be used for creating strategies for their use as intervention techniques by growers.

As soil water content plays a physical role in heat transfer in the soil, it could have a major effect on altering the efficiency of row covers. For example, a dry soil could negate any potential benefit of row covers. An understanding of the effect soil water has on the heat retention and temperature moderation of row covers could be utilized to identify more effective irrigation strategies for frost protection in combination with row covers, which could be significant for strawberry production in the mid-Atlantic region.

1.7. Statement of Research Objectives

The overall goal of the research proposed was to identify improved ways to manage irrigation and row cover use in strawberry production, for application in the mid-Atlantic region and beyond. Three complementary research studies were conducted in the laboratory as well as under natural (field) and controlled (greenhouse) conditions to address specific objectives.

The first research objective was to characterize physical properties of soils and substrates used to grow strawberries under field and greenhouse conditions, respectively. Specifically, the aim was to characterize the natural variation in water retention and hydraulic conductivity that exists throughout the depth of the raised strawberry plasticulture beds and in peat-based soilless substrates due to inherent compaction.

The second research objective was to determine the effect of incremental drought stress on strawberries. By implementing reduced irrigation application on field and greenhouse grown strawberries, the effect incremental drought stress has on strawberry plant physiology and growth, as well as yield and fruit quality were determined.

The third research objective was to characterize the microclimate modification provided by row covers and its interaction with soil moisture. Specifically, the aim was to characterize canopy temperature and soil temperature fluctuations in raised strawberry plasticulture beds with and without row covers, and how various soil moisture conditions interact with and alter the effect of row covers.

Chapter 2. Characterizing the Retention and Hydraulic Functions of Soils and Soilless Substrates Used in Strawberry Production

2.1. Introduction

The retention and hydraulic functions of soils and soilless substrates determines water holding capacity and movement, and regulates water availability and uptake by plants. Characterizing these properties for any given soil/substrate is therefore important to understand whether plant water requirements are met through effective irrigation management. Texture (particle size distribution), structure, bulk density, and porosity (including the pore size distribution) are the most important physical properties that determine the retention and hydraulic functions of soils/substrates. Since characterizing these functions on the field or in the laboratory involves cumbersome and often time-consuming procedures, various mathematical models, generally called pedotransfer functions (PTF), have been developed to predict them from particle and pore size distribution and other soil physical properties that can relatively be measured easily (Pachepsky et al., 1999; Cornelis et al., 2001).

Soil/substrate water content and water potential are the two primary variables of interest that are needed to understand plant water requirements. Water content refers to the relative content of water in a given soil/substrate, on a mass or volume basis. Water potential refers to the force with which water is held in soils/substrates (Hillel, 1980). Knowledge of water content alone is not sufficient as water movement in soils/substrates, the availability and uptake by plant roots is rather a function of water potential. Of the various forces that contribute to the total water potential in soils/substrates, the force that arises due to attraction of water to the surface of soil/substrate particles (called matric potential, MP) is the most important. Hence, water potential is synonymously used with MP for soils/substrates under normal production practices and without salinity issues.

The water content of soils/substrates can be directly or indirectly measured using several methods, on a mass or volume basis. Various sensors used to measure *in situ* soil/substrate water status rely on the very high dielectric of water, to provide precise volumetric water content (VWC) readings (van Iersel et al., 2013). Among these are time-domain reflectivity (TDR), time-domain transmissivity (TDT) and capacitance sensors. The availability of moisture sensors that are highly reliable and inexpensive (example capacitance sensors) has facilitated their utilization in irrigation management, including with wireless sensors networks (Lea-Cox et al., 2013). Calibrating moisture sensors for the specific soil/substrate type is a recommended practice that improves accuracy of measured outputs. Further improvement in the accuracy of moisture measurements is obtained by proper positioning of sensors in the soil/substrate medium, and by understanding the natural variability that exists in a given environment in order to optimize the required number of sensors. Determination of measurement frequency should consider soil/substrate properties, the type of plant species, and stage of development in order to estimate the speed with which moisture content changes (van Iersel et al., 2013).

MP measurements in soil/substrates are best done using tensiometers. Tensiometer measurements are direct, thus values are independent of soil/substrate type and do not require calibration. Tensiometers have been used to successfully manage irrigation of horticultural crops, including strawberries for many years (Hansen and Pasian, 1999; Hoppula and Salo, 2007). However, their use has drawbacks due to frequent maintenance when tensiometers cavitate. This is mainly due to the fact that the range of MP measured by tensiometers (0 to -85 kPa) represents only a small fraction of the MP that exists in soils/substrates under natural conditions. Other instrumentation available for measuring MP in soils and substrates, including recently developed hybrid sensors (van Iersel et al., 2013), often give indirect readings. Most of these sensors have accuracy and resolution issues, giving moderately reliable readings in a certain range of the MP spectrum and highly unreliable in others (Environmental Biophysics, 2020).

The soil water retention function, expressed in the form of moisture characteristics curve/moisture retention curve, provides the unique relationship that exists between the water content and MP of a given soil/substrate (Figure 2.1). Knowledge of this relationship helps to correlate VWC readings of moisture sensors with the corresponding MP, i.e. stress levels, in a given soil/substrate, and therefore is critical for irrigation management. Field experiments to derive this relationship are laborious, time consuming, and often inaccurate. Although laboratory procedures exist that derive water retention curves, the instrumentation used (such as sandbox apparatus and pressure plates) often have limitations in the number of data points they can generate. Pressure plates require long periods of time for getting hydraulic equilibrium at the applied pressure (Dane and Hopmans, 2002), making their use very time-consuming.

Hydraulic function controls how fast water moves through soils/substrates, and hence affects processes such as drainage, water infiltration and evaporation. The unsaturated hydraulic conductivity [(K(θ) or K(h)], which measures how fast water moves in unsaturated soils/substrates, also affects important process such as heat transfer through profiles. The role unsaturated hydraulic conductivity plays in heat transfer in frozen soils has been described (Fuchs et al., 1978), making it an important property for understanding freeze/frost protection of strawberries.

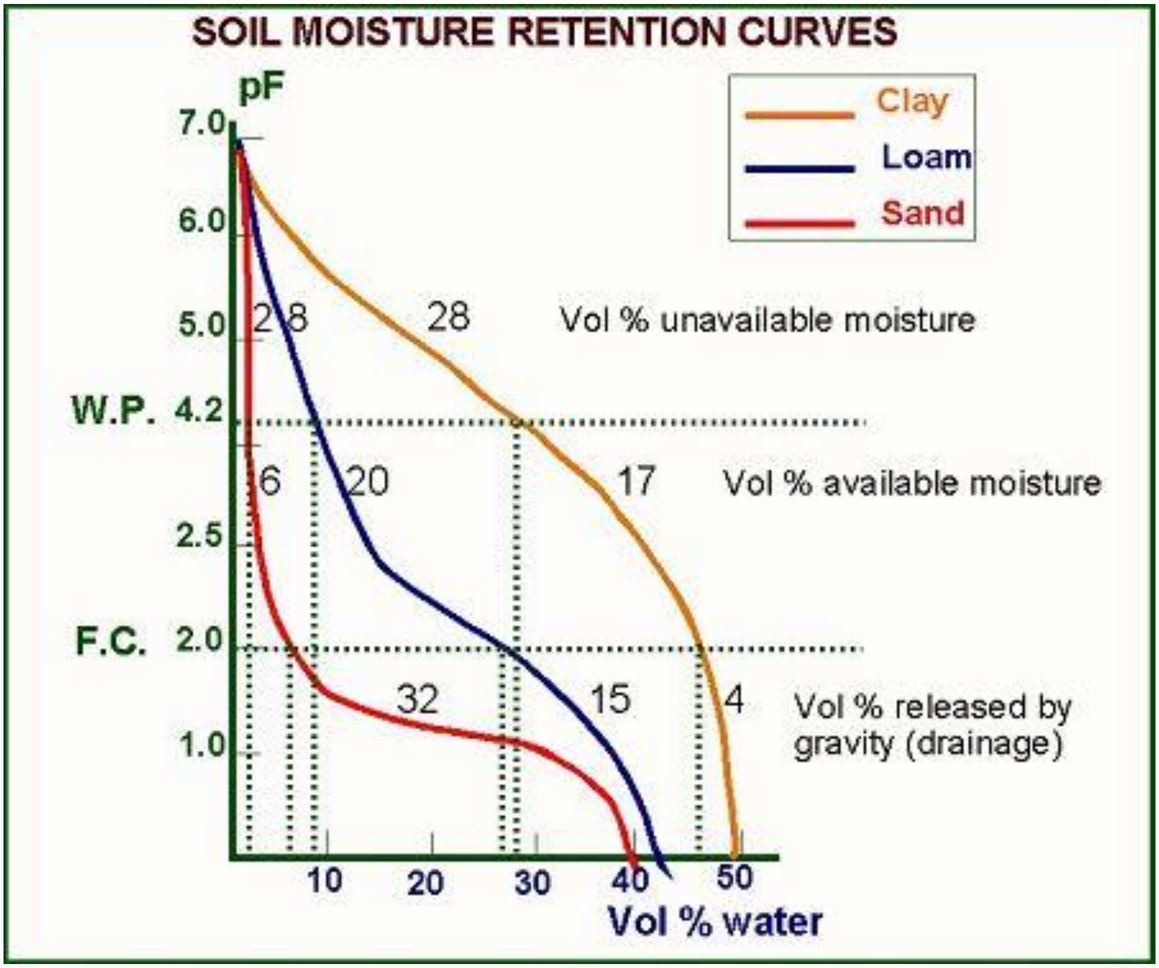


Figure 2.1. Soil moisture retention curve for the USDA textural class clay, loam and sand. Field capacity (F.C.) and wilting point (W.P.) represent the traditional upper (pF=2) and lower (pF=4.2) limits of soil water availability to plants (from Vittucci, 2015)

Soilless substrates generally consist of low bulk density organic or synthetic materials. As growth media, substrates provide a number of advantages compared to mineral soils, such as high water and nutrient retention capacities, high aeration, low mechanical impedance and a suitable environment for root proliferation and biomass growth (Caron et al., 2015). Since most substrates are made up of organic materials and decompose over time, the characterization of their retention and hydraulic properties need to be considered. Physical properties such as particle size, bulk density and porosity depend on the initial composition of the substrates but can change as substrates undergo decomposition and settle/shrink (Caron et al., 2015). Physical properties of substrates are also affected by the shapes and sizes of containers they are used with. Methods employed to characterize retention and hydraulic functions of soilless substrates need to account for these dynamic characteristics.

To implement effective irrigation control in plasticulture (field) strawberry production, it is essential to characterize the water retention and hydraulic conductivity functions of the raised beds. Plasticulture raised beds are typically 10-12 inch high and 30 inch wide, and contribute significantly to the success of the plasticulture system by providing an ideal environment for vigorous strawberry root development (Poling, 2015). Although strawberry roots can grow deeper, the 10-12 inch high raised beds usually provide an ideal air-soil-water balance and retain majority of the roots (Darrow, 1966).

Characterization and knowledge of the soil retention and conductivity functions across the depth profiles of the raised beds is especially important to implement advanced irrigation techniques. The water retention function (i.e. the relationship between θ and MP) is critical for implementing deficit-irrigation (DI) techniques that require imposing drought stress to strawberry plants, to identify the appropriate soil/substrate moisture conditions that can lead to improved WUE, save water and minimize environmental impact. A knowledge of hydraulic conductivity is also important to understand how temperature in the soil profile is moderated, to identify effective strategies for frost protection in strawberries.

As noted, field methods for determination of the water retention and unsaturated hydraulic conductivity functions of soils/substrates are laborious, time consuming and often filled with inaccuracies. Laboratory methods, on the other hand, have limitation on the number of data points that can be generated as they are time consuming. In addition, laboratory analyses of these functions are usually conducted on relatively small soil/substrate volumes (~250 cm^3), and hence do not fully represent the dynamic relationships that occur under natural conditions. Nevertheless, simulation of field conditions on small samples in the laboratory are critical to quantify these physical properties.

Recent developments in micro-tensiometers have allowed the development of a precision hydraulic property analyzer (Hyprop™) - that can be used for simultaneous characterization of water retention and hydraulic functions in soils and substrates (Schindler et al., 2010). The Hyprop instrument (UMS, Munich, Germany) provides an easy way to characterize water retention and hydraulic conductivity functions in a laboratory in relatively short time period. The Hyprop procedure is essentially based on the evaporative theory outlined by Peters and Durner (2008) and further described by Schindler et al. (2010a and 2010b). Water from a saturated soil sample is allowed to evaporate over time while simultaneous measurements of VWC and MP are measured. VWC is obtained from the continuous monitoring of the mass of the drying soil sample, whereas simultaneous MP readings are obtained using precision tensiometers installed at two depths of the soil sample. After sample preparation, the Hyprop setup allows the continuous quantification of these variables in unattended mode, making it significantly less laborious than other methods. The Hyprop instrument also comes with its own curve fitting software, making development of water retention curves and unsaturated hydraulic conductivities functions easier.

The goal of this study was to characterize the water retention and unsaturated hydraulic conductivity functions of various soil and substrate samples to define the precise relationship between VWC and MP and to identify appropriate set-points that can be used to implement/control deficit irrigation (DI) of strawberry cultivars in subsequent field and greenhouse experiments. Soil samples were obtained from various depths of new raised strawberry beds; whereas the substrate samples had different bulk densities in order to represent the settling profiles/natural compaction that occurred in the soilless substrate used for greenhouse studies. The specific objectives of this study were to:

- characterize the particle size distribution/texture of soil samples obtained from three depths of raised strawberry production beds;
- characterize the water retention curves and unsaturated hydraulic conductivity of soil samples obtained from three depths of strawberry production beds;
- characterize the water retention curves and unsaturated hydraulic conductivity of soilless substrate samples with three different bulk densities.

The main hypotheses tested in this study were:

1. H_O: Particle size distribution (soil texture) of soil samples obtained from three different depths (0, 15 and 30 cm) in the strawberry production beds are not different.

   H_A: Soil samples obtained from three depths (0, 15 and 30 cm) in the strawberry production beds have different particle size distribution (soil texture).
2. H_O: Water retention curve and unsaturated hydraulic conductivity of soil samples obtained from the three depths (0, 15 and 30 cm) are not different.

   H_A: Soil samples obtained from the three depths (0, 15 and 30 cm) have different water retention curve and unsaturated hydraulic conductivity.

3. H_O: Water retention curve and unsaturated hydraulic conductivity of the LC1 substrate samples with three bulk densities (0.09, 0.1 and 0.12 g.cm^{-3}) are not different.
   H_A: The LC1 substrate samples with three bulk densities (0.09, 0.1 and 0.12 g.cm^{-3}) have different water retention curve and unsaturated hydraulic conductivity.

2.2. Materials and Methods

2.2.1. Soil Sampling and Preparation (Field Study)

Soil samples were collected from newly prepared raised (~30 cm / 12 inch high) strawberry beds at the Wye Research and Education Center (WREC) of the University of Maryland (38^{O} 55’ N, 76^{O} 9’ W), at the beginning of the 2014-2015 growing season. The samples were collected across the experimental site in order to characterize the water retention and unsaturated hydraulic conductivity of the strawberry beds throughout their depth profile. Replicated samples (n=4) were obtained from three depths – 0 cm (0 - 5 cm), 15 cm (12.5 – 17.5 cm) and 30 cm (27.5 - 32.5cm) – of the raised beds.

Samples were obtained using soil cores/sampling rings of 250 cm^3 volume provided with the Hyprop instrument. Once soil was cleared to the targeted depth, sampling rings were carefully pushed down into the soil on their cutting edge. Soil cores were then carefully removed and cleaned of extra soil. They were immediately covered with plastic cups on both sides and brought to the lab. Disturbed soil samples of 200-250 g were collected from same depths, to characterize the particle size distribution/texture of the raised strawberry production beds.

2.2.2. Soilless Substrate Preparation (Greenhouse Study)

Substrate core samples were prepared in the laboratory in order to characterize the water retention and unsaturated hydraulic conductivity of the Sunshine loosefill complete

1 (LC1) substrate (Sun Gro Horticulture, Agawam, MA) at different bulk densities. The LC1 substrate is mainly composed of sphagnum peat moss and coarse vermiculite (70-80% and 20-30% by volume, respectively), and also contains trace amounts of starter nutrient charge, dolomitic limestone and wetting-agent. It is a formulation that is used for the production of a wide variety of crops, and was used in strawberry greenhouse irrigation experiments conducted during two seasons (2017-2019) at the University of Maryland Research Greenhouse Complex.

Three bulk densities - 0.095 (BD1), 0.10 (BD2) and 0.12 (BD3) g.cm^{-3} - which represented different settling profiles of the LC1 substrate under natural conditions were selected - a settling profile under normal conditions (BD1) and two slightly higher settling profiles (BD2 and BD3). After determination of the initial moisture content in the substrate, the weight (grams) of substrate required to make the desired bulk densities in a 250 cm^3 volume soil core was obtained. For each bulk density, the weighed substrate was packed into cores/rings following the procedure outlined by Fonteno and Harden (1995) to get a uniform compaction throughout the core. Replicated samples (n=3) of the LC1 substrate were prepared for each bulk density.

2.2.3. Particle Size Distribution/Texture Analysis

A modified version of the Hydrometer method for particle size distribution analysis outlined in the Soil Survey Field and Laboratory Methods Manual, Soil Survey Investigations Report No. 51 (Version 2) (USDA NRCS, 2014) was used. The procedures used were as follows:

1. The disturbed soil samples were air dried and kept in the laboratory until analysis. Samples were ground using a mortar and pestle, sieved through a 2 mm mesh size sieve,

and kept overnight in a laboratory oven at 105 ^{o}C. Fifty (±0.05) g of each dried and ground sample was transferred into 300 ml Erlenmeyer flasks, and 100 ml dispersing reagent (sodium hexametaphosphate, 5%) and 100 ml deionized water was added. Flasks were then capped with parafilm and string, and placed on a reciprocating horizontal shaker under moderate speeds for 16 hours. Flasks were removed and contents washed into 1 L sedimentation cylinders using deionized water filled wash bottles. The cylinders were then filled with deionized water to bring the suspension to 1 L volume. All cylinders were capped with parafilm and string and were allowed to equilibrate to room temperature (~20 ^{o}C) for 2 or more hours.

2. After equilibration, the suspension in each cylinder was thoroughly mixed (one at a time) by stirring with a rod and making sure the sediment at the bottom of the cylinder was dislodged. The cylinder was then immediately placed on a laboratory bench and a timer started. After 20 sec, a Bouyoucos Hydrometer (ASTM No. 1, 152H type, -5 to 60 $g.l^{-1}$ scale) was lowered into the suspension slowly and a reading was recorded after 40 sec. The Hydrometer was carefully removed and temperature of the suspension was recorded using a hand held thermometer. The cylinder was then covered with parafilm and allowed to stand for 2 hours without disturbance.

3. After 2 hours, the Hydrometer was slowly lowered into the suspension to get a second hydrometer reading. Temperature of the suspension was recorded again. Temperature correction to the Hydrometer readings was done by adding or subtracting 0.36 to/from the hydrometer reading for every ^{O}C that is above or below 20 ^{O}C, respectively.

4. The percentage of sand, silt and clay in each sample was obtained using the

formula give below (Equation 2.1 to 2.4). The USDA textural class of the soil samples was determined using texture triangles (Benham et al, 2009).

$$\% \text{ Silt + Clay} = \frac{\text{Corrected hydrometer reading at 40 sec}}{\text{Weight of sample (gram)}} \times 100 \qquad \text{(Equation 2.1)}$$

$$\% \text{ Sand} = 100 - \% \text{ (Silt + Clay)} \qquad \text{(Equation 2.2)}$$

$$\% \text{ Clay} = \frac{\text{Corrected hydrometer reading at 2 hours}}{\text{Weight of sample (gram)}} \times 100 \qquad \text{(Equation 2.3)}$$

$$\% \text{ Silt} = \% \text{ (Silt + Clay)} - \% \text{ Clay} \qquad \text{(Equation 2.4)}$$

2.2.4. The Hyprop Procedure

The evaporation procedure described by Schindler et al., (2010) and outlined in detail in the Hyprop manual (UMS, Munich, Germany) was followed in order to characterize the water retention and unsaturated hydraulic conductivity of the soil and substrate samples. A schematic illustration of the Hyprop device, and other instruments required in the setup are shown in Figure 2.2 (Schindler et al., 2010). In brief, the procedure followed was as follows.

Soil/substrate cores were covered with filter fabric and a perforated base (UMS, Munich, Germany) on the blunt side of the sampling ring (top side of samples) and slowly placed into a container/water bath. The container water level was initially brought to the mid-point of the soil cores to slowly push air out of the cores, and was eventually raised to approximately 1 cm below the top of the cores to allow for complete saturation. Samples were kept in the bath from 24-48 hours to allow complete saturation – presence of film of water at the surface.

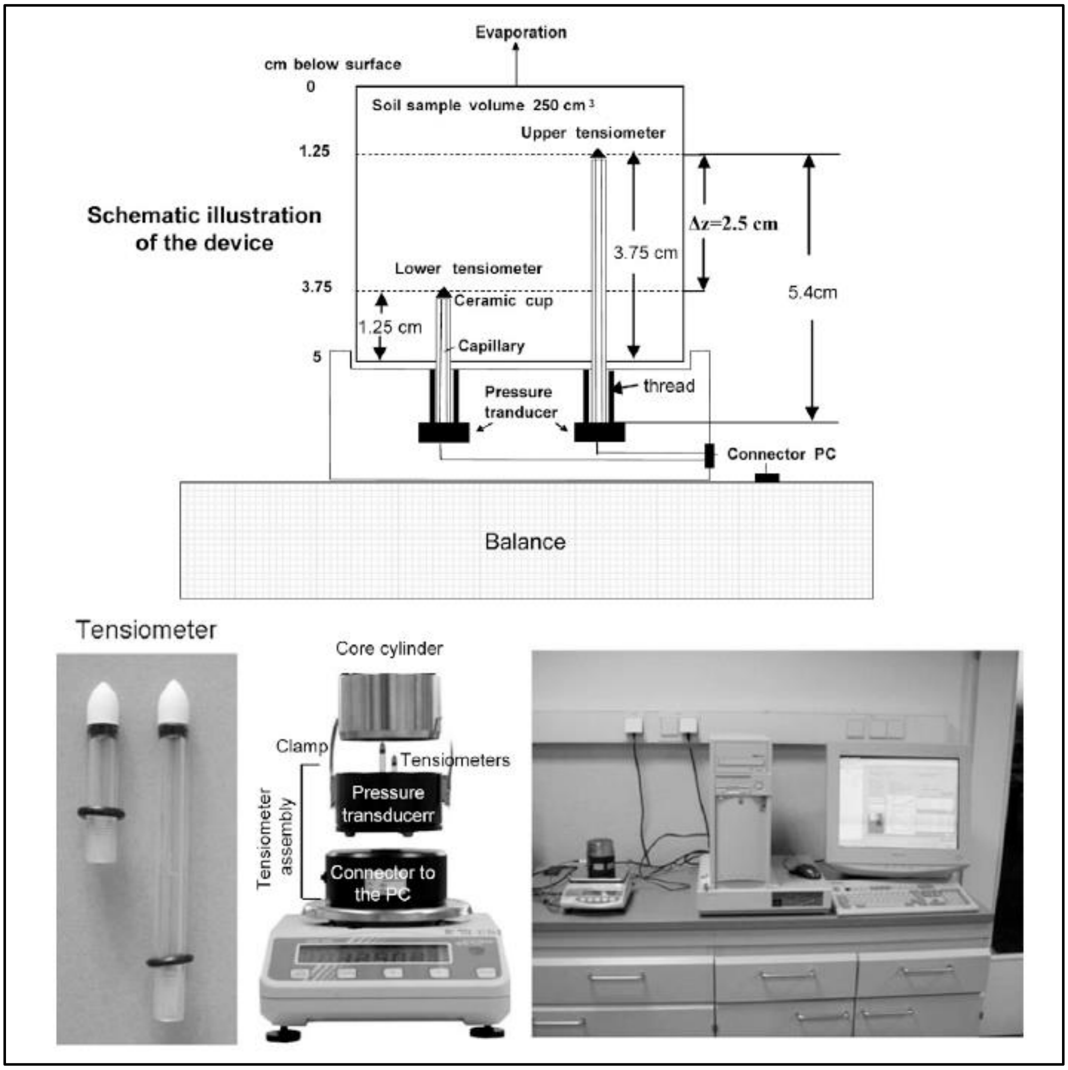


Figure 2.2. Schematic illustration of the Hyprop device, its components, and laboratory setup (from Schindler et al., 2010)

The Hyprop sensor unit and tensiometers were filled with deionized water and connected to a vacuum pump for degassing overnight. After complete degassing and filling, the two tensiometers indicated in Figure 2.2 were slowly screwed into their corresponding position on the Hyprop sensor unit, utilizing the tensioVIEW® software (UMS, Munich, Germany) to monitor the pressure rise. A protection tube filled with deionized water was attached to the ceramic cup of the tensiometers to prevent drying. The saturated soil/substrate sample was removed from the water bath and placed on a laboratory bench. A precision auger positioning tool (UMS, Munich Germany) was placed on the sampling ring and two holes (corresponding to the short and long tensiometers) were drilled into the soil/ substrate core. A silicone gasket lowered to the bottom of the Hyprop sensor unit for prevention of entry of soil/substrate particles. The Hyprop sensor unit was inverted upside down and carefully placed on the sample, positioning the short and tall tensiometer shafts into their respective holes and taking care not to create air gaps between ceramic tip and soil/substrate particles. The whole assembly was carefully inverted, the perforated base and filter fabric were removed, and sampling ring was fixed to the sensor unit using clamps. The outside surface of the sensor unit and sampling ring was wiped clean.

The assembled sample was placed on a laboratory balance and the tensioVIEW® program was started to run measurement campaigns following the procedure outlined in the Hyprop manual. Simultaneous measurements of tension/MP (average of the short and long tensiometers) and the corresponding VWC (from continuous weighing of the sample) were recorded while water was lost from sample through evaporation, allowing the determination of hydraulic properties for a range of soil/substrate moisture levels. The criteria outlined in the Hyprop manual were used to decide the end of each measurement campaign.

At the end of each measurement campaign, the residual amount of water remaining in the sample was determined by removing the soil/substrate and drying it in an oven (105 ^{o}C for soil samples and 60 ^{o}C for substrates) to a constant weight. Three separate setups of the Hyprop device were connected to the tensioVIEW® program on a computer in a laboratory, enabling simultaneous replicated (n=3) measurement campaigns.

The Hyprop data evaluation software - HYPROP-DES (UMS, Munich, Germany) - was used to evaluate measurement campaigns of single as well as combined samples. The unimodal constrained (closed-form) model of van Genuchten (1980) resulted in the best fit for the soil samples among available models in HYPROP-DES. The bimodal van Genuchten model of Durner (1994) resulted in the best fit for substrate samples among available models in HYPROP-DES. The model of Mualem (1976) was fitted to measurement data of both soil and substrate samples to generate the unsaturated hydraulic conductivity functions.

The Akaike Information Criterion (AICc, Akaike, 1974) generated in HYPROP-DES was used to compare the seven widely-used retention models in the software, representing expressions for soils with unimodal (van Genuchten, Kosugi) and bimodal (Durner, Ross-Smettem) pore-size distributions, with (Brooks-Corey) and without distinct air-entry, and a model extension that reaches water content zero at pF 7 (Fayer-Simmons). As the AIC value is normally negative, the model with the smallest value (i.e., largest absolute number) was selected as the best model.

2.2.5. Data Analysis

A one-way analysis of variance (ANOVA) was conducted using the Proc Mixed procedure in SAS (SAS, Cary, NC) to characterize differences in bulk density, porosity and particle size distribution (percentage of sand, silt and clay) between the three depths of the raised beds. Least square means differences were used for mean comparisons with 0.05 significance level.

Differences in water retention characteristic and unsaturated hydraulic conductivity of the soil and substrate samples were compared in various ways. First, a one-way ANOVA was conducted for the hydraulic parameters of the van Genuchten (soil) and bimodal van Genuchten model of Durner (substrate) retention models, and the Mualem (1976) conductivity model (both soil and substrate). Next, two non-parametric statistical analyses were carried out to determine if differences existed between replicates within a given depth (soil) or bulk density (substrate). These analyses were carried out based on water content (θ, %VWC) values obtained using the retention function (i.e., hydraulic parameters) of each replicate sample. To limit results to the measurement range of tensiometers, θ was calculated only for MP from 0 to -100 kPa in 10 unit differences.

The Kolmogorov–Smirnov two sample test (Conover, 1999) was used to test whether θ from any two replicates of a given sample were drawn from the same continuous distribution. Whereas the Kruskal-Wallis rank sum test (Hollander and Wolfe, 1973) was used to determine whether significant differences existed in the distribution of two replicates of a given sample. A one-way ANOVA was also conducted for the water content data to characterize differences between the three depths of the raised beds and the three bulk densities of the LC1 substrate within the MP range of 0 to -100 kPa (in 10 unit differences). This range was chosen for its practicality for implementation of DI in strawberries, as it contains the range of MP that can be directly and relatively accurately measured with tensiometers.

The van Genuchten (soil) and bimodal van Genuchten model of Durner (substrate) models were fitted to the combined data when non-significant differences were observed for the non-parametric tests. The hydraulic parameters obtained based on the combined data were used to calculate water contents corresponding to MP of 0 to -100 kPa in 10 unit differences, and then were used to develop the water retention curve of the soil/substrate samples. On the combined data, Kolmogorov-Smirnov two-sample test and Kruskal-Wallis rank sum test were conducted to determine differences between the water retention of the soil depths and the substrate bulk densities.

Since water retention curves had similar trends, area under the curve (AUC) of each sample was integrated. The percentage difference in AUC between two samples was calculated using Equation 2.5 given below (Fields et al., 2016), and was used as a measure of the difference between the water retention curves of the raised beds and LC1 substrate. Similar procedures were followed to characterize differences in the hydraulic conductivity functions [(K(θ) and K(h)] of the soil and substrate samples on the combined data.

$$\% \text{ Difference} = \frac{\text{AUC 1-AUC 2}}{\text{AUC 1}} \text{ x } 100 \qquad \text{(Equation 2.5)}$$

Where, AUC 1 and AUC 2 are area under the curve of samples being compared.

2.3. Results and Discussions

2.3.1. Soil Texture

There were significant differences in bulk density, porosity and particle size distribution (composition of sand, silt and clay particles) between the three depths of the raised strawberry beds (Table 2.1). There was an increase in bulk density with depth, with the bulk density recorded at 30 cm being significantly (13.4%) higher than at surface. An increase in bulk density with depth typically occurs due to the weight of the soil sitting above. Increased bulk density (compaction) leads to a decrease in the amount of pore space available between particles. Therefore, the bulk density increase with depth was accompanied by a corresponding decrease in porosity, with the porosity recorded at 30 cm depth being significantly (6.6%) lower than at the surface of the raised beds.

Table 2.1. Bulk density, porosity, particle size distribution (percentage of sand, silt and clay) and textural class of three depths of the raised strawberry beds. Means followed by different letters within columns are significantly different ($P<0.05$).

Depth (cm)	**Bulk Density ($g.cm^{-3}$)**	**Porosity (%)**	**Sand (%)**	**Silt (%)**	**Clay (%)**	**Textural Class**
0	1.27±0.02b	52.1±0.63a	48.3±2.3b	30.7±2.0a	21.0±0.4	Loam
15	1.30±0.03ab	50.9±1.26ab	55.3±1.6ab	24.4±1.5ab	20.4±0.3	Sandy Clay Loam
30	1.44±0.03a	45.5±0.97b	60.8±0.6a	19.0±0.6b	20.2±0.3	Sandy Clay Loam

There was also significant difference in particle size distribution of the three depths of the raised beds (Table 2.1). There were significantly more (12.5%) sand and significantly less (11.7%) silt particles at 30 cm compared to the surface. The composition of clay particles was similar across the depth profile of the raised beds. This difference in particle size distribution led to different USDA textural classes at surface (loam) and at 15 and 30 cm (sandy clay loam).

2.3.2. Soil Moisture Retention Curve and Hydraulic Conductivity

ANOVA of the hydraulic parameters obtained after fitting the closed-form van Genuchten-Mualem retention-conductivity model is given in Table 2.2. Significant differences between the three depths were observed for the parameters θs, α and Ks. Differences in the parameters θr, n, m, and Tau were not significant. Both θs and α were significantly higher at 0 cm depth than at 30 cm depth. The 0 cm depth also had significantly higher Ks than both the 15 and 30 cm depths. Differences between the 15 and 30 cm depths were not significant for these three parameters.

There were no significant differences in the root square mean error of the retention (RMSE-θ) and conductivity (RMSE-log K) functions of the three depths. The relatively high RMSE-log K values observed (as compared to RMSE-θ) is a function of the Hyprop-DES giving stronger weight to the retention data during model fit (Pertassek et al., 2011). In addition to the high RMSE-log K values, the Ks values obtained from the conductivity model fit for the three depths were very large. This is due to the lack of measured conductivity values in the very wet range. As the Hyprop device utilizes the evaporation method, it has limitation in measuring hydraulic conductivity at very high MP due to very small hydraulic gradients (Peters and Durner, 2008).

Table 2.2. Hydraulic parameters of the closed-form van Genuchten (1980) and Mualem (1976) models with their respective root mean square errors for three depths of the raised strawberry beds. Means followed by different letters within rows are significantly different ($P<0.05$).

Parameter	**Unit**	**Soil Depth (cm)**			**P-value**
		0	**15**	**30**	
θs	$cm^3.cm^{-3}$	0.475±0.010a	0.448±0.006a	0.394±0.008b	0.009
θr	$cm^3.cm^{-3}$	0.048±0.019	0.083±0.028	0.00±0.00	0.266
α	$1.cm^{-1}$	0.16±0.013a	0.09±0.020ab	0.04±0.006b	0.023
n	_	1.14±0.015	1.18±0.016	1.13±0.004	0.320
m	_	0.12±0.011	0.15±0.011	0.12±0.003	0.330
Tau	_	-2.0±0.00	-1.72±0.16	-2±0.00	0.405
Ks	$cm.day^{-1}$	8268±1000a	2356±686b	1290±581b	0.011
RMSE-θ	_	0.006±0.002	0.006±0.002	0.004±0.001	0.435
RMSE-log K	_	0.310±0.09	0.329±0.095	0.310±0.090	0.990

Based on guidelines of the United States Department of Agriculture, Natural Resources Conservation Service (USDA NRCS, 2020), Ks for the USDA loam and sandy clay loam soil textural classes are estimated to be between 36.5 – 121.9 $cm.day^{-1}$ and between 12.2 - 36.5 $cm.day^{-1}$, respectively. Accordingly, the Ks for the 0 cm depth (loam) and the 15 and 30 cm depths (sandy clay loam) of the raised beds is estimated to be in these ranges. The unreliable Ks values obtained from the conductivity model fit are rejected, whereas Tau value for the Mualem conductivity model is generally assumed to be 0.5 (Mualem, 1976).

ANOVA of VWC (%) data corresponding to MP values in the range of 0 to -100 kPa (in 10 unit differences) showed significant differences in water content between the three depths only at 0 kPa, i.e., saturation (Table 2.3). The water content of the raised beds at 30 cm was significantly lower than the 0 cm depth at saturation. This is due to the increased bulk density and decreased porosity at 30 cm depth. Increases in bulk density effect change in the water retention properties of soils primarily by decreasing the ratio of macrospores that are important in holding water at high MPs (Richard et al., 2001; Sasal et al., 2005; Zhang et al., 2005). The increased percentage of sand particles at 30 cm compared to the 0 cm depth will play an overall role in lower water content at saturation and beyond (Silver et al., 2000).

No significant differences were observed between the water content of the three depths of the raised beds for MP levels after saturation (Table 2.3). This more or less uniform water holding characteristic observed throughout the profile of the raised beds is an important attribute for strawberry plasticulture, as it translates to adequate availability of water and aeration throughout the soil profile to allow vigorous root development.

The Kolmogorov-Smirnov two-sample test and Kruskal-Wallis rank sum test conducted based on the water content data in order to characterize differences within samples showed significant differences between the water retention characteristic of replicates at the 0 cm depth (except for one comparison). At 15 cm depth, differences were significant for only half of the comparisons. There were no significant differences between replicates at 30 cm depth, showing increased uniformity in water retention characteristics of the raised beds at that depth. Since strawberry plasticulture beds are tilled soil layers, they have a high proportion of interaggregate pore spaces and are structurally unstable, especially at the surface (Leig et al., 2002). The test statistic and P-values of these non-parametric tests are given in Appendix A (Table A1).

Table 2.3. Volumetric water content of three depths of the raised strawberry beds obtained using hydraulic parameters of the closed-form van Genuchten (1980) model fitted to each replicate within a given depth. The VWC values correspond to matric potentials of 0 to -100 kPa (in 10 unit differences). Means followed by different letters within rows are significantly different (P<0.05).

Matric Potential (-kPa)	**Volumetric Water Content (%)**			**P-value**
	0 cm	**15 cm**	**30 cm**	
0	47.5±1.0 a	44.8±0.6 a	39.4±0.8 b	0.009
10	34.1±1.9	33.9±0.9	31.8±0.3	0.709
20	31.5±2.1	31.3±1.0	29.4±0.3	0.786
30	30.1±2.3	29.8±1.1	27.9±0.3	0.808
40	29.1±2.3	28.7±1.1	26.9±0.3	0.818
50	28.4±2.4	28.0±1.2	26.2±0.3	0.823
60	27.8±2.4	27.4±1.2	25.5±0.3	0.826
70	27.4±2.5	26.9±1.3	25.0±0.3	0.827
80	27.0±2.5	26.5±1.3	24.6±0.3	0.828
90	26.6±2.5	26.1±1.3	24.2±0.3	0.829
100	26.3±2.5	25.8±1.4	23.9±0.3	0.829

The final water retention curve of the three depths of the raised beds constructed based on the mean values of the van Genuchten model parameters for each depth are given in Figure 2.3. As the maximum MP directly measured using the Hyprop device was -170 kPa, water retention curves were developed for the MP range from 0 to -200 kPa.

The water retention data measured by the Hyprop device for the three depths of the raised beds are given in Appendix A (Figures A1).

The area under the curve (AUC) of each water retention curve was integrated for MP range of 0 to -200 kPa. Comparisons between water retention curves of the three depths (Figure 2.3) showed that AUC of the 0 cm depth was higher than both the 15 and 30 cm depths, by 5.2% and 10.2% respectively.

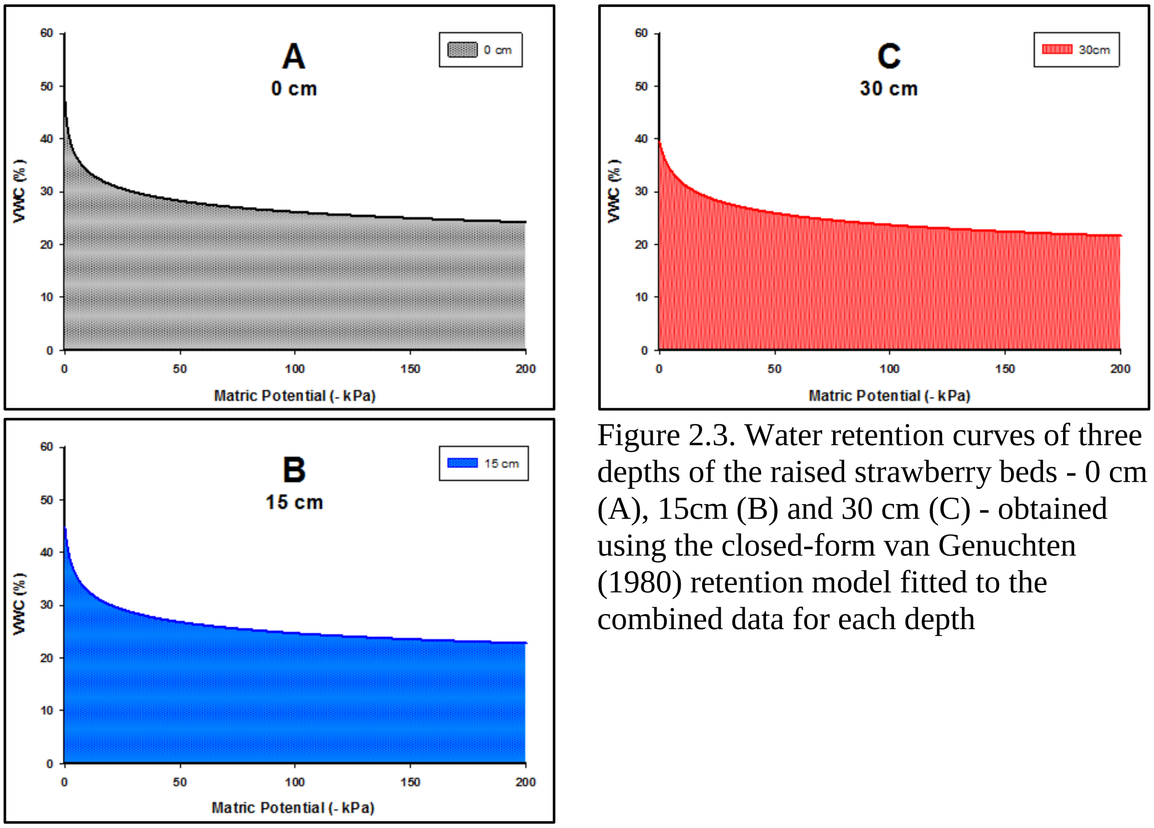


Figure 2.3. Water retention curves of three depths of the raised strawberry beds - 0 cm (A), 15cm (B) and 30 cm (C) - obtained using the closed-form van Genuchten (1980) retention model fitted to the combined data for each depth

The difference in AUC between the 15 and 30 cm depths was 4.2%, with the 15 cm depth having higher AUC. As water retention of the three depths was similar after saturation, the higher AUC observed for the 0 cm depth is mainly a function of the initial higher water content. Having a lower bulk density than the 15 and 30 cm depths, the 0 cm depth likely has a higher proportion of macrospores contributing to a higher initial moisture content and overall AUC.

Both the Kolmogorov-Smirnov two-sample test and Kruskal-Wallis rank sum test conducted to characterize differences between the water retention curves of the three depths of the raised beds) showed no significant differences. The test statistic and P-values of all comparisons made between the three depths are given in Table 2.4.

Table 2.4. Test statistic of Kolmogorov-Smirnov two-sample test (KSa) and Kruskal-Wallis rank sum test (χ^2) with corresponding P-values for comparisons of water retention and hydraulic conductivity between three depths of the raised strawberry beds.

Hydraulic Function	**Depths Compared**	**Kolmogorov-Smirnov**		**Kruskal-Wallis**	
		KSa	**P-value**	**χ^2**	**P-value**
Water Retention	0 cm v. 15 cm	0.853	0.461	1.640	0.200
	0 cm v. 30 cm	0.853	0.461	1.321	0.251
	15 cm v. 30 cm	0.213	1.000	0.130	0.718
Unsaturated Hydraulic Conductivity	0 cm v. 15 cm	0.450	0.987	0.025	0.875
	0 cm v. 30 cm	0.710	0.695	0.030	0.862
	15 cm v. 30 cm	0.872	0.433	0.149	0.700

The observed unsaturated hydraulic conductivities for the three depths of the raised beds are given in Figure 2.4. Values ranged from 0.002 to 0.158 $cm.day^{-1}$ at 0 cm, 0.004 – 0.145 $cm.day^{-1}$ at 15 cm, and 0.001 – 0.295 $cm.day^{-1}$ at 30 cm depth. The highest unsaturated hydraulic conductivity values were measured at MP values of -8.9, -11.2 and -5.9 kPa, corresponding with VWC of 28.0, 28.8 and 30.1%, respectively for BD1, BD2 and BD3.

Due to the unreliability of the Ks data obtained from the Mualem (1976) model fit, the conductivity functions were not developed. Kolmogorov-Smirnov two-sample test and Kruskal-Wallis rank sum test conducted on the observed hydraulic conductivity showed no significant differences between the three depths of the raised strawberry beds.

The test statistic and P-values of all comparisons made between the three depths are given in Table 2.4.

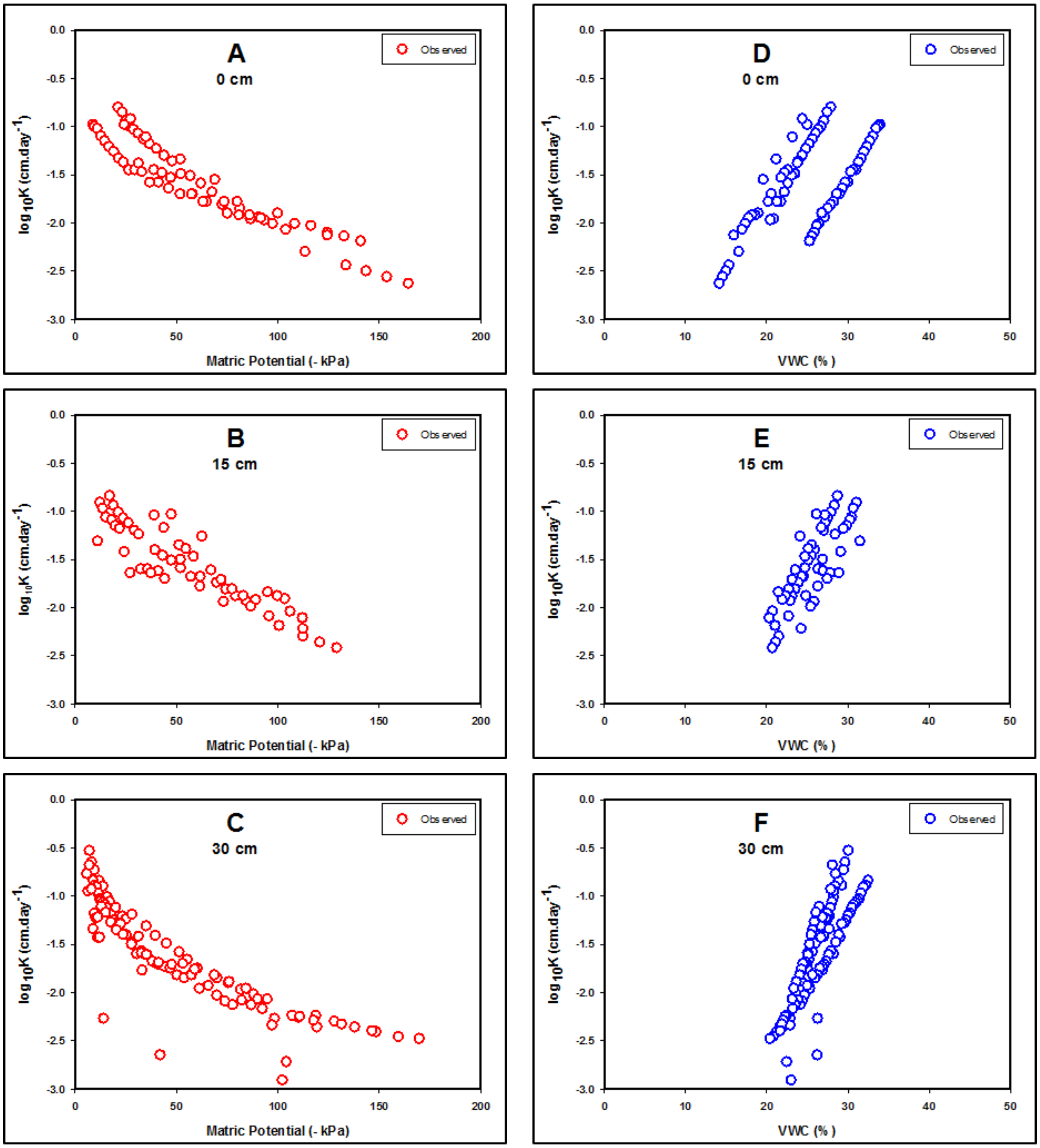


Figure 2.4. Measured unsaturated hydraulic conductivities of three depths of the raised strawberry beds. Unsaturated hydraulic conductivities as a function of matric potential are shown in A (0 cm), B (15 cm) and C (30 cm). Unsaturated hydraulic conductivities as a function of water content are shown in D (0 cm), E (15 cm) and F (30 cm).

2.3.3. Substrate Moisture Retention Curve and Hydraulic Conductivity

ANOVA of the hydraulic parameters obtained after fitting the bimodal van Genuchten model of Durner-Mualem retention-conductivity models to each replicate of the three bulk densities of the LC1 substrate is given in Table 2.5. Significant differences between the three bulk densities were observed for the parameters α1, n1, n2, w1, w2, and Ks but not for θs, θr, α2 and tau. The root mean square error of the retention function (RMSE-θ) was significantly different between the three bulk densities, with BD2 having the highest value. However, RMSE-θ values were relatively small for all three bulk densities, indicting the goodness of fit of the model. On the other hand, there was no significant difference in the root mean square error of the conductivity function (RMSE-log K) between the three bulk densities of the LC1 substrate. The relatively higher RMSE-log K values observed for all three bulk densities indicate a weaker conductivity model fit. The Ks values obtained from the conductivity model fit were of very high magnitude, and hence were rejected.

ANOVA of VWC (%) data corresponding to MP values in the range of 0 to -100 kPa (in 10 unit differences) showed significant differences between the three bulk densities in the relatively wet range (Table 2.6). The three bulk densities of the LC1 substrate had similar water contents at 0 kPa (saturation). However, significant differences in water content of the three bulk densities were observed at the relatively high MP values of -10 to -40 kPa. The water content at MP of -10, -20 and -30 kPa was significantly lower for BD2 than BD1 and BD3. Whereas at -40 kPa, the water content of BD1 was significantly higher than both BD2 and BD3. For MP ranging from -50 to -100 kPa, there were no significant differences between in the water content of the three bulk densities of the LC1 substrate.

Table 2.5. Hydraulic parameters of the bimodal van Genuchten model of Durner (1994) and Mualem (1976) models with their respective root mean square errors for three bulk densities of the LC1 substrate. Means followed by different letters within rows are significantly different ($P<0.05$).

Parameter	Unit	Bulk Density ($g.cm^{-3}$)			P-value
		0.095	0.10	0.12	
θs	$cm^3.cm^{-3}$	0.789±0.004	0.775±0.011	0.757±0.003	0.278
θr	$cm^3.cm^{-3}$	0.087±0.013	0.082±0.003	0.083±0.004	0.960
α1	$1.cm^{-1}$	0.13±0.003b	0.31±0.009a	0.17±0.019b	0.002
n1	_	2.05±0.048a	1.44±0.007b	1.70±0.080ab	0.011
α2	_	0.006±0.00	0.005±0.00	0.005±0.00	0.065
n2	_	1.99±0.071b	5.14±0.123a	2.66±0.191b	0.0002
w1	_	0.65±0.016b	0.89±0.005a	0.70±0.035b	0.010
w2	_	0.35±0.016a	0.11±0.005b	0.30±0.035a	0.010
Tau	_	1.99±0.071	5.14±0.123	2.66±0.191	0.099
Ks	$cm.day^{-1}$	6587±1453a	9455±315a	886±210b	0.018
RMSE-θ	_	0.005±0.00b	0.02±0.001a	0.004±0.00b	0.002
RMSE-log K	_	0.08±0.010b	0.1±0.015ab	0.18±0.02a	0.081

The relatively small differences in bulk density of the LC1 substrate did not affect the water content at saturation. However, there were significant differences in water content immediately after saturation, indicating differences in pore size distribution. Water that is retained between substrate particles in large-sized pores (macro pores) drain quickly as suction is increased. As there was no difference in the initial water content of the three samples at saturation, the significantly lower water content observed in BD2 at these relatively high MP values (-10, -20, and -30 kPa) is considered a function of the pore size distribution of the sample. The non-significant differences in water content observed at lower MP (-50 to -100 kPa) indicate that the adhesive forces that retain water at higher suctions were similar for the three bulk densities of the LC1 substrate.

Table 2.6. Volumetric water content of three bulk densities of the LC1 substrate obtained using hydraulic parameters of the bimodal van Genuchten model of Durner (1994) fitted to each replicate within a given bulk density. The VWC values correspond to matric potentials of 0 to -100 kPa (in 10 unit differences). Means followed by different letters within rows are significantly different ($P<0.05$).

Matric Potential (- kPa)	**Volumetric Water Content (%)**			**P-value**
	0.095 ($g.cm^{-3}$)	**0.10 ($g.cm^{-3}$)**	**0.12 ($g.cm^{-3}$)**	
0	78.9±0.44	77.5±1.14	75.7±0.33	0.278
10	33.1±0.42 a	28.9±0.36 b	34.5±0.31 a	0.002
20	26.5±0.46 a	23.1±0.30 b	26.4±0.35 a	0.017
30	22.3±0.50 a	18.3±0.23 b	21.0±0.26 a	0.009
40	19.6±0.54 a	16.1±0.19 b	17.9±0.15 b	0.018
50	17.7±0.57	15.1±0.17	16.0±0.08	0.054
60	16.4±0.60	14.4±0.17	14.8±0.06	0.137
70	15.4±0.63	14.0±0.17	13.9±0.08	0.254
80	14.7±0.66	13.6±0.17	13.2±0.11	0.369
90	14.1±0.68	13.3±0.17	12.7±0.12	0.460
100	13.6±0.70	13.1±0.17	12.3±0.14	0.523

According to Kolmogorov-Smirnov two-sample test, there were no significant differences in water retention between replicates within each bulk density of the LC1 substrate. Kruskal-Wallis rank sum test results also showed non-significant differences between replicates within each bulk density of the LC1 substrate. The test statistics (KSa and χ^2) and P-values of these tests are provided for all comparisons made between replicates within each bulk density of the LC1 substrate in Appendix A (Table A2).

The water retention curves for the three bulk densities of the LC1 substrate constructed based on the hydraulic parameters of the bimodal van Genuchten model of

Durner (1994) are given in Figure 2.5. Water retention curves were constructed for MP range of 0 to -100 kPa as the highest direct measurement of MP obtained using Hyprop was -76 kPa.

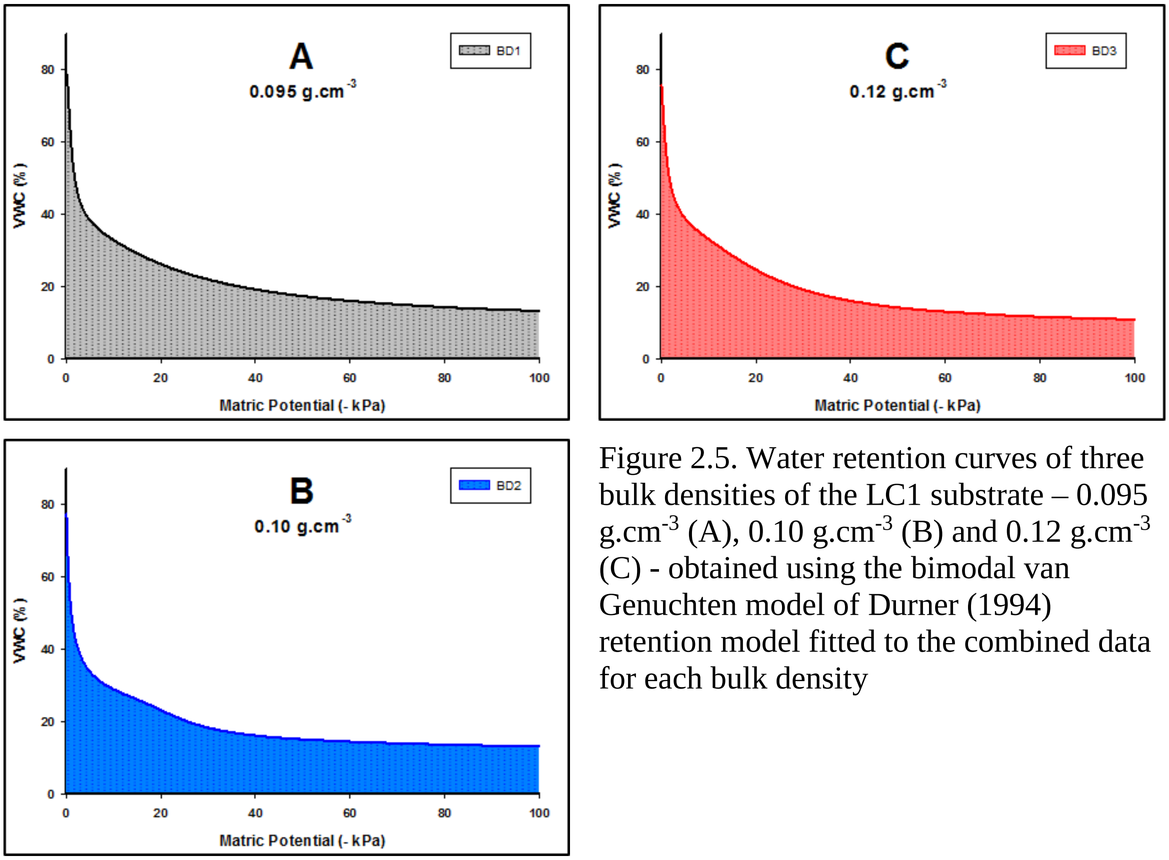


Figure 2.5. Water retention curves of three bulk densities of the LC1 substrate – 0.095 g.cm^{-3} (A), 0.10 g.cm^{-3} (B) and 0.12 g.cm^{-3} (C) - obtained using the bimodal van Genuchten model of Durner (1994) retention model fitted to the combined data for each bulk density

The percentage differences in area under the curve (AUC) between the three bulk densities were 8.72% (BD1 vs. BD2), 0.09% (BD1 vs. BD3), and 8.64% (BD3 vs. BD2), revealing a slight difference in the water retention curve of BD2 as compared to that of BD1 and BD3. Although the three bulk densities had similar water content at saturation, analysis of the curves indicated that more water was lost from BD2 between saturation and MP of -40 kPa compared to BD1 and BD3, hence resulting in a lower AUC (Figures 2.5 A, B and C). The water content of the three bulk densities were similar below a MP of -40 kPa. As adhesive forces play a bigger role in water retention as the substrate dries, the results observed imply the surface area available for water absorption in the three bulk densities was not significantly different. The water retention data for the three bulk densities of the LC1 substrate measured by the Hyprop device are shown in Appendix A (Figure A2).

The Kolmogorov-Smirnov two-sample tests and Kruskal-Wallis rank sum tests conducted to characterize differences in the water retention curve showed non-significant differences between the three bulk densities of the LC1 substrate (Table 2.7).

Table 2.7. Test statistic of Kolmogorov-Smirnov two-sample test (KSa) and Kruskal-Wallis rank sum test (χ^2) with corresponding P-values for comparisons of water retention and unsaturated hydraulic conductivity between three bulk densities of the LC1 substrate.

Hydraulic Function	**Samples Compared**	**Kolmogorov-Smirnov**		**Kruskal-Wallis**	
		KSa	**P-value**	**χ^2**	**P-value**
Water Retention	BD1 v. BD2	0.426	0.993	0.053	0.818
	BD1 v. BD3	0.426	0.993	0.001	0.974
	BD2 v. BD3	0.213	1.000	0.010	0.922
Unsaturated Hydraulic Conductivity	BD1 v. BD2	0.610	0.852	1.096	0.295
	BD1 v. BD3	0.949	0.328	2.614	0.106
	BD2 v. BD3	0.526	0.945	0.127	0.721

The observed unsaturated hydraulic conductivities of the three bulk densities of the LC1 substrate are given in Figure 2.6. Values ranged from 0.0002 to 0.102 cm.day^{-1} for BD1, 0.0001 to 0.071 cm.day^{-1} for BD2 and 0.0002 to 0.091 cm.day^{-1} for BD3. The highest unsaturated hydraulic conductivity values were measured at MP of -17.7, -14.0 and -12 kPa, corresponding with VWC of 29.4, 26.9 and 31.6%, respectively for BD1, BD2 and BD3. The Ks values obtained from the Mualem (1976) model fit were very large and hence rejected, a limitation of the evaporation procedure used by the Hyprop device. Both Kolmogorov-Smirnov two-sample test and Kruskal-Wallis rank sum test on the measured unsaturated hydraulic conductivity data revealed non-significant differences between the three bulk densities of the LC1 substrate (Table 2.7).

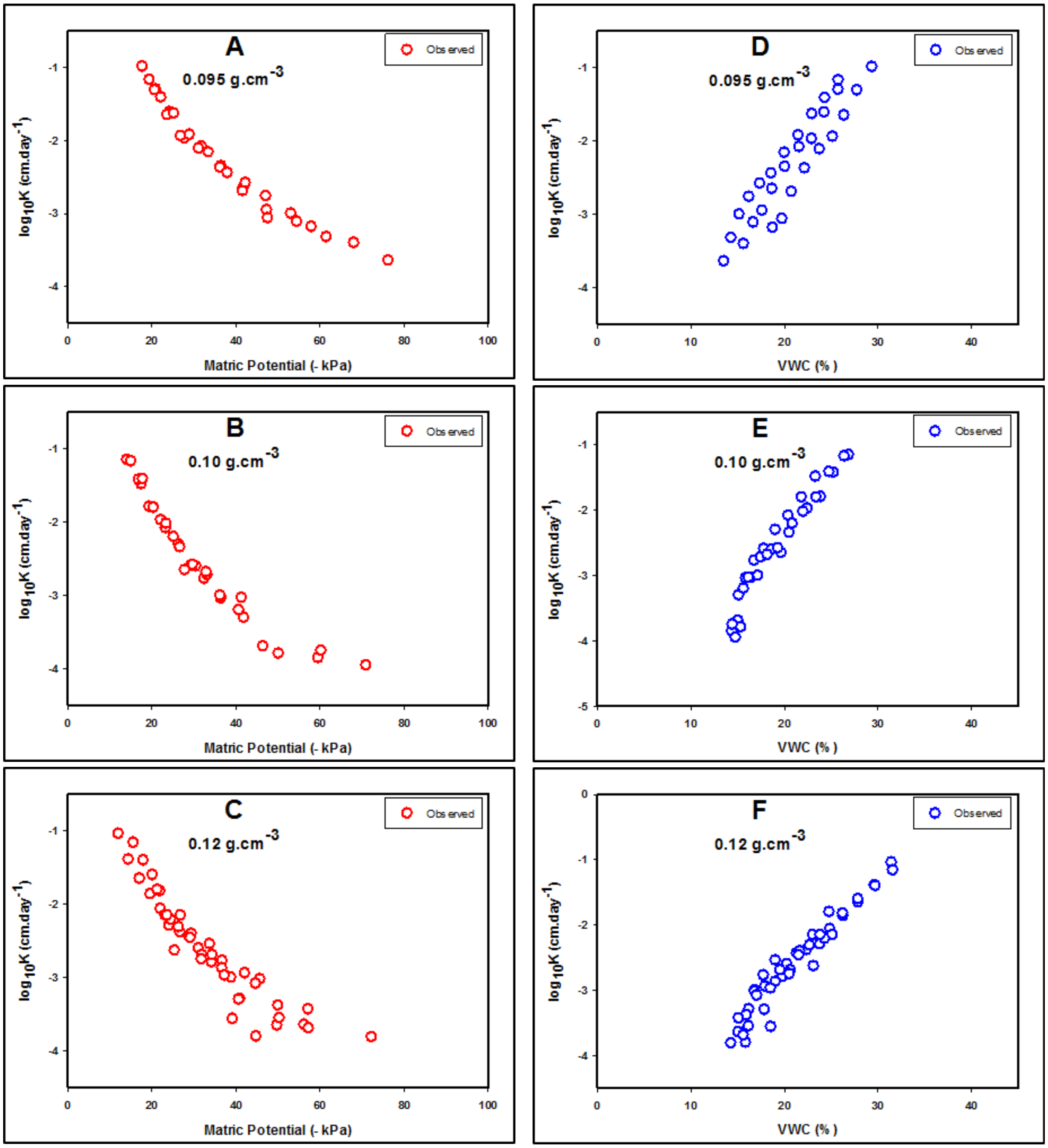


Figure 2.6. Measured unsaturated hydraulic conductivities of the three bulk densities of the LC1 substrate. Unsaturated hydraulic conductivities as a function of matric potential are shown in A (0.095 g.cm^{-3}), B (0.10 g.cm^{-3}) and C (0.12 g.cm^{-3}). Unsaturated hydraulic conductivities as a function of water content are shown in D (0.095 g.cm^{-3}), E (0.10 g.cm^{-3}) and F (0.12 g.cm^{-3}).

2.4. Conclusions

Analysis of the measured parameters for the three depths of the raised beds (0, 15 and 30 cm) revealed differences in soil physical properties. There was a slight increase in bulk density with depth of the raised beds, which was accompanied by proportional decrease in porosity. Differences were also observed in the particle size distribution of the raised beds, with the sand percentage increasing and silt percentage decreasing with soil depth. These differences are likely due to tillage-induced re-distribution of soil particles within the raised beds, resulting in slightly differing soil textural classes at surface than deeper depths.

The water retention characteristic of the raised beds was very uniform for the three depths studied, with the only difference occurring at very high MP. The unsaturated hydraulic conductivity of the raised beds was also very similar throughout the profile. Uniformity of these properties in the raised beds, which are tilled soil layers typically 10 - 12 inch (25 – 30 cm) high, has important implications as it translates to uniformity of moisture availability, drainage, aeration etc., which in return contributes to uniform plant canopy and healthy and productive plants.

Similarly, differences between the three bulk densities of the LC1 substrate were minimal for both water retention and unsaturated hydraulic conductivity. The difference in water retention characteristic observed at relatively high MP is attributed to a slight difference in the pore size distribution. The results showed that minor changes in bulk density of the LC1 substrate that occur as a result of settling of particles under natural conditions is not likely to alter the basic water retention characteristic and hydraulic conductivity of the substrate.

The uniformity of the measured physical properties in both growing media is important, and has practical implications for moisture measurement-based precision irrigation management. For sensor placement, the level of variation that exists in the growing media (both spatially and vertically) needs to be considered so that adequate irrigation can be delivered to all plants. The level of variation also determines the number of sensors needed to fully characterize the measurement area. As built-in redundancy is typically recommended when utilizing sensor networks for irrigation control, large variation in physical properties of the growing media could translate to significant costs in terms of the number of sensors that will be required.

Chapter 3. Effect of Incremental Drought Stress on Strawberry Plant Physiology, Growth, Yield and Fruit Quality: Field and Greenhouse Studies

3.1. Introduction

Irrigation management is essential in strawberry plasticulture for optimal growth and yield. Frequent irrigations are required in the fall for adequate plant establishment, which is a critical phase in the crop growth cycle. However, even larger quantities of water are applied by growers later in the spring in order to maximize yield, fruit mass and fruit quality. Soluble fertilizers are typically injected with irrigation water via in-row drip tubes to cost-effectively provide nutrients to the plant. Without correct irrigation duration and frequency, there is a potential for over-application of irrigation water that can lead to inefficient water utilization as well as environmental pollution through nutrient leaching.

Limiting irrigation to control excessive vegetative growth in horticultural crops production is a practice that has been known for a long time (Nora et al., 2012). Although very high yields in strawberry plasticulture are typically obtained from well-irrigated plants, there may be instances where reduced irrigation applications have to be implemented to save water and/or reduce the environmental impact of nutrient leaching. There is lack of information, however, about deficit irrigation application (i.e., controlled drought stress) and its effect on the physiological and morphological development of the crop, yield and yield components, and fruit quality of strawberry plants under plasticulture. Specifically, the intent is to investigate the effects of reduced irrigation applications that can be quantified in terms of the drought stress level and duration imposed on plants, which has not been definitively addressed for strawberry plasticulture production.

Water and nutrient use efficiencies in strawberry production can be improved with reduced irrigation application, through techniques such as deficit irrigation (DI) and partial root-zone drying (PRD). In a study involving reduced water application to strawberry plants through PRD and DI, Liu et al. (2007) reported decreased leaf water potential, leaf area, fresh berry yield, and individual berry mass for strawberry plants that received 60% of the water applied to fully-irrigated strawberries. WUE, however, was increased by 40% for both PRD and DI (Liu et al, 2007). Grant et al. (2010) also reported decreased leaf water potential, transpiration rate and leaf area but increased root to shoot dry mass ratio and WUE for strawberry plants that received 70% of the control irrigation regime, based on daily evapotranspiration. Furthermore, Yuan et al. (2004) reported increased plant biomass, fruit size and marketable yields for drip irrigated strawberries when irrigation application was increased from 0.75 to 1 and 1.25 times the surface evaporation measured with a standard 200 mm pan. However, the plants that received irrigation amount of 0.75 times the surface evaporation had the highest WUE as compared to plants receiving 1 and 1.25 times the surface evaporation. The duration of stress implemented in these studies however was not quantified.

Reduced irrigation application has also been shown to enhance the concentrations of some beneficial compounds in strawberries. Terry et al. (2007) reported increased levels of monosaccharides (fructose and glucose), sugars, acids, antioxidants and phenolics in the strawberry cultivar ‘Elsanta’ grown under DI. Additionally, Bordonaba and Terry (2010) also reported increased dry matter and concentration of sugars and acids for the strawberry cultivars ‘Sonata’ and ‘Symphony’ grown under reduced irrigation conditions. Such increases in the concentration of beneficial compounds could play a role in improving overall fruit quality in strawberries and maintaining profitability to growers.

In order to determine the feasibility of reduced irrigation techniques (such as DI) for implementation in strawberry production to save water and reduce environmental impact, the effect of drought stress levels on plant physiology, crop growth, yield and fruit quality need to be understood. It is critical to accurately quantify the duration of stress as the effect of drought stress is cumulative. In drought studies, whether the specific threshold soil moisture or irrigation amount has been reached (or not) is not sufficient enough to provide guidance to growers. In addition, since the drought stress caused by any reduced irrigation application are governed by the physical properties of the growing media (soil/soilless substrates), it is imperative to have an understanding of these physical properties and the dynamics of plant-available water, which in turn has physiological implications on growing plants. The primary objective was to quantify durations of stress on based on these properties, using field and more controlled greenhouse studies.

Economic considerations are the primary determinant of whether any improved crop water productivities which could be achieved under DI scenarios can be recommended to growers. Due to yield losses that could occur as a result of DI, a cost-benefit analysis need not only consider the benefits of DI in terms of savings in water and pumping costs, and environmental benefits, but also the opportunity cost of DI in the form of lost revenue as a result of reduced yields. Enterprise crop budgets for strawberries can be used to make farm level projections of the benefits and costs associated with practicing DI in order to make recommendations to strawberry growers.

The overall goal of this study was to implement reduced irrigation applications on strawberries under field (strawberry plasticulture) and more controlled (greenhouse container production) conditions, to determine the overall feasibility for application in strawberry production. The specific objectives of the study were to implement incremental drought stress on strawberry plants grown under plasticulture and quantify effects on:

- plant physiological parameters, such as leaf water potential and stomatal conductance
- plant growth parameters such as number of branch crowns, leaf area, fresh and dry biomass
- yield components (number of fruit per plant, individual fruit mass, total yield over time), and
- fruit quality parameters - pH, titratable acidity (TA) and total soluble solids (TSS)/°Brix.

The following main hypotheses were tested in this study. Incremental drought stress refers to soil/substrate MP that were implemented between -30 and -60 kPa.

1. H_O: Incremental drought stress does not affect strawberry plant physiology (leaf water potential and stomatal conductance).

   H_A: Strawberry plant physiology is significantly affected by incremental drought stress.

2. H_O: Incremental drought stress does not affect strawberry plant growth (number of branch crowns, leaf area, and fresh and dry biomasses).

H_A: Strawberry plant growth significantly decreases in response to incremental drought stress.

3. H_O: Incremental drought stress does not affect strawberry yield and yield components (number of fruit per plant and individual fruit mass).

   H_A: Strawberry yield and yield components significantly decrease in response to increasing drought stress.

4. H_O: Incremental drought stress does not affect strawberry fruit quality (pH, TA and TSS/^{o}Brix).

   H_A: Strawberry fruit quality parameters are significantly affected by incremental drought stress.

3.2. Materials and Methods

3.2.1. Field Studies

Site Description and Experimental Design

Field experimentation was carried out at the University of Maryland's Wye Research and Education Center (38^o 55' N, 76^o 9' W), to study the effects of incremental drought stress on strawberry plants using commercial plasticulture production system protocols. The study was conducted for three years (2014-2017) during the typical strawberry plasticulture season for the area (early September to mid-June), and was laid out in a randomized complete block design (RCBD) with four replications. Plots of size 0.8 m by 6.1 m (width x length) with 1.5 m spacing between the raised bed centers served as experimental units throughout the study (Figure 3.1).

Planting

Fragaria X ananassa cv. ‘Chandler’ is the strawberry cultivar that is widely grown in the mid-Atlantic region under plasticulture, and was used for this study. During the 2014/15 study (year 1), thirty plugs of ‘Chandler’ were transplanted in each plot in two rows using an offset/staggered geometry for greater light and air penetration. Spacing (between rows and between plants) was 0.3 m. Irrigation was provided via two 8 mm drip tubes with a 30-cm (12 inch) spacing and 0.95 liter per minute per 30.5 m (0.25 gallons per minute per 100 feet) output (John Deere, Moline, IL) laid out in each plot. The drip tubes were buried 5 cm below the top of each raised bed under the plastic, 15 cm (6 inch) apart and 30 cm (12 inch) from the sides of the raised bed.

Figure 3.1. The experimental plots for field studies at the University of Maryland’s Wye Research and Education Center in Queenstown, Maryland

At the end of the study in year 1 (2014/15), plants were maintained throughout the summer and carried-over to the next season following the standard cultural practices for renovation. However, this is not the typical practice in strawberry plasticulture and was mainly done due to logistical reasons preventing re-planting. Under renovation, disease pressure typically leads to the death of plants and/or heavy yield declines. At the beginning of the study in year 2 (2015/16), renovated plants that died over the previous summer were replaced with new plugs of ‘Chandler’.

In year 3 (2016/17), the experiment was rotated to an adjacent plot of land (standard practice to reduce disease pressure) and new plasticulture beds were made. The length of plots/experimental units remained the same, but planting was done using 20 plugs of ‘Chandler’ per plot with the same spacing as the previous years.

Irrigation Treatments

During prior strawberry research conducted at the study site, irrigation was scheduled based on soil MP measurements made using tensiometers, with a MP of -30 kPa used as the threshold to trigger irrigation events (M. Newell, *pers. comm.*). The soil at the study site was classified as MqA-Mattapex-Butlertown silt loams, 0 to 2 percent slopes. Based on the water retention curves developed for the soil (detailed in Chapter 2), a MP of -30 kPa represented a soil moisture status that can supply the crop water demand with no significant stress. Therefore, this MP level was selected as the threshold level for the irrigation treatment Cont. in the study. In order to implement incremental drought stress on plants, three deficit irrigation (DI) levels which progressively applied less water than Cont. were chosen, with the threshold MP set at 10 unit differences: -40 kPa (DI1), -50 kPa (DI2), and -60 kPa (DI3).

To implement the control and three DI treatments based on VWC measured in the root-zone, the threshold MP levels were translated to their corresponding VWC using the water retention curve developed for the soil. The closed-form van Genuchten (1980) water retention model parameters for the 15 cm depth of the raised plasticulture beds (Chapter 2) were used for this purpose. More or less uniform water retention characteristics were observed across the profile of the raised beds (Chapter 2). In addition, the majority of strawberry roots are centered around and absorbed water from this depth. Corresponding VWC values for the MP levels were 36.7% (Cont.), 34.6% (DI1), 33.4% (DI2) and 32.5% (DI3). These values were reached after adjustments for variations in VWC readings due to sensor placement.

Sensor Network and Treatment Implementation

Throughout the study, an advanced automated sensor-control network (Kohanbash et al., 2013) was used to independently control irrigation for all 16 experimental units. The sensor network consisted of two 10HS capacitance sensors (Meter Group, Inc., Pullman, WA) that were inserted in the root-zone of strawberry plants at approximately 6 inch/15 cm depth to measure VWC in each plot. MPS-1 (year1&2)/MPS-6 (year 3) matric potential and GS3 (electrical conductivity and soil temperature) sensors (Meter Group, Inc., Pullman, WA) were also inserted at 15 cm depth in each plot. Irrigation volume for each plot was continuously measured by Badger flow meters (Model 25, Badger Meter, Milwaukee, WI). Data for all sensors were recorded on a 15-min basis using nR5 prototype control data loggers (Meter Group, Inc., Pullman, WA), and was transmitted via radio frequency to a base computer with Sensorweb^{TM} software (Mayim LLC., Pittsburgh, PA).

In addition to soil parameters, microclimatic conditions at the site were measured throughout the study period using an on-farm weather station. The station was equipped with a PYR sensor (solar radiation), QSO-S sensor (photosynthetically active radiation PAR), VP-3 sensor (temperature, relative humidity and vapor pressure deficit), DS-2 sonic anemometer (wind speed and direction) and ECRN-100 rain gauge (precipitation) (Meter Group Inc., Pullman, WA). Weather parameters were recorded on a 5-minute basis using an Em50R data logger (Meter Group Inc., Pullman, WA).

During the fall growing period in each year, all plots were irrigated at the same rate using the time-based irrigation control function in Sensorweb^{TM} (Kohanbash et al., 2013). This was done because the establishment phase of strawberry plants is critical and by-and-large determines the final yield obtained. Fertilization was carried out through soil incorporation during bed formation and fertigation through drip lines in the spring. Standard recommended rates for ‘Chandler’ in the mid-Atlantic region were used. The control and DI treatments were only implemented during the spring growing season once plants reached full flowering stage. Irrigation commands from Sensorweb^{TM} were sent to the nR5 control nodes, which opened and closed solenoid valves on each plot that were wired to a relay on the nodes (Kohanbash et al., 2013).

During years 1 and 2, the sensor-based irrigation control function in Sensorweb^{TM} was used to implement the control and DI treatments. Whenever the average VWC of the two 10HS sensors in each plot dropped below the corresponding set-point, a 4-minute irrigation event was applied through the drip irrigation system. Irrigation events were repeated on a 5-minute basis until the average VWC sensed was above the set-point. In order to continuously maintain the soil VWC above the critical levels of the control and

DI treatments, irrigation events were allowed to occur throughout the day whenever the threshold levels were reached.

During year 3, irrigation treatments were implemented based on real-time measurements of soil MP using MPS-6 sensors instead of the VWC measurement of the 10HS sensors. The MPS-6 sensors were installed at a depth of 30 cm (12 inch) and gave comparable soil MP data to the very accurate T8-field tensiometers (Meter Group Inc., Pullman, WA), which were installed at the same depth in 2 replicates of each treatment.

Yield and Destructive Harvests

From late April to mid-June during each year, ripe fruit was harvested every 3 to 5 days from six (years 1 and 2) or 5 (year 3) plants in each replicate plot. The harvested fruit were categorized into 3 groups based on their mass (less than 10 g, 10 – 20 g and more than 20 g) and weighed separately. The number of fruit in each category was recorded, and then stored in a laboratory freezer at -30^{O}C for fruit quality analysis.

At the end of the study in year 2, five of the six sampled plants (from which yield data was obtained) were dug out of the raised beds with their rootballs, bagged and destructively harvested. The number of branch crowns per plant was counted and recorded. Leaves were separated and the leaf area was measured using Li-3000C leaf area meter (LI-COR, Lincoln, NE). Fresh mass of leaves and stems was recorded to the nearest 0.1 g. Roots were carefully separated by washing the soil from the rootballs. All plant parts were dried to a constant weight in a laboratory oven at 70^{o}C and the dry mass for each component was recorded. At the end of the study in year 3, destructive harvests were conducted in the same way outlined above for the 5 sampled plants from each replicate plot.

3.2.2. Greenhouse Studies

Site Description and Experimental Design

Experiments were carried out at the University of Maryland's Research Greenhouse Complex to determine the effect of substrate moisture on strawberry plant physiology, growth, yield, and fruit quality. The study was carried out for two years - from October to June during 2017/18 (year 1) and 2018/19 (year 2) - and was laid out in a randomized complete block design (RCBD) with four replications. Four greenhouse benches of size 5.8 x 1.8 m (19 x 6 feet) (length x width) were utilized, with each bench divided into four plots/experimental units. As irrigation treatments for the field studies were impacted by significant precipitation that occurred during the treatment periods, the greenhouse experiments were conducted to validate results observed in the field in controlled-environment settings.

Planting

In year 1, *Fragaria X ananassa* cv. - 'Chandler' and 'Sweet Charlie' - two strawberry cultivars that are widely grown in the mid-Atlantic region were used in the study. Before transplanting, plugs of both cultivars were placed in a cold room at 40 ^{o}F for roughly one week (160 hours) to ensure their chilling requirements for fruiting were met. Plugs of each cultivar were then transplanted in 3.9 L (1 gallon) pots filled with a commercial substrate (Sunshine mix LC1, Sun Gro Horticulture, Agawam, MA). Ten plants of each cultivar were placed in each plot and randomly distributed with maximum spacing to allow light and air penetration. Irrigation was delivered to individual plants/pots using yellow spray stakes with 300 ml per minute output (Netafim USA, Fresno, CA). Spray stakes were connected to irrigation laterals that were laid out on each bench and supplied by a pressure regulated main line. In year 2, a third cultivar – ‘Camarosa’, another widely grown cultivar in the mid-Atlantic region - was added to the experiment. To accommodate the three cultivars, only eight plants of each cultivar were placed in each plot. The rest of the experimental layout remained the same.

Irrigation Treatments

The water retention curve of the LC1 substrate was developed following the simplified evaporation method using the Hyprop device as described in Chapter 2. Using the water retention curve of the LC1 substrate at a bulk density of 0.095 $g.cm^{-3}$, four VWC values were selected as the threshold levels (set-points) to implement incremental drought stress on growing plants. These set-points were 40% VWC (Cont., well-watered treatment), 30% VWC (DI1, low drought stress), 20% VWC (DI2, moderate drought stress) and 15% VWC (DI3, high drought stress). These VWC values represented, respectively, two-third, one-half, one-third and one-fourth of the container capacity of the LC1 substrate (~ 60% VWC), corresponding to MP values of -4.1 kPa, -13.7 kPa, -36.6 kPa and -70.0 kPa, respectively.

Sensor Network and Treatment Implementation

A precision sensor network was utilized to provide independent irrigation control to all plots. GS-1 moisture sensors (Meter Group, Inc., Pullman, WA) were inserted into the root zone of three plants in each plot by cutting a horizontal slit through the outside of each pot at approximately half the pot height. The sensors were carefully inserted through the slit and into the middle of the root ball, with the sensor prongs oriented horizontally into the packed substrate; the back of the sensor was covered with the substrate to ensure no interference by air. Pots were then resealed with water proof duct tape. Similarly, two

MPS-6 sensors (Meter Group, Inc., Pullman, WA) were installed in each replicate plot (one per cultivar) to collect in-situ substrate MP data, in a similar fashion to the GS-1 sensors. However with this sensor, the LC-1 substrate was slurried around the clay discs to ensure excellent contact with the soil solution. One GS-3 sensor (moisture, temperature and electrical conductivity) was also installed in each plot, inserted in the wetter part of the pot roughly one-third from the bottom of the pot, similar to the GS-1 sensors. The GS-3 sensor was installed in both cultivars, alternating between the four replications. Irrigation application for each plot were measured using flow meters (Model 25, Badger Meter Inc., Milwaukee, WI). All sensor data were recorded on a 5-min basis using Em50R data loggers (Meter Group, Inc., Pullman, WA) and remotely transmitted to the Sensorweb**TM** base station (Mayim, LLC., Pittsburgh, PA) in the greenhouse.

Environmental conditions inside the greenhouse range were controlled via a centralized system (Priva Greenhouse Control System, Ontario, Canada), and monitored at crop canopy level using two microclimate stations equipped with a PYR sensor (solar radiation), VP-3 sensor (temperature, relative humidity and vapor pressure deficit) and DS-2 sonic anemometer (wind speed and direction) (Meter Group, Inc., Pullman, WA). These parameters were measured on a 1-minute basis and the 5-minute average logged using Em50R data loggers.

To ensure successful plant establishment in the control and deficit irrigation treatments, all plots were irrigated to container-capacity every 2-3 days for four weeks after transplanting using the timed irrigation control function in Sensorweb^{TM}. All treatments were also fertigated with 100 ml of modified Hoagland’s solution every 4/5 days for the duration of the study. The solution used had the following concentrations of essential nutrients: 210 ppm Nitrogen, 40 ppm Phosphorus, 235 ppm Potassium, 200 ppm Calcium, 48 ppm Magnesium, 139 ppm Sulphur, 5 ppm Iron, 0.5 ppm Manganese, 0.02 ppm Copper, 0.05 ppm Zinc, 0.5 ppm Boron, and 0.01 ppm Molybdenum.

Each plot had irrigation control valve with a 24 V AC solenoid that was wired to a relay on a PlantPoint^{TM} control node (Meter Group, Inc., Pullman, WA). To implement irrigation treatments after the establishment period, the three GS1 sensor VWC readings in each replicate plot were averaged on a 15-min basis. The averaged values were continuously compared to the corresponding set-point VWC values of each treatment that were entered into the irrigation scheduler of the Sensorweb^{TM} software. Irrigation was automatically applied to independent plots whenever the average VWC dropped below the corresponding set-point. Irrigation duration was limited to short cycles (15 – 30 sec, depending on the growth stage) to reduce leaching from pots. The irrigation treatments were imposed after establishment and were maintained for the remainder of the study.

Physiological Measurements

During spring, mid-day stomatal conductance (g_s) and leaf water potential (ψ_{leaf}) measurements were obtained to study the effect of incremental drought stress on plant physiology. The measurements were conducted during bright sunny days under non-cloudy conditions. During each measurement, two newly-matured leaves (on two different plants) that were fully exposed were selected for each cultivar. g_s readings were obtained with a porometer (Leaf Porometer, Meter Group, Inc., Pullman, WA). The leaves were immediately cut at their base, sealed in plastic bags and transported to a greenhouse laboratory. ψ_{leaf} readings were obtained with pressure chamber (Model 100, PMS Instruments, Albany, OR) in the laboratory.

Destructive Harvests and Yield

To determine substrate moisture effects on strawberry plant growth during the vegetative phase, destructive harvests were carried out in both years. In year 1, three destructive harvest were conducted to determine the effect of incremental drought stress on fall vegetative growth (DH1), spring vegetative growth (DH2), and mature plants (DH3). Two plants per cultivar per plot were destructively harvested for DH1 and DH2. For DH3, conducted on mature plants after fruit harvest was completed, four plants per cultivar per plot were used. In year 2, only two destructive harvests were made. The first destructive harvest (DH-F) was conducted at the end of the fall growing period using two plants per cultivar per plot; whereas the second destructive harvest (DH-S) in late spring was conducted after fruit harvest was concluded using four plants per cultivar per plot.

At each destructive harvest, individual plants were cut off at their base and transported to the greenhouse lab in plastic bags. The number of branch crowns was counted and plants were separated into leaves and shoot, and fresh mass of both were recorded. Leaf area was measured using leaf area meter (Model 3000, LiCor, Lincoln, NE). All samples were then transferred to labelled paper bags and placed in a laboratory oven. Similarly, root balls of all harvested plants were washed under running water to remove substrate particles and cleaned roots were transferred to paper bags and placed in a laboratory oven. All samples were dried to a constant mass in the oven at 50^{O}C and dry weights were recorded.

From late April to early June, ripened fruit were harvested every 3 to 5 days from six plants per cultivar in each plot in both years. Harvested fruit were categorized into three size groups (less than 10 g, 10 – 20 g, and more than 20 g) and weighed separately.

The number of fruit in each category was recorded as well. Fruit were placed in plastic bags and kept in a laboratory freezer at -30^{O}C for further analysis.

Fruit Quality Analysis

Fruit quality parameters - pH, TA, TSS/^{o}Brix - were analyzed for each harvest throughout both field and controlled-environment studies. First, preserved fruit in zip lock bags (~500 g) were removed from laboratory freezer and allowed to thaw to room temperature (~20^{O}C) overnight. Juice was extracted by squeezing fruit and filtering through cheese cloth into 250 ml Erlenmeyer flasks. Approximately 20 ml of the filtered juice was transferred to 50 ml beakers and the pH was measured using a calibrated hand-held pH meter (Hanna Instruments, Woonsocket, RI). TSS/^{o}Brix was measured using a digital benchtop Abbe Refractometer. For TA determination, 10 g juice was transferred to 500 ml beakers and 50 ml deionized water was added. The resulting solution was titrated using 0.1 N NaOH solution to an end point pH of 8.2. TA (%) results are expressed as equivalent of citric acid.

3.2.3. Data Analysis

As the duration of stress is critical for drought experiments, the percentage of time the control and DI treatments were kept in various VWC and MP ranges were determined for both field and greenhouse studies. Total irrigation volumes applied to the control and DI treatments from transplanting to harvest for each study were obtained from flow meters and irrigation application (L per plant) was determined. WUE (field studies) and CWP (greenhouse studies) of the control and DI treatments was calculated as the ratio of total yield (g/plant) to irrigation water applied (L/plant) from transplanting to harvest. Analysis of variance for all data collected during the studies was performed using the

Proc Mixed procedure in SAS (SAS Institute, Cary, NC). Mean comparisons between treatments were made using Tukey's test to identify honestly significant differences between all treatment means, using 0.05 level of significance in all instances.

3.3. Results and Discussions

3.3.1. Field Studies

Soil Moisture and Matric Potential Dynamics

During the study in year 1, incremental drought stress was implemented by the three DI treatments. Soil VWC dynamics of the control and DI treatments during the spring treatment period (mid-April to mid-June) is illustrated in Figure 3.2. The duration analysis conducted for each treatment showed that for 96.6% (Cont.), 91.8% (DI1), 76.7% (DI2) and 54.1% (DI3) of the time, VWC of the treatments were within ±2.5% of their corresponding set point, indicating the fairly high level of precision achieved in maintaining the intended levels of drought stress.

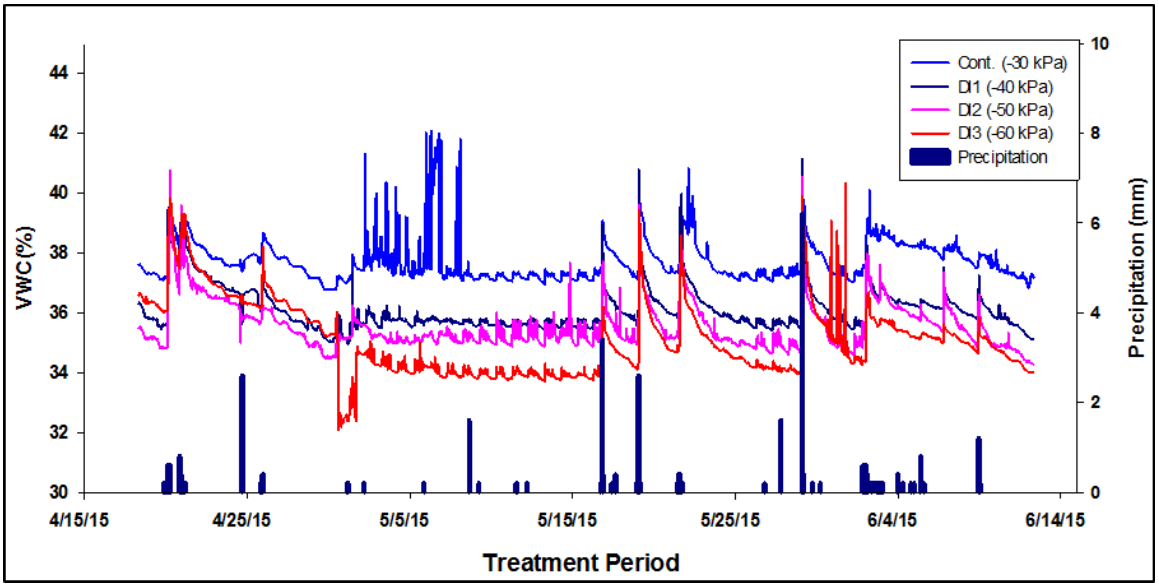


Figure 3.2. 10HS sensor soil volumetric water content dynamics of the control and deficit irrigation treatments during the treatment period of the field study in year 1 (n=8), and precipitation measured at the study site during the treatment period

However, during this spring treatment period, there were significant precipitation events that increased the soil moisture levels and affected the duration of drought stress targeted in the deficit irrigation treatments (Figure 3.2). During prolonged rainfall events, the soil VWC between the plastic covered beds was high enough to affect changes in the root-zone VWC via capillary and lateral water movement. Due to installation issues, MP measurements obtained using the MPS-1 sensors during years 1 and 2 were not reliable (data not shown).

For the study in year 3, duration analysis of the soil MP in the control and DI treatments that was obtained using MPS-6 sensors is provided in Table 3.1. The control and DI treatments were in the relatively wet soil MP range from 0 to -20 kPa for a significant portion of the treatment period, ranging from 61.8% in Cont. to 47.4% in DI3. The total duration the treatments were above a MP of -40 kPa (i.e., wetter) was 88.7% in Cont., 83.0% in DI1, 73.5% in DI2 and 71.4% in DI3. This relatively high duration in a relatively wet range was the result of significant rain events during the treatment period, with the effects being predominantly on the lower DI2 and DI3 treatments. The DI3 treatment had a duration of only 11.5% below -60 kPa (i.e., drier); whereas the DI2 treatment was in the range of -40 to -60 kPa for 19.3% and below -60 kPa for only 7.2% of the treatment duration.

For the study in year 3, the MPS-6 sensors were properly installed and had a comparable reading with the more accurate T8-field tensiometers. The soil MP dynamics observed for the control and DI treatments during the treatment period, and a comparison of the soil MP recorded using the MPS-6 sensors and T8-field tensiometers are provided in Appendix B (Figures B.1 and B.2, respectively).

Table 3.1. Duration (%) of MPS-6 sensor soil matric potential in the control and deficit irrigation treatments during the treatment period of the field study in year 3. Threshold matric potentials used to control irrigation treatments were -30 kPa (Cont.), -40 kPa (DI1), -50 kPa (DI2) and -60 kPa (DI3).

Treatment	**Duration (%) in Matric Potential Ranges (- kPa)**				
	0 - 20	**20 - 40**	**40 - 60**	**60 - 80**	**>80**
Cont.	61.8	26.9	9.7	1.3	0.3
DI1	60.4	22.6	12.7	4.1	0.2
DI2	51.6	21.9	19.3	5.7	1.5
DI3	47.4	24.0	17.1	6.7	4.8

Yield and Yield Components

During year 1, significant differences between the control and the deficit irrigation treatments were observed for fruit yield, number of fruit per plant and amount of irrigation water applied; whereas individual fruit mass and irrigation WUE were not significantly different (Table 3.2). The control treatment had a significantly higher yield than DI2 and DI3. DI1 also had a significantly higher yield than DI3 but the difference between DI2 and DI3 was not significant. The number of fruit per plant was significantly higher for the control and DI1 treatment as compared to DI3, with no significant difference between DI2 and DI3. The amount of irrigation water applied for the control treatment was significantly larger than all DI treatments. In turn, irrigation water volumes for DI1 and DI2 were significantly higher than for DI3. There was no significant difference in irrigation WUE, however, as the reduced water applications in the DI treatments resulted in proportional yield losses (Table 3.2).

There was a significant decline in yield for the carried-over plants in year 2. Yield declines ranged from 18% in DI3 to 32% in Cont., compared to year 1 results. The number of fruit per plant and individual fruit mass also decreased compared to the previous year as a result of plant being carried-over. The drought stress levels in the DI treatments and results observed were affected by rain events as in the previous year. The yield, yield parameters, irrigation application, irrigation WUE, as well as the soil MP dynamics during year 2 are given in Appendix B (Table B.1 and Figure B.3).

Table 3.2. Fruit yield, number of fruit per plant, individual fruit mass, irrigation application per plant and water use efficiency (WUE) of the control and deficit irrigation treatments in the field study in year 1. Threshold matric potentials used to control irrigation treatments were -30 kPa (Cont.), -40 kPa (DI1), -50 kPa (DI2) and -60 kPa (DI3). Values indicated are mean ± SEM. Means followed by different letters within columns are significantly different (P<0.05).

Treatment	Fruit Yield (g/plant)	Number of Fruit per Plant	Individual Fruit Mass (g)	Irrigation Application (L/Plant)	WUE (g/L)
Cont.	600.5±13.9a	56.2±1.5a	10.7±0.2	19.4±0.4a	31.2±1.1
DI1	537.3±16.6ab	49.2±1.5a	11.0±0.2	16.9±0.2b	31.8±0.9
DI2	463.8±15.8bc	45.0±1.6ab	10.9±0.4	16.1±0.3b	28.9±0.8
DI3	410.4±17.7c	34.8±1.1b	11.2±0.2	14.0±0.1c	29.3±1.4

In year 3, the control treatment had higher yield compared to all DI treatments. There was a 6.9%, 7.9%, and 11.3% yield decline with the incremental drought stress in DI1, DI2 and DI3, respectively. The number of fruit per plant for control was also higher than all DI treatments, with very similar number of fruit in the DI treatments. Differences in both parameters however were not statistically significant. Individual fruit mass on the other hand was virtually the same for the control and DI treatments. There were significant differences in irrigation application and irrigation WUE. Irrigation application was significantly higher (57% on average) and irrigation WUE significantly lower (28.2% on average) for the control treatment compared to the three deficit irrigation treatments. Differences between the three DI treatments were very small and non-significant for both parameters (Table 3.3), due to frequent rain events in Year 3.

Table 3.3. Fruit yield, number of fruit per plant, individual fruit mass, irrigation application per plant and water use efficiency (WUE) of the control and deficit irrigation treatments in the field study in year 3. Threshold matric potentials used to control irrigation treatments were -30 kPa (Cont.), -40 kPa (DI1), -50 kPa (DI2) and -60 kPa (DI3). Values indicated are mean ± SEM. Means followed by different letters within columns are significantly different ($P<0.05$).

Treatment	Fruit Yield (g/plant)	Number of Fruit per Plant	Individual Fruit Mass (g)	Irrigation Application (L/Plant)	WUE (g/L)
Cont.	644.5±3.6	52±1.4	12.5±0.3	42.5±0.8a	15.7±0.8b
DI1	600.1±12.5	48±0.7	12.6±0.1	27.5±2.2b	22.0±0.7a
DI2	593.7±15.7	48±1.0	12.4±0.1	27.1±3.6b	22.1±0.5a
DI3	571.9±15.5	46±0.8	12.4±0.3	26.6±1.4b	21.5±0.5a

Differences in yield and number of fruit per plant were not significant despite the significantly different irrigation application. The non-significant difference is attributed to the high amount of precipitation observed during the critical period of fruit setting and development. High rainfall events (appx. > 1 inch) had a significant effect on the DI treatments by raising the soil moisture levels through capillary action.

Fruit Size Distribution

Fruit size distribution of the control and DI treatments based on the complete harvest made in year 1 indicated that a high percentage (91.3% on average) of fruit weighed less than 20 g. Fruit weighing between 10 and 20 g made up 41% of the total fruit on average, whereas the percentage of relatively small fruit weighing less than 10 g on average was 50.3%. The fruit size distribution was very similar for the control and deficit irrigation treatments (Figure. 3.3A).

The fruit size distribution for year 3 is shown in Figure 3.3B. In year 3, the percentage of fruit weighing above 20 g was slightly higher compared to year 1 (12.6% vs. 8.7% in year 1, on average). Fruit weighing from 10 - 20 g made up 47.7% of total yield on average, with virtually no difference between the control and DI treatments. The percentage of fruit weighing less than 10 g was slightly lower compared to year 1, with 39.7 % of fruit falling in this range. Overall, there was a noticeable improvement in fruit size for the control as well as DI treatments during year 3 due likely to the significant rainfall observed.

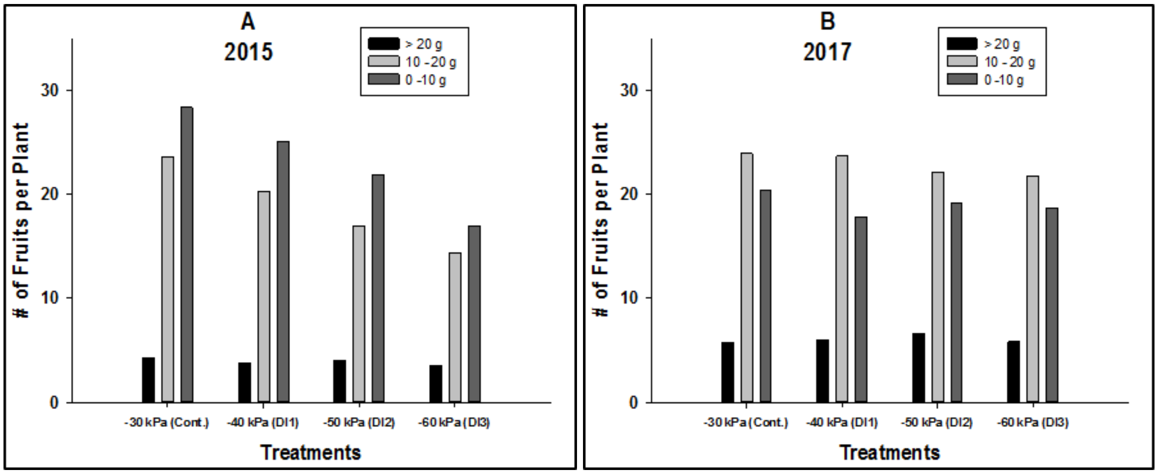


Figure 3.3. Fruit size distribution of the control and deficit irrigation treatments in three size categories (0-10 g, 10-20 g and >20 g) during the field study in year 1 (A) and 3 (B)

Plant Growth

For the first destructive harvest conducted on the carried-over plants at the end of the study in year 2, differences between the control and DI treatments were significant only for root dry mass. The control treatment had significantly higher root dry mass compared to the DI3 treatment, with no significant difference between the DI treatments. Difference in the number of branch crowns, leaf area, shoot dry mass, and root to shoot ratio were not significant (Table 3.4).

Since the DI treatments were implemented in the later stages of the plant growth cycle, effects on vegetative growth were minimal and the incremental drought stress did not result in statistically significant declines in any above-ground plant growth parameters measured. Nevertheless, the slight decreases observed in the number of branch crowns and leaf area were still biologically significant and resulted in yield declines, indicating that strawberry yield is highly sensitive to drought stress (Serrano et al., 1992). The control and DI treatments had optimum number of branch crowns of 5-7, with very high number of branch crowns not desirable as it leads to a reduction in marketable yield due to small fruit size (Poling, 2005; Fernandez et al., 2001). Decrease in leaf area has a direct impact on yield, as it implies decreased photosynthetic capacity.

Table 3.4. Number of branch crowns, leaf area, root dry mass, shoot dry mass, and root to shoot ratio of the control and deficit irrigation treatments for the destructive harvest conducted at the end of the field study in year 2. Threshold matric potentials used to control irrigation treatments were -30 kPa (Cont.), -40 kPa (DI1), -50 kPa (DI2) and -60 kPa (DI3). Values indicated are mean ± SEM. Means followed by different letters within columns are significantly different (P<0.05).

Treatment	**# Branch Crowns**	**Leaf Area (m^2/plant)**	**Root Dry Mass (g/plant)**	**Shoot Dry Mass (g/plant)**	**Root to Shoot Ratio**
Cont.	6.8 ± 0.4	0.22 ± 0.01	8.8 ± 0.4a	40.9 ± 1.5	0.21 ± 0.01
DI1	5.7 ± 0.3	0.20 ± 0.01	6.7 ± 0.2ab	36.9 ± 2.6	0.19 ± 0.01
DI2	5.8 ± 0.1	0.19± 0.00	6.6 ± 0.6ab	36.3 ± 0.5	0.18 ± 0.01
DI3	5.2 ± 0.1	0.19± 0.01	5.3 ± 0.4b	36.9 ± 1.3	0.15 ± 0.01

For the destructive harvest conducted during the study in year 3, differences between the control and three DI treatments were not statistically significant between any measured plant growth parameters (Table 3.5). The number of branch crowns, leaf area and shoot dry mass for the control and DI treatments were virtually the same and generally higher than in year 1. The number of branch crowns were higher than year 1 by a magnitude of 2, whereas leaf area and shoot dry mass were ~3 and 2.5 times higher than year 1, respectively. This indicates the more vigorous plant growth observed overall during year 3. In addition to the high yield losses observed in year 2, plant growth was also highly affected due to carried-over plants from the previous year.

Table 3.5. Number of branch crowns, leaf area, root dry mass, shoot dry mass, and root to shoot ratio of the control and deficit irrigation treatments for the destructive harvest conducted at the end of the field study in year 3. Threshold matric potentials used to control irrigation treatments were -30 kPa (Cont.), -40 kPa (DI1), -50 kPa (DI2) and -60 kPa (DI3). Values indicated are mean ± SEM. Means followed by different letters within columns are significantly different (P<0.05).

Treatment	# Branch Crowns	Leaf Area (m^2/plant)	Root Dry Mass (g/plant)	Shoot Dry Mass (g/plant)	Root to Shoot Ratio
Cont.	8.0 ± 0.2	0.66 ± 0.02	7.9 ± 0.1	95.5 ± 4.1	0.08 ± 0.0
DI1	8.0 ± 0.1	0.62 ± 0.0	7.5 ± 0.5	91.9 ± 1.1	0.08 ± 0.0
DI2	7.7 ± 0.2	0.60± 0.01	7.9 ± 0.3	94.6 ± 2.7	0.08 ± 0.0
DI3	7.9 ± 0.1	0.57± 0.02	8.6 ± 0.3	92.8 ± 1.1	0.09 ± 0.0

Fruit Quality

Analysis of the fruit quality data showed that there was no significant effect of incremental drought stress on all fruit quality parameters measured in the study. No significant differences between the control and DI treatments were observed for pH, TA, TSS and sugar to acid ratio for both year 1 and year 3 (Table 3.6). pH values were only slightly different in year 1 (within a range of 3.3 to 3.4) and virtually the same in year 3 (3.5). TA values were very similar between the control and DI treatments during both years, averaging 0.9 and 1.1 % in year 1 and year 3, respectively. TSS values stayed virtually the same between the control and DI treatments in each year and between the two years. While there were no differences in the sugar to acid ratios of the control and DI treatments, values were slightly higher during year 1 due to the slightly lower TA values obtained.

While incremental drought stress didn’t affect the fruit quality parameters measured in this study, it may have an effect on the concentration of essential compounds (which was not addressed in this study). However, the economic importance of this improvement in fruit quality is very likely heavily outweighed by the yield declines that were resulted as a result of DI. As a majority (>80%) of harvested strawberries are sold for fresh consumption (Boriss et al., 2006), growers are unlikely to prioritize quality improvements over yield. Nevertheless, the fruit quality observed in the field studies may have been affected by rainfall events that occurred during the critical fruit development period in the spring of both years. As strawberries are heavy consumer of water, heavy rainfall events can significantly affect all fruit quality parameters.

Table 3.6. Strawberry fruit quality parameters - pH, titratable acidity (TA), total soluble solids (TSS/°Brix) and sugar to acid ratio - of the control and deficit irrigation treatments for the field studies in year 1 and 3. Threshold matric potentials used to control irrigation treatments were -30 kPa (Cont.), -40 kPa (DI1), -50 kPa (DI2) and -60 kPa (DI3). Values indicated are mean ± SEM. Means followed by different letters in columns are significantly different within a year (P<0.05).

Year	**Treatment**	**pH**	**TA (%)**	**TSS/°Brix**	**Sugar:Acid Ratio**
Year 1	Cont.	3.4±0.01	0.9±0.01	7.4±0.09	8.0±0.03
	DI1	3.3±0.01	0.9±0.01	7.5±0.12	7.8±0.12
	DI2	3.4±0.01	1.0±0.01	7.8±0.04	8.3±0.05
	DI3	3.3±0.01	0.9±0.01	7.7±0.05	8.2±0.09
Year 2	Cont.	3.5±0.01	1.1±0.01	7.5±0.12	6.9±0.14
	DI1	3.5±0.01	1.1±0.01	7.8±0.06	6.9±0.09
	DI2	3.5±0.01	1.1±0.01	7.6±0.09	6.8±0.08
	DI3	3.5±0.01	1.1±0.01	7.7±0.18	6.9±0.14

3.3.2. Greenhouse Studies

A. 2017/18 Season (Year 1)

Substrate Moisture and Matric Potential Dynamics

Incremental drought stress was implemented by controlling the moisture status of the control and DI treatments within a relatively narrow range of their corresponding set-points. During the spring treatment period in May (8-14), all treatments were fertigated continuously to correct tip burning on plants. The GS-1 sensor VWC dynamics during the critical spring treatment period (from late March to early June) is give in Figure 3.4. The VWC of the control and DI1 treatments was within ±5% of the corresponding set-point for 58.4% of the time, indicating the relatively high level of precision in maintaining the intended levels of drought stress. For the lower threshold treatments (DI2 and DI3), VWC were within ±5% of the set point only for 30.3 and 25.4% of the time, respectively, indicating the relative difficulty in maintaining their intended moisture targets.

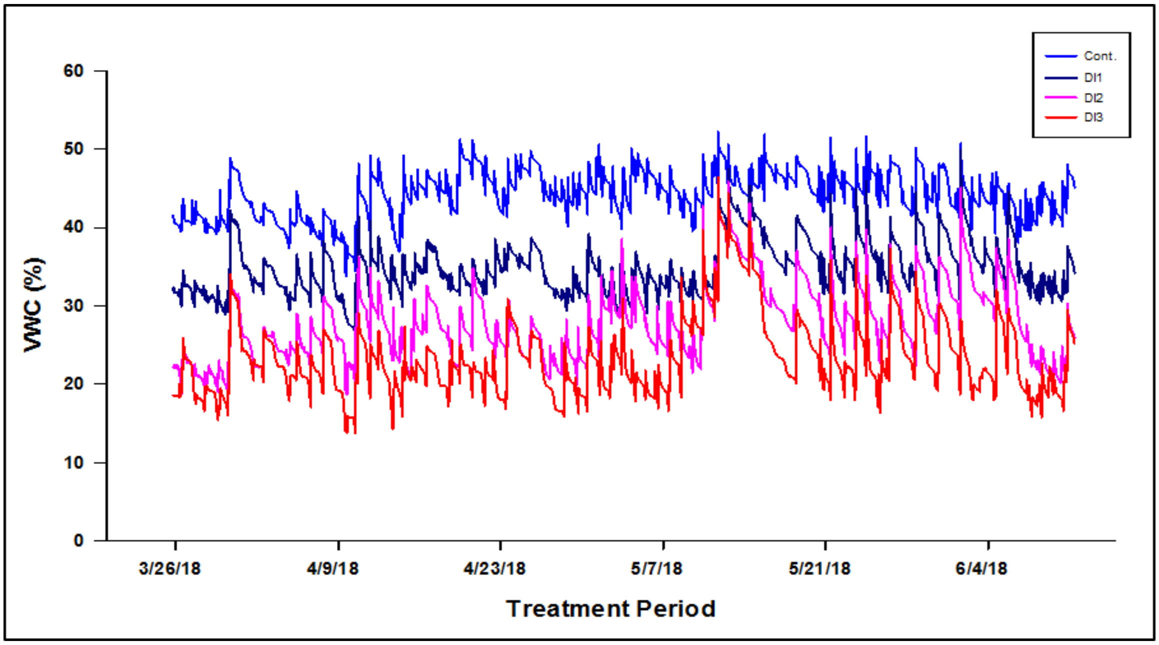


Figure 3.4. GS-1 sensor substrate volumetric water content dynamics of the control and deficit irrigation treatments during the spring treatment period of the greenhouse study in year 1 (n=12). Threshold volumetric water contents used to control irrigation treatments were 40% (Cont.), 30% (DI1), 20% (DI2) and 15% (DI3).

The duration (%) of MPS-6 sensor substrate MP for the control and DI treatments in various MP ranges is given in Table 3.7. The duration analysis revealed that incremental drought stress was imparted by the treatments DI1, DI2 and DI3. The control treatment was maintained within the higher MP range (0 to -20 kPa) for a majority of the spring treatment period (97%). The duration within this high MP range decreased from

Cont. to DI1, DI1 to DI2, and DI2 to DI3. On the other hand, duration in the lower MP range (below -40 to -100 kPa) increased from 2.6 to 19.5 and 31.3% for DI1, DI2 and DI3, respectively.

Table 3.7. Duration (%) of MPS-6 sensor substrate matric potential in the control and deficit irrigation treatments during the spring treatment period of the greenhouse study in year 1. Threshold volumetric water contents used to control irrigation treatments were 40% (Cont.), 30% (DI1), 20% (DI2) and 15% (DI3).

Treatment	**Duration (%) in Matric Potential Ranges (-kPa)**				
	0-20	**20-40**	**40-60**	**60-80**	**80-100**
Cont.	96.6	3.4	0	0	0
DI1	51.2	46.2	2.6	0	0
DI2	29.5	51	16.4	3.1	0
DI3	21.6	47.1	19	11.0	1.3

Physiological Measurements

Stomatal conductance (g_s) and leaf water potential (ψ_{leaf}) measurements done for the two strawberry cultivars during the spring treatment period revealed differences in the way the two parameters are regulated in strawberries. For measurements conducted on five days during the spring treatment period (May 24, May 26, May 30, June 4 and June 5), there was a consistently significant effect of incremental drought stress on g_s of both cultivars ‘Chandler’ and ‘Sweet Charlie’. Effect of incremental drought stress on ψ_{leaf} on the other hand was consistently non-significant (except for June 5 in ‘Sweet Charlie’).

A summary of the two parameters averaging the five measurements during the study period is given in Table 3.8. For the averaged data, g_s was significantly affected by the DI2 and DI3 treatments in ‘Chandler’ and all DI treatments in ‘Sweet Charlie’. The DI3 treatment recorded the lowest g_s in both cultivars. There was no significant effect of incremental drought stress on ψ_{leaf} of ‘Chandler’; whereas the effect on ‘Sweet Charlie’ was only significant for the treatment imposing the highest drought stress (DI3).

Table 3.8. Stomatal conductance (g_s) and leaf water potential (ψ_{leaf}) of 'Chandler' and 'Sweet Charlie' for the control and deficit irrigation treatments during the spring treatment period of the greenhouse study in year 1. Threshold volumetric water contents used to control irrigation treatments were 40% (Cont.), 30% (DI1), 20% (DI2) and 15% (DI3). Values indicated are mean ± SEM. Means followed by different letters within columns are significantly different ($P<0.05$).

Treatment	Stomatal Conductance (g_S) ($mol.m^{-2}s^{-}$)		Leaf Water Potential (ψ_{leaf}) (-MPa)	
	Chandler	**Sweet Charlie**	**Chandler**	**Sweet Charlie**
Cont.	0.56±0.02a	0.61±0.01a	0.58±0.04	0.48±0.04a
DI1	0.49±0.004a	0.43±0.02b	0.63±0.05	0.79±0.04ab
DI2	0.32±0.02b	0.32±0.02bc	0.82±0.11	0.85±0.05ab
DI3	0.28±0.01b	0.27±0.01c	0.95±0.08	1.02±0.08b

Destructive Harvests

The effects of incremental drought stress imposed by the DI treatments on the number of branch crowns and leaf area of 'Chandler' and 'Sweet Charlie' is shown in Figure 3.5. Incremental drought stress did not affect the number of branch crowns in 'Chandler' during DH1. However, significant effects were observed during DH2 and DH3, with the DI2 and DI3 treatment resulting in a significant decrease in the number of branch crowns. Leaf area of 'Chandler' on the other hand, was significantly affected by drought stress during all destructive harvests. The DI2 and DI3 treatments consistently resulted in significant decreases in leaf area. The effect of the DI1 treatment on the other hand was not significant for all three destructive harvests.

Incremental drought stress significantly affected the number of branch crowns in 'Sweet Charlie' during both DH1 and DH2. The effect was significant only for the DI3 treatment during DH1, and for both the DI2 and DI3 treatments during DH2. The DI1 treatment had no significant effects during both DH1 and DH2 periods. Similarly, no significant differences in the number of branch crowns were observed at DH3. On the other hand, effect of incremental drought stress on leaf area was only significant for DH2 and DH3, with these treatments causing a significant decrease in leaf area in both cultivars. The DI1 treatment was not significantly different from the control treatment.

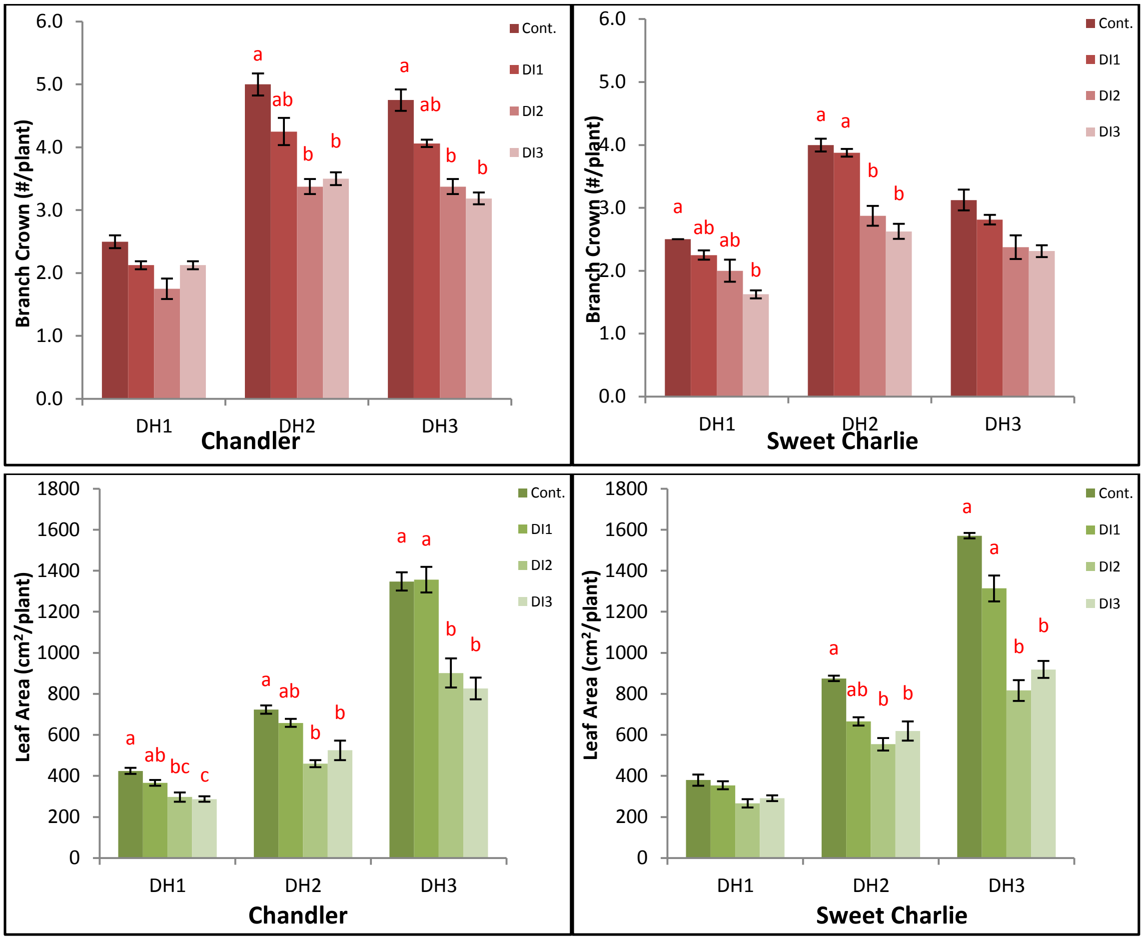


Figure 3.5. Number of branch crowns per plant and leaf area (cm^2/plant) of 'Chandler' and 'Sweet Charlie' for the control and deficit irrigation treatments under three destructive harvests conducted during the greenhouse study in year 1. Threshold volumetric water contents used to control irrigation treatments were 40% (Cont.), 30% (DI1), 20% (DI2) and 15% (DI3). Bars with different letters indicate significant differences within a destructive harvest ($P<0.05$).

The effect of incremental drought stress on dry biomass of the strawberry cultivars 'Chandler' and 'Sweet Charlie' during the three destructive harvests in year 1 is given in Figure 3.6. DI2 and DI3 resulted in significant decreases in shoot dry mass (above ground biomass) during DH2 and DH3 in 'Chandler', and during DH1 in 'Sweet

Charlie'. Effects during DH1 ('Chandler') and DH2 and DH3 ('Sweet Charlie') were not significant. The effect of incremental drought stress on root dry mass (below ground biomass) was also less pronounced, with only DI3 during DH1 and DI2 during DH2 in 'Chandler' resulting in significant differences. There was no effect of incremental drought stress on root dry mass during DH3 in 'Chandler' and all harvests in 'Sweet Charlie'. In addition, incremental drought stress from control to DI1 had no significant effect on both parameters for both cultivars, at all three destructive harvests.

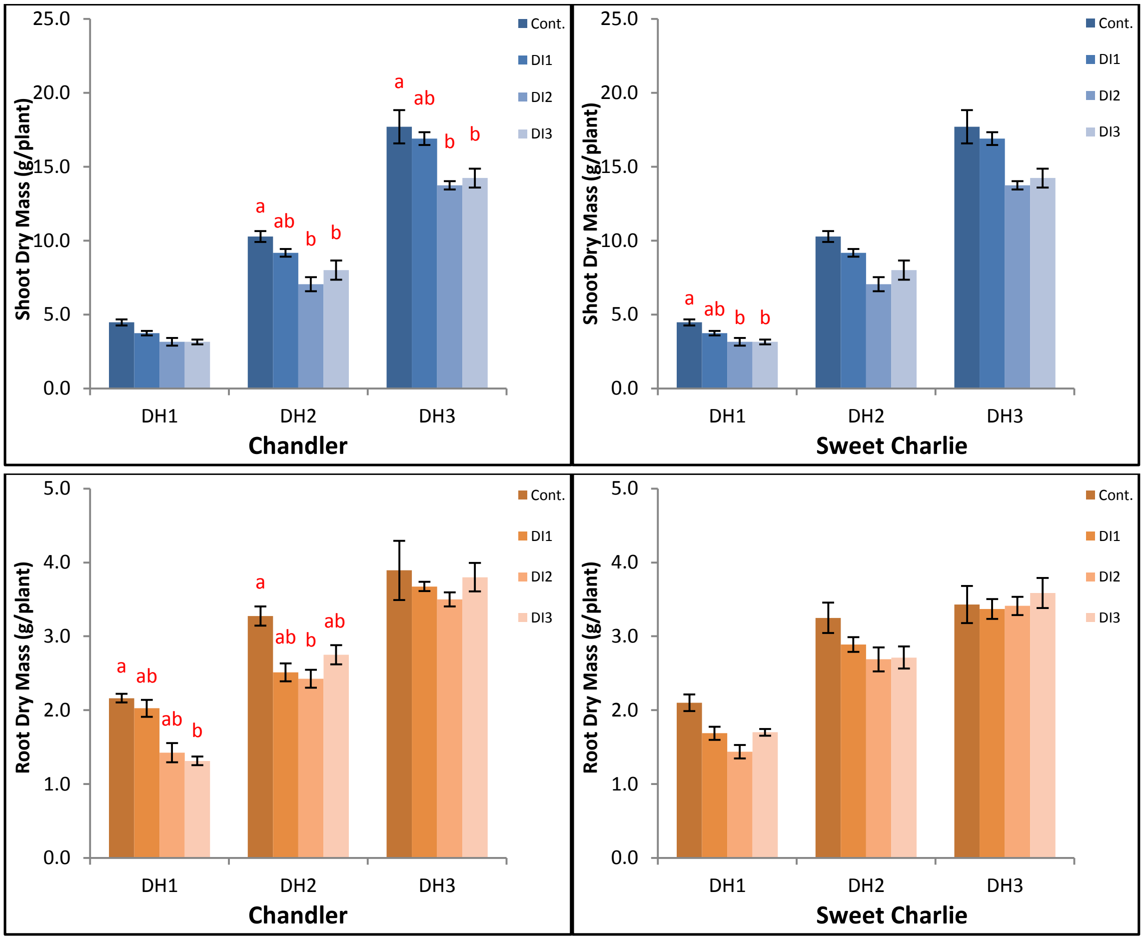


Figure 3.6. Shoot dry mass (g/plant) and root dry mass (g/plant) of 'Chandler' and 'Sweet Charlie' for the control and deficit irrigation treatments under three destructive harvests conducted during the greenhouse study in year 1. Threshold volumetric water contents used to control irrigation treatments were 40% (Cont.), 30% (DI1), 20% (DI2) and 15% (DI3). Bars with different letters indicate significant differences within a destructive harvest ($P<0.05$).

Yield

Incremental drought stress affected yield of the strawberry cultivars ‘Chandler’ and ‘Sweet Charlie’ primarily by decreasing the number of fruit per plant (Table 3.9). The DI2 and DI3 treatment significantly decreased the number of fruit per plant, and hence the yield, in both cultivars. Reductions in yield from control were 46.2% and 48.8% in ‘Chandler’ and 38.8% and 46.6% in ‘Sweet Charlie’ for the DI2 and DI3 treatments, respectively. There was no statistically significant effect of the DI1 treatment on number of fruit per plant and yield for both cultivars. However, the yield losses observed for the DI1 treatment were still considerable (28.4% in ‘Chandler’ and 17.2% in ‘Sweet Charlie’). Effect of drought stress on individual fruit mass was only significant for the DI3 treatment in ‘Chandler’, with no significant effect in ‘Sweet Charlie’.

Table 3.9. Fruit yield, number of fruit per plant, individual fruit mass, irrigation application and crop water productivity (CWP) of ‘Chandler’ and ‘Sweet Charlie’ for the control and deficit irrigation treatments during the greenhouse study in year 1. Threshold volumetric water contents used to control irrigation treatments were 40% (Cont.), 30% (DI1), 20% (DI2) and 15% (DI3).Values indicated are mean ± SEM. Means followed by different letters in columns are significantly different within cultivars (P<0.05).

Cultivar	**Trt.**	**Fruit Yield (g/plant)**	**# of Fruit per plant**	**Individual Fruit Mass (g)**	**Irrigation (L/plant)**	**CWP (g/l)**
Chandler	Cont.	420±29a	33.2±1.8a	12.6±0.2a	15.0±0.6a	28.1±1.6
	DI1	301±15 ab	24.1±0.9ab	12.4±0.3a	12.7±0.4a	24.0±1.4
	DI2	226±17b	20.9±1.7b	10.8±0.2ab	8.3±0.4b	26.9±0.9
	DI3	215±31b	21.3±1.0b	10.2±0.3b	7.1±0.3b	30.7±1.3
Sweet Charlie	Cont.	277±14a	27.8±1.4a	10.0±0.3	15.0±0.6a	18.8±1.3
	DI1	229±13ab	23.7±0.7ab	9.6±0.1	12.7±1.4a	18.3±1.1
	DI2	169±9b	19.3±0.5b	8.7±0.1	8.3±0.4b	20.5±0.8
	DI3	148±10 b	18.4±0.9b	7.9±0.3	7.1±0.3b	21.3±1.6

Irrigation water applied by the control treatment was significantly higher than DI2 and DI3, with the two treatments applying 44.7% and 52.7% less water than control, respectively. The reduction in irrigation volume to the DI1 treatment (15.3%) was not significant. Yield declines as a result of the reduced irrigation applications were proportional, leading to irrigation crop water productivity values that were not significantly different for the control and deficit irrigation treatments in both cultivars.

Fruit Quality

The incremental drought stress implemented by the DI treatments had no significant effect on any of the fruit quality parameters in both cultivars (Table 3.10). pH (3.2) and TA (1.2%) were virtually the same between the control and DI treatments, as well as the two cultivars. TSS was slightly higher in the DI2 and DI3 treatments in both cultivars compared to control; and in ‘Sweet Charlie’ compared to ‘Chandler’, resulting in a higher sugar to acid ratio in ‘Sweet Charlie’.

Table 3.10. Strawberry fruit quality parameters- pH, titratable acidity (TA), total soluble solids (TSS)/ºBrix and sugar to acid ratio - of ‘Chandler’ and ‘Sweet Charlie’ for the control and deficit irrigation treatments during the greenhouse study in year 1. Threshold volumetric water contents used to control irrigation treatments were 40% (Cont.), 30% (DI1), 20% (DI2) and 15% (DI3).Values indicated are mean ± SEM. Means followed by different letters in columns are significantly different within cultivars (P<0.05).

Cultivar	Treatment	pH	TA (%)	TSS/ºBrix	Sugar:Acid Ratio
Chandler	Cont.	3.2±0.00	1.3±0.02	5.9±0.15	4.7±0.07
	DI1	3.2±0.02	1.2±0.01	5.9±0.11	4.8±0.07
	DI2	3.2±0.01	1.3±0.01	6.2±0.21	4.9±0.21
	DI3	3.2±0.01	1.2±0.01	6.1±0.19	5.2±0.17
Sweet Charlie	Cont.	3.2±0.02	1.1±0.02	7.3±0.35	6.4±0.36
	DI1	3.2±0.01	1.2±0.01	7.2±0.17	6.1±0.12
	DI2	3.3±0.02	1.3±0.02	7.9±0.34	6.5±0.29
	DI3	3.2±0.01	1.2±0.01	7.8±0.16	6.5±0.13

B. 2018/19 Season (Year 2)

Soil Moisture and Matric Potential Dynamics

During the greenhouse study in year 2, the control and DI treatments were maintained within a narrow range of their corresponding set-points. The GS-1 sensor VWC dynamics during the critical spring treatment period (from early March to late May) is given in Figure 3.7. Substrate VWC were maintained within ±5% of the corresponding set-point for 84.0, 72.4, 68.9 and 64.7% of the time for the control, DI1, DI2 and DI3 treatments, respectively. These percentages were higher compared to the previous year, indicating drought stress levels were better maintained during year 2. However, substrate VWC were only within ±2.5% of their corresponding set-point for 55.5, 42.4, 39.2 and 32.3% of the time, respectively for the control, DI1, DI2 and DI3 treatments, showing the difficulty to maintain within very narrow ranges.

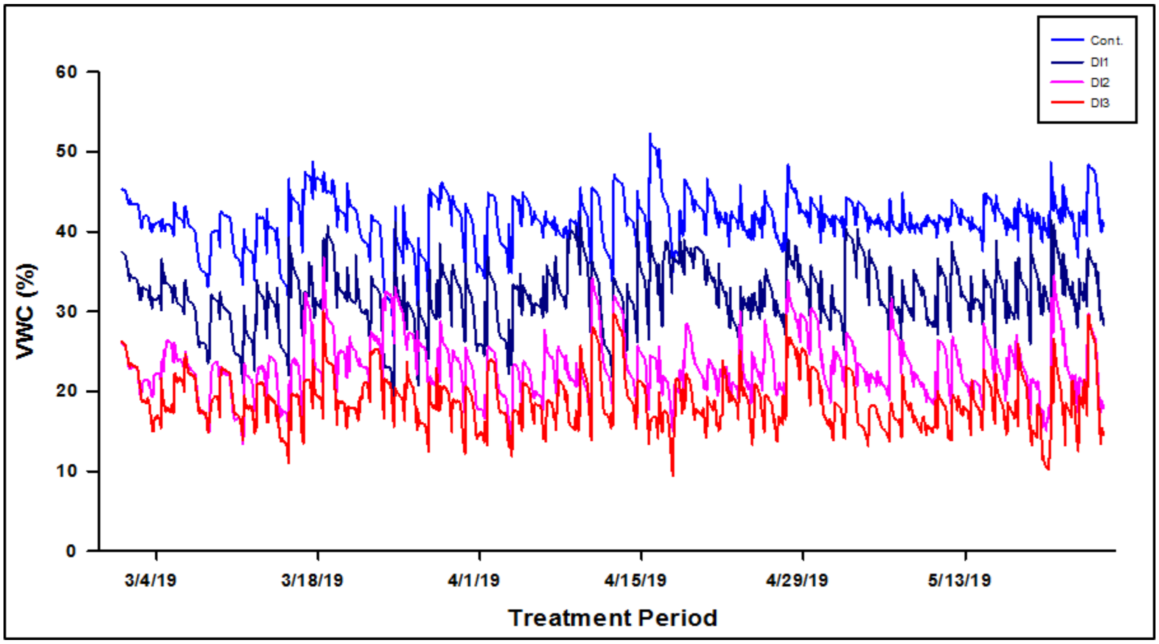


Figure 3.7. GS-1 sensor substrate volumetric water content dynamics of the control and deficit irrigation treatments during the spring treatment period of the greenhouse study in year 2 (n=12). Threshold volumetric water contents used to control irrigation treatments were 40% (Cont.), 30% (DI1), 20% (DI2) and 15% (DI3).

The percent duration of MPS-6 sensor substrate MP measurements in the control and DI treatments is given in Table 3.11 for various MP categories. Increasing drought stress was implemented by the three DI treatments. Duration of the MPS-6 sensor MP reading in the relatively wet range 0 to -20 kPa was 94.3 and 74.0% for the control and DI1 treatments, respectively. Duration of the MP of the DI2 treatment in the range of 0 to -40 kPa was 84.3% and in the range of -40 to -100 kPa 15.7%. For the highest deficit treatment (DI3) the duration of the MP in the 0 to -40 kPa range was only 32.3%, with MP in the drier -40 to -100 kPa range for most of the time (67.7%).

Table 3.11. Duration (%) of MPS-6 sensor substrate matric potential in the control and deficit irrigation treatments during the spring treatment period of the greenhouse study in year 1. Threshold volumetric water contents used to control irrigation treatments were 40% (Cont.), 30% (DI1), 20% (DI2) and 15% (DI3).

Treatment	**Duration (%) in Matric Potential Ranges (-kPa)**				
	0-20	**20-40**	**40-60**	**60-80**	**> 80**
Cont.	94.3	5.7	0	0	0
DI1	74.0	22.5	2.6	0.8	0.1
DI2	37.9	46.4	9.9	2.6	3.2
DI3	4.5	27.8	33.5	17.4	16.8

Physiological Measurements

Stomatal conductance (g_s) and leaf water potential (ψ_{leaf}) measurements of the strawberry cultivars ‘Chandler’, ‘Sweet Charlie’ and ‘Camarosa’ during the spring treatment period showed similar dynamics as in year 1, i.e., incremental drought stress had significant effect on g_s and non-significant effect on ψ_{leaf} (for all three cultivars). Data for each measurement conducted during the spring treatment period is given in Appendix B (Table B2 and B3). Summarized values of the parameters (averaged for all measurements) are given in Table 3.12.

Table 3.12. Stomatal conductance (g_s) and leaf water potential (ψ_{leaf}) of ‘Chandler’, ‘Sweet Charlie’ and ‘Camarosa’ for the control and deficit irrigation treatments during the spring treatment period of the greenhouse study in year 2. Threshold volumetric water contents used to control irrigation treatments were 40% (Cont.), 30% (DI1), 20% (DI2) and 15% (DI3). Values indicated are mean ± SEM. Means followed by different letters within columns are significantly different ($P<0.05$).

Treatment	**Stomatal Conductance (g_s) ($mol.m^{-2}s^{-}$)**			**Leaf Water Potential (ψ_{leaf}) (-Mpa)**		
	Chandler	**Sweet Charlie**	**Camarosa**	**Chandler**	**Sweet Charlie**	**Camarosa**
Cont.	0.45±0.03a	0.52±0.02a	0.54±0.02a	1.65±0.03	1.57±0.02	1.78±0.01
DI1	0.45±0.03a	0.42±0.02ab	0.47±0.02ab	1.75±0.02	1.67±0.03	1.80±0.02
DI2	0.32±0.01ab	0.37±0.02bc	0.37±0.02 ab	1.73±0.02	1.74±0.03	1.86±0.04
DI3	0.26±0.01b	0.29±0.01c	0.37±0.01b	1.80±0.02	1.80±0.03	1.97±0.01

Based on the averaged data, g_s was significantly affected by the DI3 treatment in ‘Chandler’, by the DI2 and DI3 treatments in ‘Sweet Charlie’, and by the DI3 treatment in ‘Camarosa’. There was no significant effect on g_s at the DI1 level in all three cultivars. On the other hand, there was no significant effect of incremental drought stress on the ψ_{leaf} measured in all three cultivars. Compared to the control treatment, there was a 9.1, 14.6 and 10.7% decrease in the ψ_{leaf} in ‘Chandler’, ‘Sweet Charlie’ and ‘Camarosa’, respectively, for the DI3 treatment. The decreases in ψ_{leaf} however were not statistically significant. The relatively higher ψ_{leaf} of ‘Chandler’, ‘Sweet Charlie’ observed for the control and DI treatments during year 1 (compared to year 2) is attributed to the fertigation events that were implemented to control tip burn in year 1. Therefore, the g_s and ψ_{leaf} results observed in year 2 are considered more reliable.

Destructive Harvests

For the first destructive harvests conducted after fall growth in year 2 (DH-F), there was a significant effect of incremental drought stress on the number of branch crowns in all three cultivars (Figure 3.8). The DI3 treatment in ‘Chandler’ and the DI2 and DI3 treatments in both ‘Sweet Charlie’ and ‘Camarosa’ significantly decreased the number of branch crowns. The effect of DI1 on the number of branch crowns was not significant for all three cultivars. The effect of incremental drought stress on leaf area nearly tracked that of the number of branch crowns. The DI2 and DI3 treatments significantly decreased leaf area in all three cultivars; whereas the effect of the DI1 treatments was not significant (Figure 3.8). There was no significant difference between the DI2 and DI3 treatments for both growth parameters in all three cultivars.

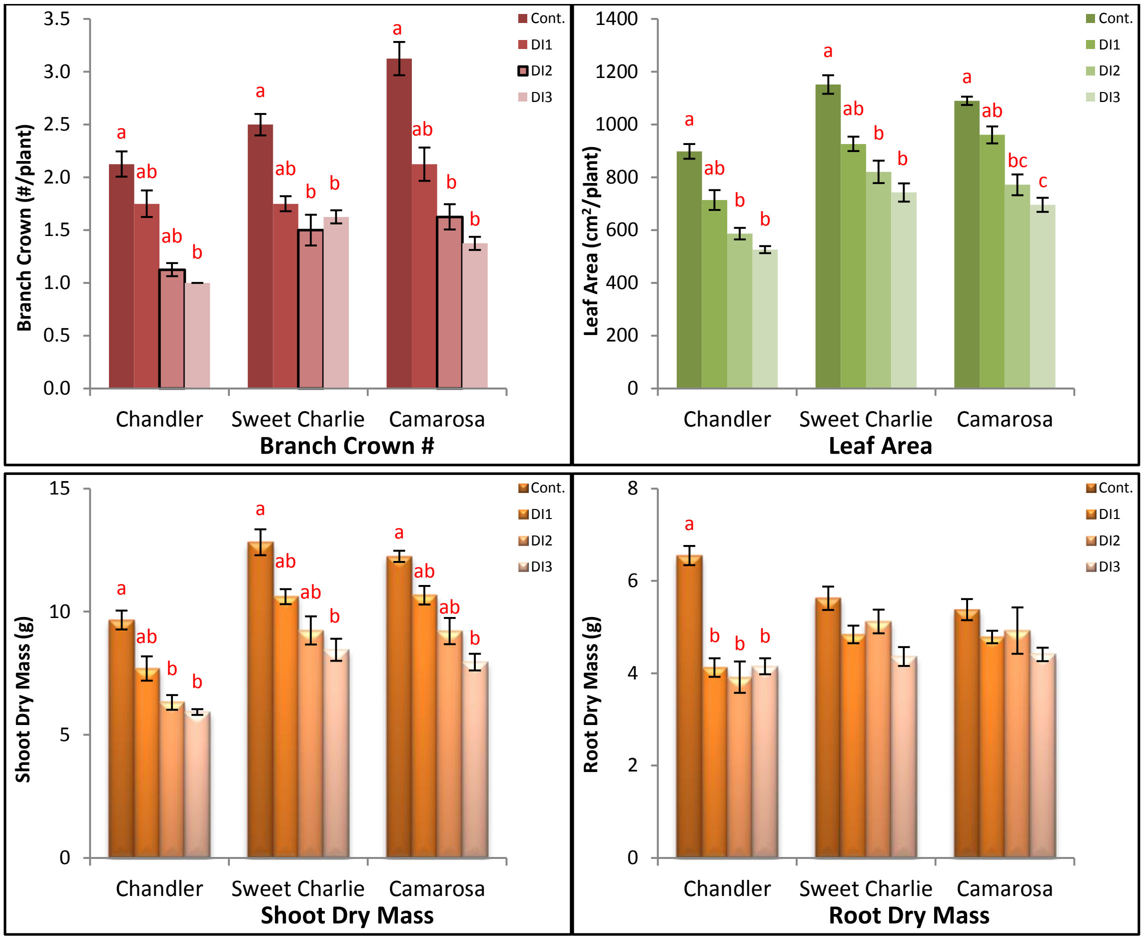


Figure 3.8. Number of branch crowns per plant, leaf area (cm^2/plant), shoot dry mass (g/plant) and root dry mass (g/plant) of ‘Chandler’, ‘Sweet Charlie’ and ‘Camarosa’ for the control and deficit irrigation treatments during the fall destructive harvest conducted in the greenhouse study in year 2. Threshold volumetric water contents used to control irrigation treatments were 40% (Cont.), 30% (DI1), 20% (DI2) and 15% (DI3). Bars with different letters indicate significant differences within a cultivar (P<0.05).

Similarly, the effect of incremental drought stress on shoot and root dry mass of the three strawberry cultivars during DH-F is shown in Figure 3.8. The DI2 treatment in ‘Chandler’ and the DI3 treatment in all three cultivars resulted in significant decreases in shoot dry mass. The effect of the DI1 treatment was not significant in all three cultivars. On the other hand, incremental drought stress didn’t have a pronounced effect on root dry mass of all cultivars, the only exception being the root dry mass of ‘Chandler’ which was significantly affected by all three DI treatments.

For the second destructive harvest conducted on mature plants after fruit were harvested in year 2 (DH-S), there was a significant effect of incremental drought stress on the number of branch crowns in all three strawberry cultivars (Figure 3.9). The DI treatments significantly decreased the number of branch crowns in all three cultivars. Increasing drought stress from DI1 to DI2 (except in ‘Sweet Charlie’) and DI1 to DI3 in all three cultivars resulted in significant decrease in the number of branch crowns per plant. However, differences between DI2 and DI3 were not significant for all cultivars.

Leaf area of the three strawberry cultivars was affected by increasing drought stress similar to the number of branch crowns. The DI1 treatment significantly reduced leaf area in all three cultivars, with further significant decreases for the DI3 treatment (Figure 3.9). Differences between DI2 and DI3 were not significant except for ‘Camarosa’. Shoot dry mass of the three cultivars was also affected by incremental drought stress imposed in the DI treatments (Figure 3.9). The DI1 treatment significantly decreased shoot dry mass in ‘Chandler’ and ‘Sweet Charlie’; whereas the effect of the DI2 and DI3 treatments was significant in all three cultivars. There was no effect of incremental drought stress on root dry mass in all three cultivars.

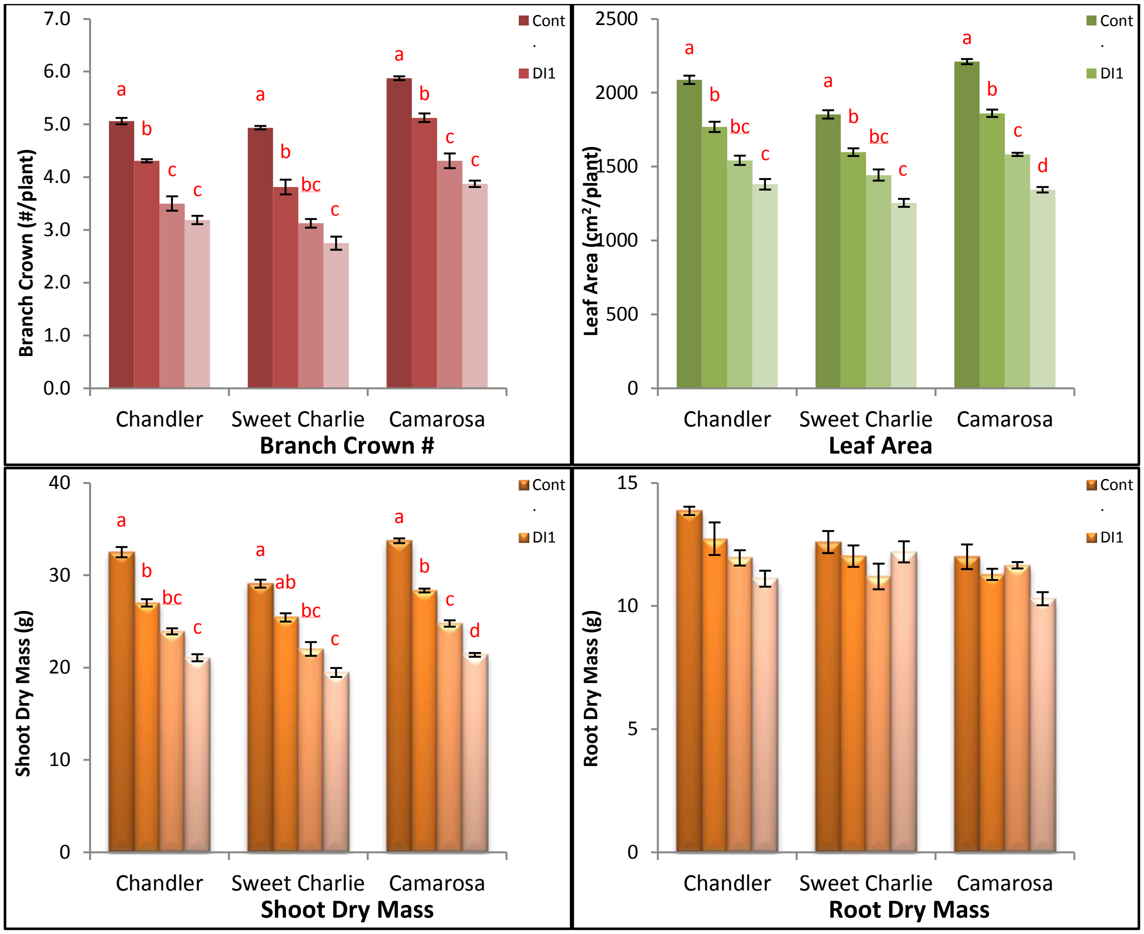


Figure 3.9. Number of branch crowns per plant, leaf area (cm^2/plant), shoot dry mass (g/plant) and root dry mass (g/plant) of ‘Chandler’, ‘Sweet Charlie’ and ‘Camarosa’ for the control and deficit irrigation treatments during the spring destructive harvest conducted in the greenhouse study in year 2. Threshold volumetric water contents used to control irrigation treatments were 40% (Cont.), 30% (DI1), 20% (DI2) and 15% (DI3). Bars with different letters indicate significant differences within a cultivar ($P<0.05$).

Yield

Incremental drought stress significantly decreased the yield of all three cultivars (Table 3.13). In ‘Chandler’, DI2 and DI3 resulted in a 41.2 and 47.1% decline in yield, respectively, which were significant. Whereas the DI1 treatment reduced yield by 17.3% which was not significantly different from control. In ‘Sweet Charlie’, all DI treatments had significant effect on yield, with yield reduction from control amounting to 21.9, 31.2 and 34.0% for DI1, DI2 and DI3, respectively. Similarly, significant yield reductions of

30.6 and 40.3% occurred under the DI2 and DI3 treatments in ‘Camarosa’, with the DI1 treatment resulting in a non-significant yield decreases of 16.8%.

Table 3.13. Fruit yield, number of fruit, individual fruit mass, irrigation application and crop water productivity (CWP) of ‘Chandler’ ‘Sweet Charlie’ and ‘Camarosa’ for the control and deficit irrigation treatments during the greenhouse study in year 2. Threshold volumetric water contents used to control irrigation treatments were 40% (Cont.), 30% (DI1), 20% (DI2) and 15% (DI3).Values indicated are mean ± SEM. Means followed by different letters in columns are significantly different within cultivars (P<0.05).

Cultivar	**Trt.**	**Fruit Yield (g/plant)**	**# of Fruit per plant**	**Individual Fruit Mass (g)**	**Irrigation (L/plant)**	**Crop Water Productivity (g/l)**
Chandler	Cont.	422.8±9.0a	32.4±1.0a	13±0.1 a	20.4±0.4a	20.8±0.3
	DI1	349.5±5.3ab	28±0.3ab	13±0.2 a	18±0.4ab	20.1±0.4
	DI2	248.5±17bc	22±1.8ab	11±0.4 b	16±0.3bc	16.1±1.1
	DI3	223.5±17.4c	20.5±1.5b	11±0.1 b	13.0±0.6c	17.0±0.5
Sweet Charlie	Cont.	438.9±7.4a	33.2±0.7a	13.3±0.2	20.4±0.4a	21.6±0.4
	DI1	342.8±6.8b	26.0±0.7b	13.2±0.1	18±0.4ab	19.6±0.03
	DI2	302.1±5.6bc	24.7±0.4b	12.2±0.1	16±0.3bc	19.7±0.7
	DI3	289.8±3.9c	22.7±0.5b	12.8±0.3	13.0±0.6c	22.8±0.8
Camarosa	Cont.	340.5±5.3a	29.8±1.3	11.6±0.5	20.4±0.4a	16.8±0.4
	DI1	283.4±17ab	24.1±1.1	11.7±0.2	18±0.4ab	16.3±1.0
	DI2	236.3±11.7b	22.1±0.7	10.7±0.3	16±0.3bc	15.2±0.5
	DI3	203.3±12.1b	21.1±1.6	9.8±0.2	13.0±0.6c	16.1±1.2

The number of fruit per plant was significantly affected by the DI treatments in ‘Chandler’ and ‘Sweet Charlie’. The DI3 treatment in ‘Chandler’ and all three DI treatments in ‘Sweet Charlie’ resulted in significant decrease in the number of fruit per plant. There were no significant effects of incremental drought stress on the number of fruit in ‘Camarosa’. The effect of the DI treatments on individual fruit weight was only significant for the DI2 and DI3 treatments in ‘Chandler’. Non-significant effects were observed for both ‘Sweet Charlie’ and ‘Camarosa’ (Table 3.13). The DI2 and DI3 treatments applied significantly less water than control (24.1 and 36.3%, respectively).

Whereas the DI1 treatment applied 14.2% less water than control, which was not significant. Nevertheless, there were no significant differences in the irrigation CWP of the control and DI treatments in all three strawberry cultivars (Table 3.13).

Fruit Quality

The effect of incremental drought stress on all fruit quality parameters measured for the three strawberry cultivars was not significant (Table 3.14). In general, pH ranged between 3.3 and 3.5 and was virtually the same between the control and DI treatments in all three cultivars. 'Chandler' and 'Camarosa' had slightly lower pH compared to 'Sweet Charlie', and hence leading to a slightly higher TA (~1.2% vs. 1%). TSS was slightly higher in 'Chandler' and 'Sweet Charlie' than 'Camarosa'. 'Sweet Charlie' had the highest sugar to acid ratio of the three cultivars, followed by 'Chandler' and 'Camarosa'.

Table 3.14. Strawberry fruit quality parameters- pH, titratable acidity (TA), total soluble solids (TSS)/ºBrix and sugar to acid ratio - of 'Chandler' and 'Sweet Charlie' for the control and deficit irrigation treatments during the greenhouse study in year 2. Threshold volumetric water contents used to control irrigation treatments were 40% (Cont.), 30% (DI1), 20% (DI2) and 15% (DI3).Values indicated are mean ± SEM. Means followed by different letters in columns are significantly different within cultivars ($P<0.05$).

Cultivar	Treatment	pH	TA (%)	TSS/ºBrix	Sugar:Acid Ratio
Chandler	Cont.	3.4±0.02	1.1±0.02	7.1±0.14	6.4±0.22
	DI1	3.3±0.01	1.2±0.01	7.1±0.1	6.1±0.08
	DI2	3.4±0.01	1.2±0.02	7.5±0.13	6.1±0.12
	DI3	3.4±0.02	1.2±0.02	7.3±0.16	6.3±0.18
Sweet Charlie	Cont.	3.5±0.02	0.9±0.03	7.0±0.16	7.7±0.3
	DI1	3.5±0.03	1.0±0.03	7.1±0.16	7.4±0.28
	DI2	3.5±0.02	1.0±0.03	7.2±0.13	7.6±0.24
	DI3	3.5±0.03	1.0±0.03	7.1±0.16	7.2±0.22
Camarosa	Cont.	3.4±0.02	1.2±0.02	6.7±0.12	5.7±0.11
	DI1	3.4±0.04	1.2±0.02	6.5±0.18	5.3±0.17
	DI2	3.4±0.02	1.2±0.02	6.8±0.13	6.9±0.16
	DI3	3.3±0.03	1.2±0.02	6.9±0.08	5.8±0.12

Discussion

Incremental drought stress was implemented by the DI treatments in the field and greenhouse studies as shown by the VWC and MP duration analysis. Drought stress studies on strawberries based on threshold levels of soil MP (Serrano et al., 1992; Pires et al., 2006; Létourneau and Caron, 2019), soil VWC (Klamkowski and Treder, 2006; Jensen et al., 2009; Bordonaba and Terry, 2010), evapotranspiration measurements (Yuan et al., 2004; Liu et al., 2007) or water balance calculations that combines two or more methods (Kruger et al., 1999) have been previously conducted. However, none of these studies quantified the duration of drought stress implemented on plants. When drought stress is based on parameters such as soil water content or soil water potential, not only the threshold value of the parameter used for irrigation control but also the accuracy (i.e., proportion of time in % the parameter stayed within plus/minus of the threshold value) is a critical component to be reported (ICCEG, 2016).

The duration of stress of the DI treatments in the field studies was affected (i.e., reduced) by rainfall events that occurred during the spring treatment period. The frequent and large rainfall events that occurred during the spring treatment period in all three years increased the VWC of the plasticulture beds, reducing the duration of drought stress intended for the DI treatments. The overall non-significant effects on plant growth parameters that was observed from the destructive harvests conducted for the field studies is attributed to the reduced duration of drought stress. The greenhouse studies under controlled-environmental conditions on the other hand had higher rates of accuracy in maintaining the targeted moisture conditions. Thus, effects on plant physiology, plant growth parameters, and yield were more definitive for these DI treatments.

From the greenhouse studies, it was clear that the deficit irrigations implemented at a MP of -50 and -60 kPa (DI2 and DI3) significantly affected strawberry plant physiology, plant growth parameters, and yield and yield parameters. Stomatal conductance as well as leaf area of the three strawberry cultivars ‘Chandler’, ‘Sweet Charlie’ and ‘Camarosa’ were significantly reduced by the -50 and -60 kPa treatments. The significant yield reductions observed in the three cultivars are a result of both reduced assimilation rates (Klamkowski and Treder, 2006) and reduction in the total leaf surface area (Serrano et al., 1992; Liu et al., 2007). Interestingly, yield effects were primarily through reduced number of fruit per plant than individual fruit weight. For the field studies, this is most likely due to the fact that DI treatments were implemented during the spring season at full flowering, perhaps indicating that floral abortion was caused by subtle increases in plant drought stress. For the greenhouse studies, the decreased number of fruit was likely the result mild stress imposed by the DI2 and DI3 treatments. Notably, individual fruit weight was not affected by the increased drought stress in the field studies but was significantly reduced by the DI2 and DI3 treatments in the greenhouse studies.

The DI1treatment (MP of -40 kPa) did not result in significant differences for most of the parameters measured, indicating that the drought stress implemented was relatively minor. Plant physiology as well as plant growth parameters (most) were not affected by the DI1 treatment during both field and greenhouse studies. Serrano et al. (1992) has reported that physiological (stomatal conductance and photosynthetic rates) and growth parameters (leaf area) were not affected when the threshold soil MP to trigger irrigation was lowered from -0.01 to -0.03 MPa (-10 to -30 kPa).

Similarly, the effect of the DI1 treatment on yield was not significant, with the only exception being the significant effect observed in the greenhouse study during year 2 in ‘Sweet Charlie’. Despite this non-significance, yield declines attributed to the DI1 treatment are most likely biologically significant. Yield reductions averaged 8.7 and 22.9% for ‘Chandler’ in the field and greenhouse studies, respectively. For ‘Sweet Charlie’, the average yield decline due to the DI1 treatment in the greenhouse studies was 19.6%. Similarly, a 16.8% reduction in the yield of ‘Camarosa’ was observed in the greenhouse study in year 2.

The control treatment applied significantly more water than all DI treatments in the field studies; whereas in the greenhouse studies water applications were significantly more than the DI2 and DI3 treatments but not DI1. Irrigation WUE values observed in the field study in year 1 were very similar between the control and DI treatments. In year 3, significantly higher WUE was observed for all DI treatments compared to the control treatment. However, these results are likely due to the increased yield observed in the DI treatments as a result of significant rain events. Due to the proportional yield losses observed for the DI treatments as a result of decreasing water applications, there were no improvements in CWP of the three strawberry cultivars in the greenhouse studies.

An enterprise crop budget for strawberry production in California (Bolda et al., 2016) was used to compare results observed in the field studies by making projections for irrigation application and yield of the control and DI treatments. The crop budget used was based on the typical strawberry production practiced in the Central Coast Region of California – Santa Cruz and Monterey counties - using plasticulture. As opposed to the typical strawberry season for June-bearing cultivars in the mid-Atlantic region, year-round strawberry production occurs in this region of California, enabling more harvest than other regions of the country. A harvest period lasting from April to early October is assumed in the budget. A summary of the production costs, yield and returns are given in Table 3.15. Irrigation costs accounted for a very small fraction (1.4%) of the total cost, with harvest costs making up roughly two-third (66.2%) of the total cost of production. Cost of irrigation water according to the enterprise budget was $22.50 per acre-inch.

Yield (g/plant) and irrigation application (L/plant) of ‘Chandler’ in the control and DI treatments in the field studies were converted to per acre basis considering 21,780 plants per acre, the planting density considered in the enterprise budget (Bolda et al., 2016). Typical planting density for strawberry plasticulture in the mid-Atlantic region is 17,500 plants per acre (Poling, 2015). In order to account for differences in yield potential due to regional differences, the irrigation application and yield values obtained in the field studies were assumed to double. Returns are calculated based on the same price considered in the enterprise budget ($1.25 per lb). Prices will most likely be higher however, especially for small scale growers (ex. With pick your own operations) where quality attributes such as individual fruit size are very critical and can attract higher prices (Gallardo et al., 2015). As the effect of incremental drought stress on individual fruit weight was not significant for the field studies, similar prices were assumed for the control and DI treatments.

Further production assumptions and costs from the enterprise budget were maintained. This analysis is conducted based on the average results observed during the field studies in year 1 and3. Projections of irrigation water and total costs, yield and returns for the control and DI treatments are given in Table 3.16.

Table 3.15. Summary of enterprise budget for strawberry production in the Central Coast Region of California – Santa Cruz and Monterey counties (from Bolda et al., 2016)

Operation	**Irrigation Volume (acre-inch)**	**Operation Time**	**Cash and Labor Costs per Acre ($)**					
			Labor Cost	**Fuel Cost**	**Repair Cost**	**Material Cost**	**Rental Cost**	**Total Cost**
Cultural:								
Sprinkler irrigation - pre plant	1	1.3	55.00	8.00	3.00	23.00	0.00	$89.00
Sprinkler irrigation - post plant	2.5	1.8	78.00	11.00	3.00	56.00	0.00	$148.00
Drip irrigation - season	24	10.5	169.00	0.00	0.00	540.00	0.00	$709.00
Total irrigation costs	**27.5**	**13.6**	**302.00**	**19.00**	**6.00**	**619.00**	**0.00**	**$946.00**
Other cultural costs		174.8	3,205.00	232.00	115.00	7,298.00	4,356.00	15,205.00
Total cultural costs		188.3	3,507.00	251.00	121.00	7,917.00	4,356.00	16,151.00
Total harvest costs		7.7	21,025.00	115.00	61.00	11,918.00	11,690.00	44,809.00
Interest on operating capital at 4.25%								1,296.00
Total operating costs		196.0	24532.0	366.0	182.0	19835.0	16046.0	62,256.00
Total cash overhead costs								4,901.00
Total non-cash overhead costs								517.00
Total costs per acre								$67,674.00
Total yield – 56,000 lbs per acre								
Gross returns @ $1.25 per lb								$70,000.00
Net returns per acre								**$2,326.00**

The analysis conducted indicated that implementation of deficit irrigation in strawberries leads to substantial declines in yield, and hence consequent economic losses. The DI2 and DI3 treatments resulted in negative returns (losses), amounting to 5.5 and 12.2 %. The reduced irrigation application in DI2 and DI3 resulted in savings of 31.3 and 37.3% in terms of total irrigation costs compared to the control treatment. However, irrigation costs accounted only for a very small fraction of the total cost (0.65 and 0.62% for the DI2 and DI3 treatments, respectively). The yield reductions associated with DI2 and DI3 on the other hand resulted in $11,254 and $15,767 in lost revenue, which were 16.8 and 23.5% of the total cost, respectively. The DI1 treatment had a net return (profit) of $1,096 (1.6%). The lost revenue associated with DI1 compared to the control treatments was $6,458.

Table 3.16. Comparison of costs and returns for the control and deficit irrigation treatments based on enterprise crop budgets

Trt.	**Irrigation Volume (acre-inch)**	**Cost of Water**	**Cost of Irrigation**	**Total Cost**	**Total Yield (lbs/acre)**	**Total Returns**	**Net Return**
Cont.	16.6	374	572	$67300	59781	$74,726	$7,426
DI1	12.9	290	444	$67172	54614	$68,268	$1,096
DI2	12.7	285	435	$67163	50778	$63,472	($3,691)
DI3	12.1	272	416	$67144	47167	$58,958	($8,186)

The control irrigation treatment resulted in a higher net return ($5,100 or 219.3%) as compared to the estimated profit from the enterprise crop budget. Water applications however were 65.5% higher in the crop budget estimates compared to the control treatment, resulting in an increase in irrigation cost of $374. These values are reasonable as typical irrigation practices in the area are based on timed schedules and without soil moisture status measurements. The yield values observed in the control treatment are likely overestimated however, with higher yields likely in the crop budget estimates. Nevertheless, these results indicate that comparable yields to growers can be obtained by using soil moisture status measurement based approaches such as the one implemented in this study while still using significantly less water (Gendron et al., 2018).

3.4. Conclusions

The incremental drought stress imposed by the DI treatments in the field and greenhouse studies revealed the sensitivity of strawberry plant growth and yield to drought stress. The high sensitivity of stomatal conductance, and by extension yield, to relatively mild drought stress without effect on leaf water potential indicates that strawberry has isohydric properties. The effect of drought stress on plant growth parameters on the other hand showed that it is rather cumulative, with growth differences that were not significant during the early stages of plant growth becoming significant later on.

Effect of incremental drought stress on yield was due to reduction in leaf surface area (under relatively low drought stress), and due to both reduction in assimilation surface and assimilation rate (under mild and moderate stress). The number of fruit per plant was significantly affected under mild and moderate drought stress; whereas the effect on individual fruit mass was less pronounced. This shows a regulation mechanism to drought stress (decrease in the number of fruit) that allows strawberries to maintain fruit size by allocating resources to only a smaller number of fruit.

Improvements in the irrigation WUE or CWP of strawberries due to DI was not significant. DI treatments were accompanied by proportional yield declines, resulting in

WUE/CWP values that were very similar to the control treatment. However, analysis of costs and returns based on enterprise budgets revealed that even significant improvements in WUE/CWP were likely not economically beneficial due to the high losses in revenue associated with reduced yields. However, the results obtained showed that irrigation management based on monitoring the real-time moisture status of soils and soilless substrates is a strategy that can be adopted to meet plant water demands, and can significantly improve current irrigation practices.

In addition, economic gains due to any fruit quality improvements that can be obtained as a result of reduced irrigation application are negligible and significantly outweighed by resulting yield losses. Thus, while reduced irrigation can lead to increases in the concentration of some desirable compounds such as monosaccharides (fructose and glucose), antioxidants and phenolics (Terry et al., 2006) and taste-related compounds such as sugars and acids (Terry et al., 2006; Bordonaba and Terry, 2010), the economic implications of DI means its adoption is very unlikely by growers.

Chapter 4. Optimizing Row Cover Use in Strawberry Production in the mid-Atlantic Region

4.1. Introduction

Row covers are generally plastic materials that are made from clear polyethylene, from fabric-like flexible spunbonded polyester, or spunbonded polypropylene (Wells, 1996). They are flexible, transparent or semi-transparent materials, and are applied to single or multiple rows of plants in order to enhance crop growth and yield by increasing soil and air temperature, protect from frost and reduce wind damage (Hochmuth et al., 2015). The polyethylene based covers can be clear or pigmented, are usually installed over support structures such as high and low tunnels, and can be vented automatically through pre-installed slits or circular perforations (Hochmuth et al., 2015).

The fabric-like spunbonded covers are lightweight (0.3 to 1.75 oz.yd^{-2}), porous and fully or semi-transparent materials, allowing adequate light penetration for crop growth (Wells, 1996). Since they can be deployed on growing plants without supplementary support, they are also refereed as floating row covers (FRC; Figure 4.1). Depending on weight, their use can vary from insect control (0.3 oz.yd^{-2}) to growth enhancement and freeze protection to about 28 ^{o}F (0.5 to 0.6 oz.yd^{-2}), and freeze and winter injury protection (1.0 to 1.75 oz.yd^{-2}) (Wells, 1996).

For strawberry plasticulture growers in regions that experience cold winters or regular frost events (such as the North East, mid-Atlantic and South East regions of the US), costs associated with freeze (winter) and frost (early spring) protection of plants are a significant portion of the overall production costs (Poling 1993). Thus, FRC have been widely adopted by strawberry growers for freeze/frost protection of plants during winter and early spring (Hochmuth et al., 1993). Under severe weather conditions, a combination of row covers and sprinkler irrigation has been reported to be the most effective in providing adequate freeze protection, to reduce damage to strawberry plants and yield (Poling et al., 1991; Turner et al., 1992; Hochmuth et al., 1993).

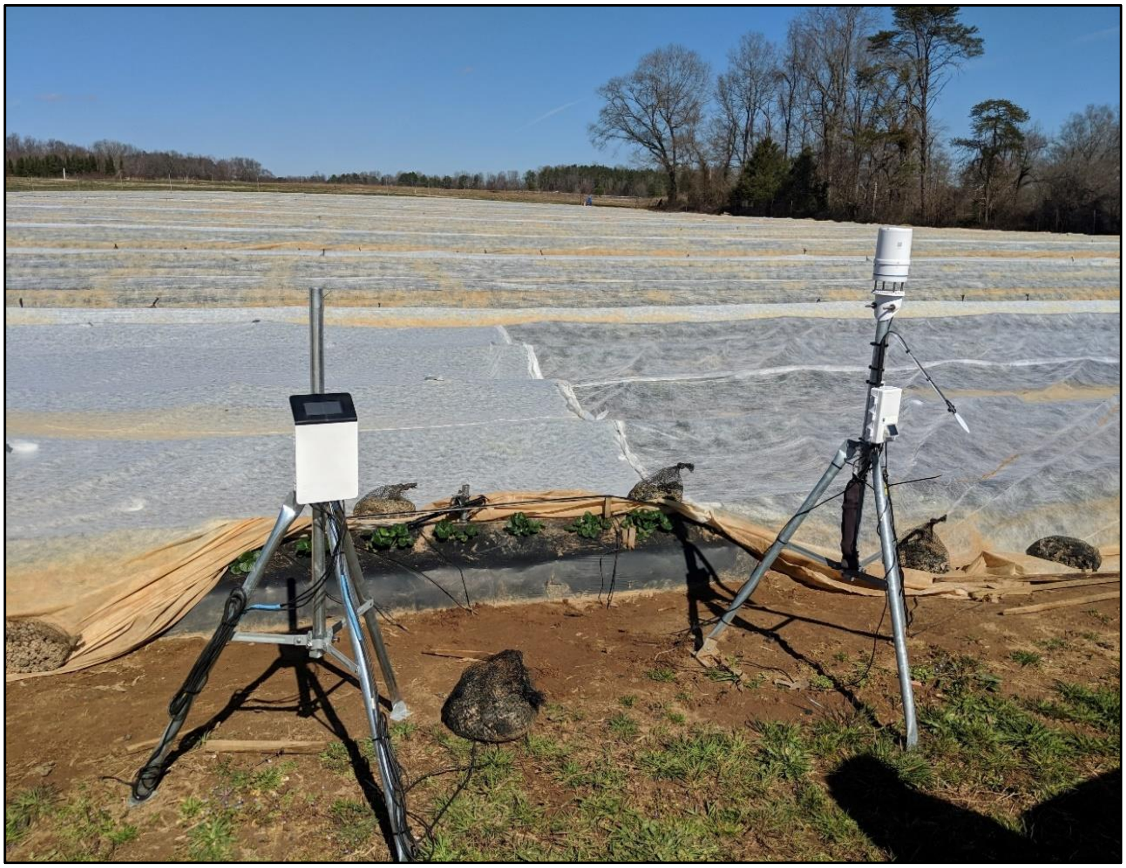


Figure 4.1. Floating row covers deployed in a commercial strawberry field (Courtesy of B. Poling and J. Lea-Cox, unpublished study).

FRC increase canopy temperatures by allowing light penetration with minimum reflectance and retaining long-wave re-radiation from the soil overnight (Wells, 1996). Therefore, they have traditionally been used by strawberry growers to aid plant growth and development during the fall, enabling earlier harvests and improved yields (Hochmuth et al., 1986; Gent, 1990; Poling et al., 1991). This functionality has also led to the use of FRC as intervention tools by strawberry growers to adjust for delayed planting and unfavorable growth conditions during fall (Pattinson et al., 2013). FRC can increase degree day accumulation for crop establishment in the fall, and thereby enhancing floral initiation and differentiation in the late fall (Pattison et al., 2013). The temperature improvements under row covers not only vary based on the type of cover (i.e., their weight/thickness) but also the prevailing environmental conditions and light penetration (Poling et al., 1991; Turner et al., 1992).

The temperature moderation provided by row covers is especially important during frost events during spring because even slightly improved temperatures in the plant canopy below the cover can be critical. This is especially true if plants have semi- or fully-opened flower blossoms as they are the most susceptible to cold temperatures (generally in the range of 28 -30 ^{o}F) (Poling, 2005); whereas other growth stages (buds inside the crown to emerging buds) can be hardy and resist cold temperatures in the teens and twenties (Poling, 2015). In addition, by retaining heat within the canopy FRC also moderate temperatures in the soil profile, which is important for variety of biochemical and physiological process taking place in the soil.

FRC alters the canopy temperature dynamics, as noted above. These changes in environmental conditions immediately surrounding the plant have important implications when proper FRC use is not followed. For example, warmer air temperatures that could occur in late winter/early spring can lead to very high temperatures under FRC (greater than 90 °F; Poling and Lea-Cox, unpublished data) during sunny days in February and March. FRC left on strawberry fields under such conditions could lead to quicker de-acclimation of plants to cold temperature and enhanced growth, making plants more susceptible to early spring frosts. Similarly, deploying FRC over plants during flowering decreases pollination activity of insects, thereby leading to lower yields and deformed fruits (Poling, pers. comm.)

Warmer temperatures (generally 60 ^{o}F and above) and moisture create conducive conditions to the plant pathogens that cause the two primary diseases affecting the strawberry industry in the US – botrytis fruit rot and anthracnose fruit rot (Wilson et al., 1990). The fungal species causing these diseases (*Botrytis spp.* and *Colletotrichum acutatum,* respectively) are commonly present, due to the latent infection of nursery plants (Oliveira et al., 2017; Smith, 2008; Calleja et al., 2013). Thus, strawberry plasticulture growers need to monitor environmental conditions (rainfall, temperature, relative humidity and leaf wetness) to reduce the development of diseases with causative temperatures under FRC (Mengjun Hu, *pers. comm.*).

FRC costs can be a significant part of overall production costs, since they have relatively short lifetimes due to deterioration from ultraviolet radiation and wind, and may need to be replaced every 2-3 years. Furthermore, the labor costs required to deploy and remove FRC are high and may be very difficult under windy or very cold conditions.

While canopy temperature improvements provided by FRC have been established, the amount of canopy temperature elevation under the cover and at different soil depths, in relation to ambient temperatures are not known. This knowledge is critical when making decisions to deploy or remove FRC, for an effective use that minimizes the unintended negative impacts of FRC. Knowledge of the level of soil temperature moderation gained by FRC use across the profile of strawberry plasticulture beds is essential and could be used for creating strategies for their use as intervention techniques by plasticulture growers.

As soil water content plays a physical role in heat transfer within soils, it could have major effect on the efficacy of FRC. For example, a dry soil could negate any potential benefit of deploying FRC before freeze/frost events. An understanding of the function soil water status plays in soil temperature moderation of FRC could be utilized to develop better strategies for frost protection, which could be significant for strawberry plasticulture growers in the mid-Atlantic region.

The goal of this study was therefore to determine the extent of microclimate modification provided by FRC in order to improve their use and management in strawberry production in the mid-Atlantic region, and to determine the implications of soil moisture on their effectiveness. The specific objectives of the study were to:

- compare canopy temperature differences in strawberry plots with and without FRC,
- compare soil temperature differences (at three depths) in strawberry plots with and without FRC, and
- compare soil temperature differences at various soil moisture levels in strawberry plots with and without FRC.

The three hypotheses tested in this study were:

1. H_O: FRC do not affect canopy temperature measured in strawberry plasticulture beds.

   H_A: There is a significant effect of FRC on canopy temperature measured in strawberry plasticulture beds.
2. H_O: FRC do not affect soil temperature measured at various depths of strawberry plasticulture beds.

H_A: There is a significant effect of FRC on soil temperatures measured at various depths of strawberry plasticulture beds.

3. H_O: Soil moisture does not affect soil temperature measured in strawberry plasticulture beds with or without FRC.

   H_A: There is a significant effect of soil moisture on soil temperature measured in strawberry plasticulture beds with or without FRC.

4. H_O: There is no interaction effect of row covers (with or without FRC) and soil moisture on soil temperature measured in strawberry plasticulture beds.

   H_A: There is a significant interaction effect of row covers (with or without FRC) and soil moisture on soil temperature measured in strawberry plasticulture beds.

4.2. Materials and Methods

4.2.1. Site Description and Experimental Design

A study was carried out at the University of Maryland's Wye Research and Education Center (38^o 55' N, 76^o 9' W) to determine the effect of row covers on canopy temperature and soil temperature at three depths in the raised strawberry plasticulture beds. The study was conducted in the 2015-2016 growing season and was laid out in a completely randomized design (CRD) with three replications.

4.2.2. Sensor Installation

At the beginning of the 2015/16 season, 5TM sensors (METER Group Inc., Pullman, WA) were installed in raised strawberry beds at the study site. The sensors (Figure 4.2 A) - equipped to measure both soil temperature and VWC - were inserted at three depths - 5, 10 and 15 cm from the surface - in strawberry plots that were covered (FRC) for a four week period (November 6 – December 4, 2015) with a 1.2 oz.yard^{-2}

Atmore Gro-Guard row covers (Berry Hill Irrigation, Buffalo Junction, VA). Similarly, 5TM sensors were installed at three depths in plots that remained uncovered (NoFRC) during the fall growing season. All sensors were pushed into the beds horizontally and placed in the root-zone of strawberry plants by auguring the soil (Figure 4.2 B).

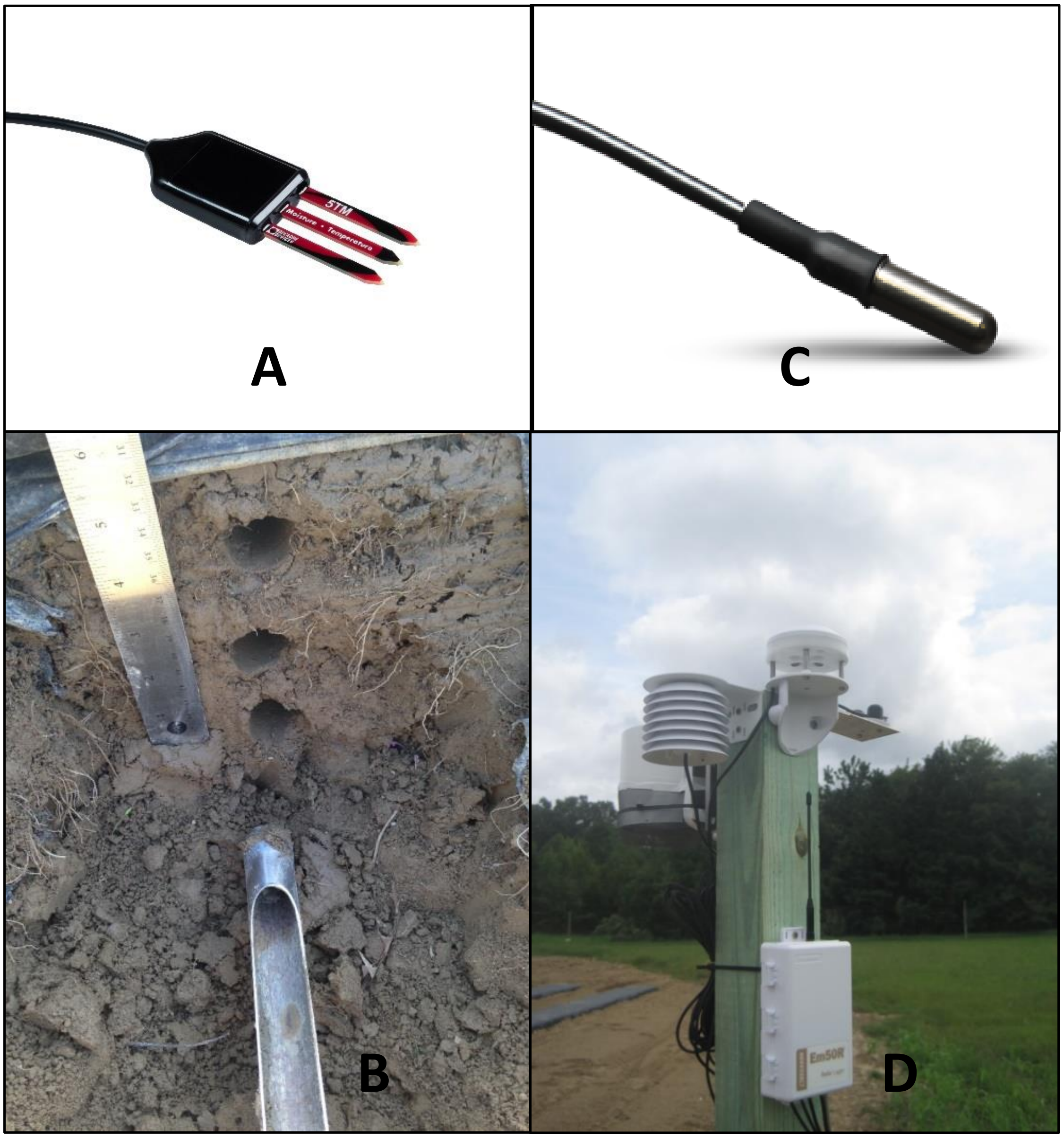


Figure 4.2. The 5TM sensor used to measure soil temperature and volumetric water content of the plots with and without floating row covers (A). Holes were augured at three depths (5, 10 and 15 cm) and sensors were pushed horizontally and placed in the root zone (B). The ECT/RT-1 sensors used to measure canopy temperatures (C), and the on-site weather station at the Wye Research and Education Center.

In addition, canopy temperatures in the FRC and NoFRC plots were measured using ECT/RT-1 temperature sensors (METER Group Inc., Pullman, WA) (Figure 4.2 C). Environmental conditions at the site were also measured throughout the study period using on-site weather station (Figure 4.2 D). The station was equipped with a PYR sensor (solar radiation), QSO-S sensor (photosynthetically active radiation PAR), VP-3 sensor (temperature, relative humidity and vapor pressure deficit), DS-2 sonic anemometer (wind speed and direction) and ECRN-100 rain gauge (precipitation) (METER Group Inc., Pullman, WA) installed at approximately 2.5 m height.

Soil temperature and VWC (at each of the three depths), canopy temperature, and environmental conditions at the site were collected from November 6, 2015 06:00 pm to December 5, 2015 10:00 am on a 5-minute basis using Em50R data loggers (METER Group Inc., Pullman, WA).

4.2.3. Data Analysis

Minimum, maximum and average temperatures recorded at the plant canopy level and at three depths (5, 10 and 15 cm) in the soil profile were determined from the 5-minute data, or both FRC and NoFRC plots. The ambient minimum, maximum and average air temperature measured by the weather station for the duration of the study was also calculated. To determine the effect of FRC in terms of the cumulative effect of temperature above the minimum/threshold required for crop growth, the growing degree days (GDD) corresponding to the ambient temperature and canopy temperatures (for both FRC and NoFRC plots) were calculated using the formula given below.

$$GDD = \sum_{t=i}^{n} \left((Ti - 50) \times \frac{5}{1440} \right) \quad \text{(Equation 4.1)}$$

Where GDD = Growing degree days, and Ti = Temperature (^{o}F) at time i.

The base temperature (the threshold temperature below which plant growth is affected) was set at 50 ^{o}F. Similarly, the maximum temperature above which plant growth is affected (and hence will not contribute to GDD) was set at 90 ^{O}F. To determine the cumulative effect of FRC on soil temperature, a similar approach as above was followed by calculating GDD using the same formula as it can be used as a proxy to the amount of heat added/subtracted from the soil.

To identify the effect of row cover (RC), the temperature measurement depth (MD), and the interaction effect of these two factors (RC*MD) on the minimum, maximum, and average temperatures and GDD, a repeated-measures analysis was conducted using the Proc Mixed procedure in SAS (SAS Inc., Cary, NC). Least square means differences were used for mean comparisons with Tukey adjustment and a 0.05 significance level.

In order to understand the interaction of soil moisture with row cover, the three temperature measurement locations were ordered according to their soil moisture into low, medium and high. This categorization was based on the naturally existing variation and used the VWC data of the 5TM sensors. The average VWC over the study period for these categories were 27.6, 29.1 and 31.3% for FRC plots and 27.6, 28.5 and 31.3% for NoFRC plots, respectively for low, medium and high.

The minimum, maximum, and average soil temperature measured, and GDD accumulated under the three soil moisture categories during the study period were determined. A factorial analysis was conducted using the Proc Mixed procedure in SAS to determine the effect of row cover (RC), soil moisture (SM), and the interaction between the two factors (RC*SM) on the minimum, maximum and average soil temperatures and GDD. The three soil depths under each measurement site were considered pseudo-replicates in the analysis. Least square means differences were used for mean comparisons with Tukey adjustment and a 0.05 significance level.

4.3. Results and Discussions

4.3.1. Effect of FRC on Canopy and Soil Temperatures

The minimum, maximum and average temperatures measured and the GDD accumulated at the canopy level and three soil depths of the raised strawberry beds in the FRC and NoFRC plots are given in Table 4.1. There was a significant interaction effect of row cover and measurement depth on the minimum temperatures measured under the FRC and NoFRC plots. The interaction effect significantly increased the minimum temperatures measured at the three soil depths compared to the canopy in both FRC and NoFRC plots. Similarly, there was a significant interaction effect of row cover and measurement depth on the maximum temperature measured under the FRC plots. The maximum temperature measured in the canopy was significantly higher than all three soil depths in FRC plots. However, there was no significant difference between the maximum temperature measured in the canopy and three soil depths in the NoFRC plots.

There was no significant interaction effect of row cover and measurement depth on the average temperature measured in the FRC and NoFRC plots. Row cover treatment significantly increased the average temperature measured in the canopy and three soil depths of the raised beds. There was a 3.5 and 5 ^{o}F increase in the average temperature, measured in the canopy and soil (average for three depths), respectively, under FRC plots as compared to NoFRC plots. The effect of measurement depth was significant, with the average temperature measured in the canopy of FRC plots significantly lower than that of all three soil depths. However, there was no difference between the average temperature measured in the canopy and three soil depths of the NoFRC plots.

Table 4.1. The minimum, maximum and average temperatures measured and growing degree days (GDD) accumulated in the canopy and at three soil depths (5, 10 and 15 cm) of the raised strawberry beds with floating row covers (FRC) and without (NoFRC). Means followed by different letters within columns are significantly different ($P<0.05$).

Row Cover	**Depth (cm)**	**Temperature (^{O}F)**			**Growing Degree Days**
		Minimum	**Maximum**	**Average**	
Air Temp.	__	29.3	71.6	50.4	104.2
NoFRC	Canopy	34.1±1.4e	67.1±0.3b	50.5±0.3c	90.6±1.8b
	5	39.0±0.5d	67.6±0.2b	51.3±0.1c	84.9±0.9b
	10	39.5±0.2d	67.8±0.0b	51.4±0.1c	84.1±1.0b
	15	40.3±0.1cd	67.5±0.3b	51.7±0.2c	84.6±3.2b
FRC	Canopy	33.9±0.6e	87.4±1.7a	54.0±0.1b	166.9±0.3a
	5	43.5±0.1bc	73.9±1.6b	56.4±0.4a	186.2±9.4a
	10	45.1±0.1ab	71.7±0.8b	56.5±0.4a	187.3±10.5a
	15	46.6±0.2a	70.8±0.8b	56.7±0.5a	189.3±11.7a
P-value	RC	0.002	0.0005	< 0.0001	0.0002
	MD	< 0.0001	0.0004	0.007	0.892
	RC*MD	0.0005	0.0002	0.287	0.590

Similarly, there was no significant interaction effect of row cover and measurement depth on the GDD accumulated under the FRC and NoFRC plots. Row cover treatment significantly increased GDD, resulting in an increase of 84.2% (canopy) and 122% (average of three soil depths) in FRC plots compared to NoFRC plots. There was no significant effect of measurement depth on GDD in the FRC and NoFRC plots. The GDD accumulation at canopy level and in the soil (average for three depths) under both FRC and NoFRC plots in relation to the ambient air is given in Figure 4.3.

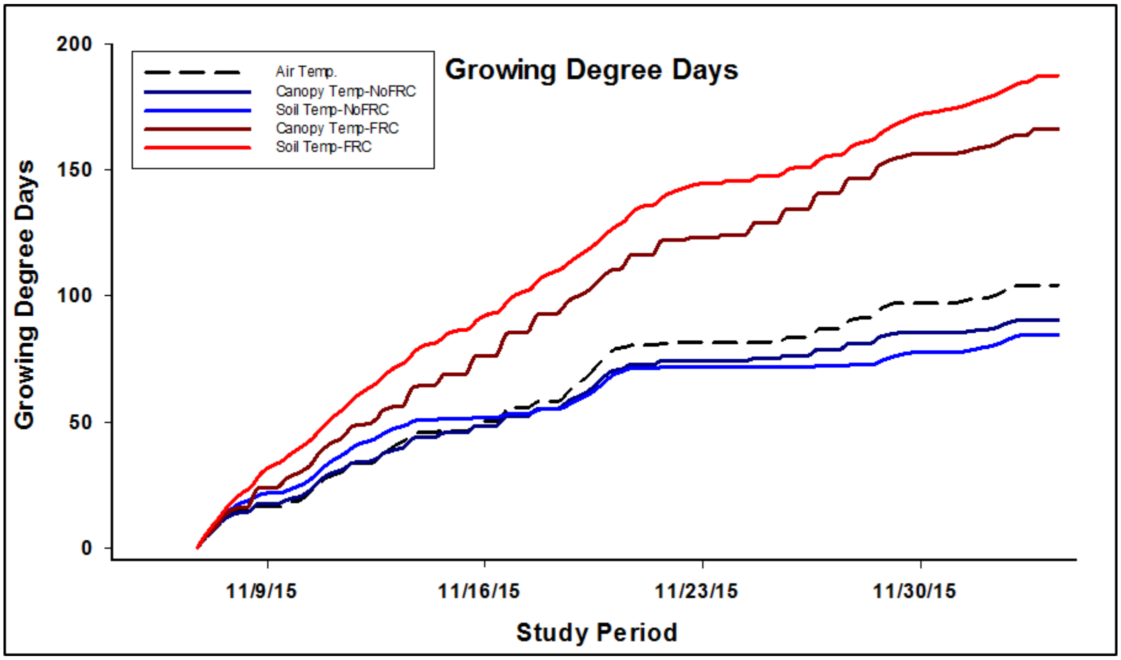


Figure 4.3. Growing degree days (GDD) accumulation at canopy level and in the raised strawberry beds (average for three depths – 5, 10 and 15 cm) with floating row covers (FRC) and without (NoFRC), in comparison with the GDD for the ambient air during the fall study period

The application of FRC modifies environmental conditions and create a unique microclimate in the plant canopy. The minimum temperature measured in the canopy of the FRC plots was 4.6 ^{o}F higher than the ambient air. Transfer of heat from the warmer soil below at night contributes to higher canopy temperatures compared to the ambient air at night. The maximum temperature measured in the FRC plots on the other hand was much higher (15.8 ^{o}F) than the maximum temperature of the ambient air. This is a due to the retention of outgoing longwave radiation under the canopy of FRC plots during the day, a major attribute of FRC that makes them useful in agricultural applications. Similarly, the average temperature measured in the canopy of the FRC plots was 3.6 ^{o}F higher than that of the ambient air. This temperature increase is critical particularly during the fall growing period with less than optimum growing conditions. More importantly, the 3.6 ^{o}F higher average temperature in the FRC plots translated to an increase in GDD of 62.7 units (60.2%) over that of the ambient air for the fall study period, showing the potential of FRC in altering adverse growing conditions.

The canopy temperature increase provided by FRC during the fall growing season is critical, especially when ambient air temperatures rapidly decline. Fall growing conditions are strongly correlated to increase number of branch crowns and hence yields in the spring (Pattison et al., 2013). In short day (June-bearing) cultivars, flower bud initiation and development have higher threshold temperature requirements (59 ^oF) than crown growth and development which occurs at temperatures above 50 ^oF (Strand 1994). When temperatures during the fall growing season are marginally lower than the critical temperature required for growth, a slight increase in canopy temperature as a result of FRC maintains crop growth without interruption. While the average temperature increase due to the use of FRC in the fall growing period observed in this study was 3.5 ^oF, the temperature increases during the day period are likely of a higher magnitude. More importantly, the temperature increases due to FRC translated to a significant increase in GDD over its fall application period. Such GDD increases could more than compensate for delayed planting dates or adverse growth conditions during the growing season, making FRC an important tool to effectively counter such conditions.

The increase in temperature provided by FRC also forms the basis for use in freeze and frost protection of strawberries. Poling et al., (1991) reported improvements in canopy temperatures ranging from 1.8 -3.6 ^oF for winter application of FRC. Similarly, Fernandez (2001) reported a 2.7 ^oF increase in average temperature for a 1.25 $oz.yd^{-2}$ row cover applied during the fall. The 3.5 ^oF average temperature increase obtained in this study due to the use of FRC is comparable to these results. Additional protection can be obtained by using heavy-weight floating row covers. Hochmuth et al. (2005) reported that a 1.5 oz.yd^{-2} row cover protected strawberries exposed to temperatures below 20 °F.

4.3.2. Effect of Soil Moisture on Soil Temperature

The minimum, maximum and average soil temperatures measured and GDD accumulated in the raised strawberry beds under three soil moisture conditions (low, medium and high) in the FRC and NoFRC plots are given in Table 4.2. There were no significant interactive effects between row cover and soil moisture on the minimum, maximum and average temperatures measured and GDD accumulated in the raised strawberry beds. Similarly, there were also no significant effects of soil moisture on the minimum, maximum and average soil temperatures measured and GDD accumulated.

Table 4.2. The minimum, maximum and average soil temperatures measured and growing degree days (GDD) accumulated in the raised strawberry beds with floating row covers (FRC) and without (NoFRC) as affected by three soil moisture conditions (low, medium and high). Means followed by different letters within columns are significantly different ($P<0.05$).

Row Cover	**Soil Moisture**	**Soil Temperature (^{O}F)**			**Growing Degree Days**
		Minimum	**Maximum**	**Average**	
NoFRC	Low	39.6±0.2b	67.3±0.1b	51.3±0.1b	81±1.3b
	Medium	40.2±0.1b	67.5±0.1b	51.5±0.1b	84±0.9b
	High	39.0±0.3b	68.1±0.1b	51.5±0.1b	88±1.3b
FRC	Low	44.8±0.4a	71.1±0.6a	56.0±0.1a	174±3.3a
	Medium	45.4±0.4a	70.5±0.5a	56.3±0.4a	182±9.2a
	High	45.0±0.3a	74.8±1.0a	57.3±0.2a	207±4.9a
P-value	RC	<0.0001	0.0008	<0.0001	<0.0001
	SM	0.617	0.1303	0.294	0.226
	RC*SM	0.832	0.351	0.496	0.491

The effect of soil moisture on the measured parameters were not statistically significant due to the small natural variation in VWC observed at the three sites in both

FRC and NoFRC plots. The observed results however have biological significance. Under the FRC plots, improved average soil temperature was observed in the raised beds as soil moisture increased. The 1.3 °F average temperature increase observed (for the high soil moisture compared to low soil moisture) can be biologically significant for a number of physiological, chemical and biological processes taking place in the soil. The small increase in soil temperature with moisture also translated to a relatively higher increase in GDD accumulation, which is biologically important as soil moisture plays a crucial role in serving as heat repository in the soils (Abu-Hamdeh, 2002).

The positive correlation (Figure 4.4) observed between soil moisture and soil temperature indicate that application of irrigation before frost events could play a critical role in increasing heat retention and heat capacity in the soil. More importantly, soil moisture is an important means of heat transfer in the soil (Kane et al., 2001). Thus, irrigation applied before frost events during the day can play a role in transferring heat to deeper soil profiles. This could be particularly important for plant root as the temperature cushion provided can help them maintain their functions during frost events.

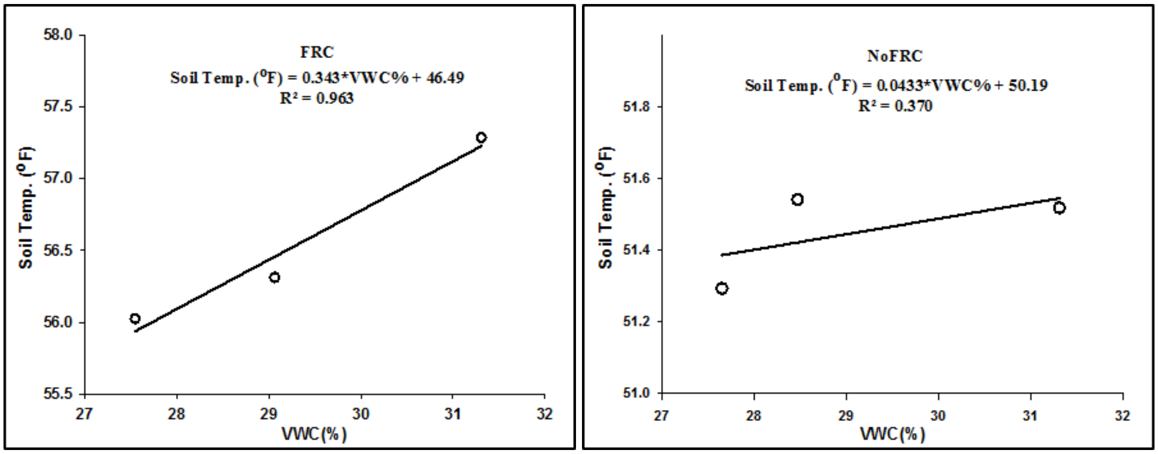


Figure 4.4. Correlation between soil temperature and soil moisture in the raised strawberry beds with floating row covers (FRC) and without (NoFRC) under three soil moisture categories (low, medium and high) based on 5TM sensors volumetric water content data. The explained variation (R^2) was 96.3% (FRC) and 37.0% (NoFRC).

4.4. Conclusions

The use of FRC significantly increased canopy temperatures in raised strawberry beds, by 3.5 ^{o}F on average. Such temperature improvements can be critical, especially during the fall growing period when ambient air temperatures are generally declining. This average temperature increase in the canopy due to the use of FRC translated to a significant increase in GDD (84.2%) during this fall study period. Such GDD increases could more than compensate for adverse growth conditions during establishment, making FRC an effective tool for growers to compensate for lower temperatures or late planting. The canopy temperature increase provided by FRC also has importance in freeze and frost protection of strawberries. Slightly improved temperatures under FRC can be critical in protecting strawberry plants from cold injury during sensitive growth stages.

The use of FRC also significantly improved soil temperatures in the raised strawberry beds. On average, soil temperature in the raised strawberry beds during the study period was increased by 5 ^{o}F. This increase is critical during the fall growing period as plants can extend their growth with soil temperature above 50 ^{o}F, without entering dormancy. Increased soil temperatures also ensures the continuation of important physical, chemical and biological processes taking place in the soil. Increase in soil temperature also has significance in freeze/frost protection of strawberries during winter and early spring.

Soil moisture had a positive correlation with soil temperature in FRC plots, which has implications for frost protection. Irrigation application to increase soil moisture before frost events, especially under FRC, can play a crucial role by increasing heat retention and heat capacity of the soil.

Chapter 5. Conclusions

To develop effective irrigation management in strawberry production, characterizing the physical properties of the growing media (soil/substrate) which determine water movement and availability to plants is important. An analysis of the three depths (0, 15 and 30 cm) in the raised strawberry plasticulture beds revealed slight increase in bulk density with depth that was accompanied by a proportional decrease in porosity. Differences were also observed in the particle size distribution, an increasing sand and decreasing silt content with soil depth. However, the water retention characteristic and saturated hydraulic conductivity the raised beds was uniform for the three depths studied. Similarly, differences in water retention and unsaturated hydraulic conductivity between three bulk densities of a commercial soilless peat : perlite substrate (0.095, 0.10 and 0.12 $g\cdot cm^{-3}$, respectively) were minimal.

The uniformity of physical properties in each growing medium is important and has practical implications for precision irrigation management. For example, uniformity considerations (both spatially and by depth) determine sensor placement (site selection) as well as the optimal number of sensors (i.e., resources) that are required to adequately characterize measurement variation. Uniformity of physical properties also translates to uniformity of moisture availability, drainage, aeration etc., which in return contributes to uniform plant canopy and healthy and productive plants.

Both the field and greenhouse studies showed that strawberry plants are very sensitive to drought stress, with declines in water availability in the range of -30 to -60 kPa significantly affecting plant physiology, growth and yield. Yield declines occurred as a result of decreased leaf area under slight deficit irrigation (DI1), and significantly decreased rate of assimilation under moderate and higher water deficits (DI2 and DI3). Thus, the DI treatments implemented in the study didn’t improve crop water productivity. There was no significant effect of incremental stress on any fruit quality parameter (pH, TA and TSS) of strawberries.

Deficit irrigation in strawberry production led to a significant loss in revenue as a result of these yield declines. Since the cost of irrigation (including the price of water) is only a fraction of total production costs, water savings did not compensate for lost revenue. Implementing deficit irrigation is therefore not recommended for commercial strawberry production. However, irrigation management that is based on real-time crop water demand (for example through soil moisture monitoring) can lead to reduction in irrigation application from current levels practiced by growers, without impacting revenue.

The use of floating row covers (FRC) on raised strawberry beds significantly increased the temperatures measured in the canopy and soil (at three depths), averaging 3.5 and 5 ^{o}F, respectively. Such temperature increases have implications, especially for crop establishment during fall, and freeze and frost protection during winter and early spring. The average temperature increases in the canopy and soil due to FRC also translated to a significant increase in degree day accumulation (GDD of 84.2 and 122%, respectively), quantifying the potential of FRC as a tool for growers. The positive correlation between soil moisture and soil temperature in FRC plots has important implications, as it shows the potential to influence soil temperature by applying irrigation before frost events, which increases heat retention and heat capacity of the soil.

Recommendations

Sensor networks could play a crucial role in strawberry production as they can be effectively used for both irrigation scheduling and row cover management. Use of advanced sensor networks in the ornamental industry in the US have been shown to reduce irrigation application (Belayneh et al., 2013) and nutrient leaching (Bayer et al., 2013), which will be useful to the strawberry industry. Similarly, advanced sensor networks (such as Ag-Zoom Software, Verdu, Spain) not only provide the means to monitor environmental conditions but can also integrate environmental data into more useful information (such as GDD, reference evapotranspiration, day light integral and plant available water), which can be directly used by growers for daily decisions. The alert capability by such networks will be useful especially during frost events when environmental conditions need to be monitored at critical times.

In addition, the use of sensor networks has been shown to provide a return on investment in a relatively short period of time in ornamental crops (Belayneh et al., 2013; Lichtenberg et al., 2013; Saavoss et al., 2016), and also strawberries (Gendron et al., 2018). Thus, the adoption of such systems by strawberry growers could be useful in addressing challenges and will contribute to a sustainable industry.

Appendix A: Differences within Soil and Substrate Samples

Table A.1. Comparisons between replicates of the three soil depths of the raised strawberry beds using the Kolmogorov-Smirnov two-sample test and Kruskal-Wallis rank sum test. Tests were based on water content data of replicates. The test statistic (KSa and χ^2) and corresponding P-values are provided. Significance level are: *p<0.05, **p<0.01, ***p<0.001.

Soil Depth	**Replicates Compared**	**Kolmogorov-Smirnov**		**Kruskal-Wallis**	
		KSa	**P-value**	χ^2	**P-value**
0 cm	Rep 1 v. Rep 2	2.13	0.0002***	11.00	0.0009***
	Rep 1v. Rep 3	2.13	0.0002***	11.00	0.0009***
	Rep 1 v. Rep 4	2.13	0.0002***	11.00	0.0009***
	Rep 2 v. Rep 3	1.71	0.0059**	6.73	0.0095***
	Rep 2 v. Rep 4	1.92	0.0013**	8.54	0.0035**
	Rep 3 v. Rep 4	1.28	0.0758	3.50	0.0613
15 cm	Rep 1 v. Rep 2	2.13	0.0002***	10.57	0.0012**
	Rep 1v. Rep 3	0.64	0.8079	0.05	0.8182
	Rep 1 v. Rep 4	1.07	0.2058	2.18	0.1396
	Rep 2 v. Rep 3	1.92	0.0013**	7.79	0.0053**
	Rep 2 v. Rep 4	2.13	0.0002***	10.57	0.0012**
	Rep 3 v. Rep 4	1.07	0.2058	1.17	0.2786
30 cm	Rep 1 v. Rep 2	1.07	0.2058	2.80	0.0940
	Rep 1v. Rep 3	1.07	0.2058	1.99	0.1580
	Rep 1 v. Rep 4	1.07	0.2058	3.03	0.0818
	Rep 2 v. Rep 3	0.21	1.0000	0.13	0.7180
	Rep 2 v. Rep 4	0.21	1.0000	0.01	0.9215
	Rep 3 v. Rep 4	0.21	1.0000	0.05	0.8182

Figure A.1. Observed water retention data (red circles) of three depths of the raised strawberry beds – 0 cm (A), 15cm (B) and 30 cm (C). The closed form van Genuchten model (1980) was fitted to the observed data (black line).

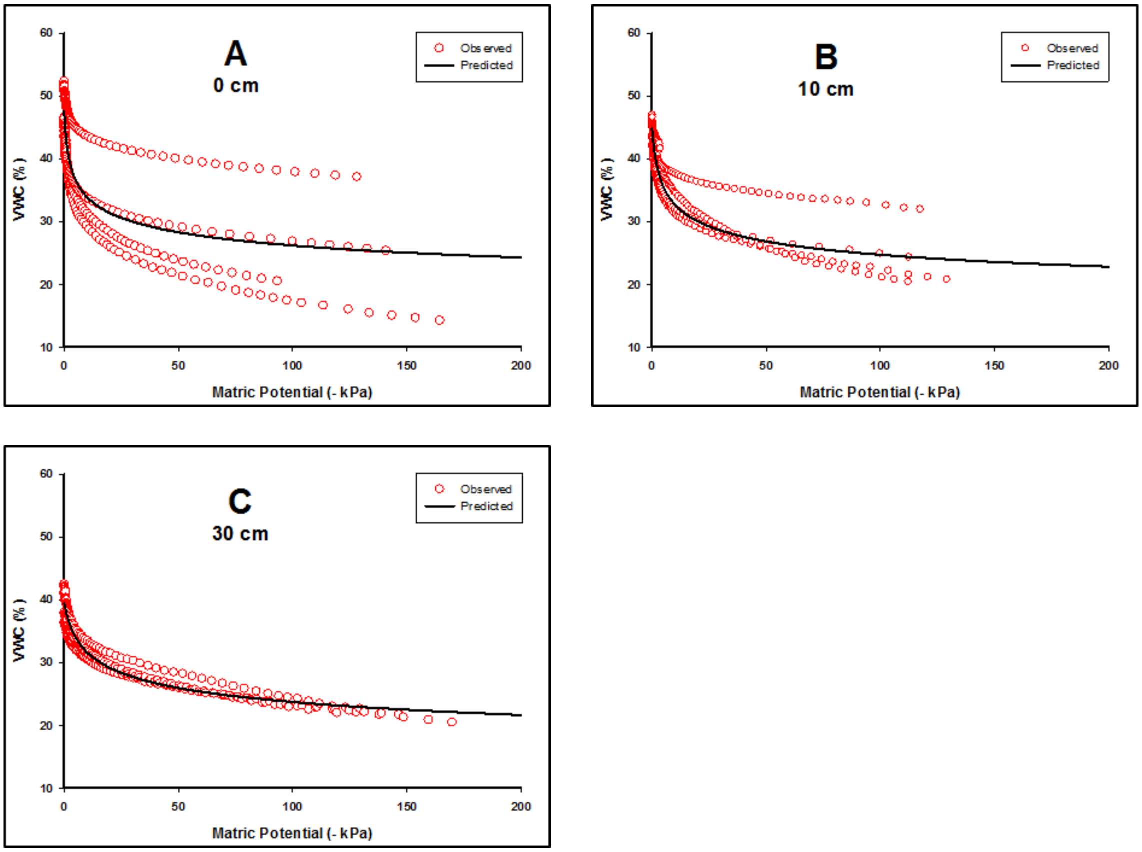
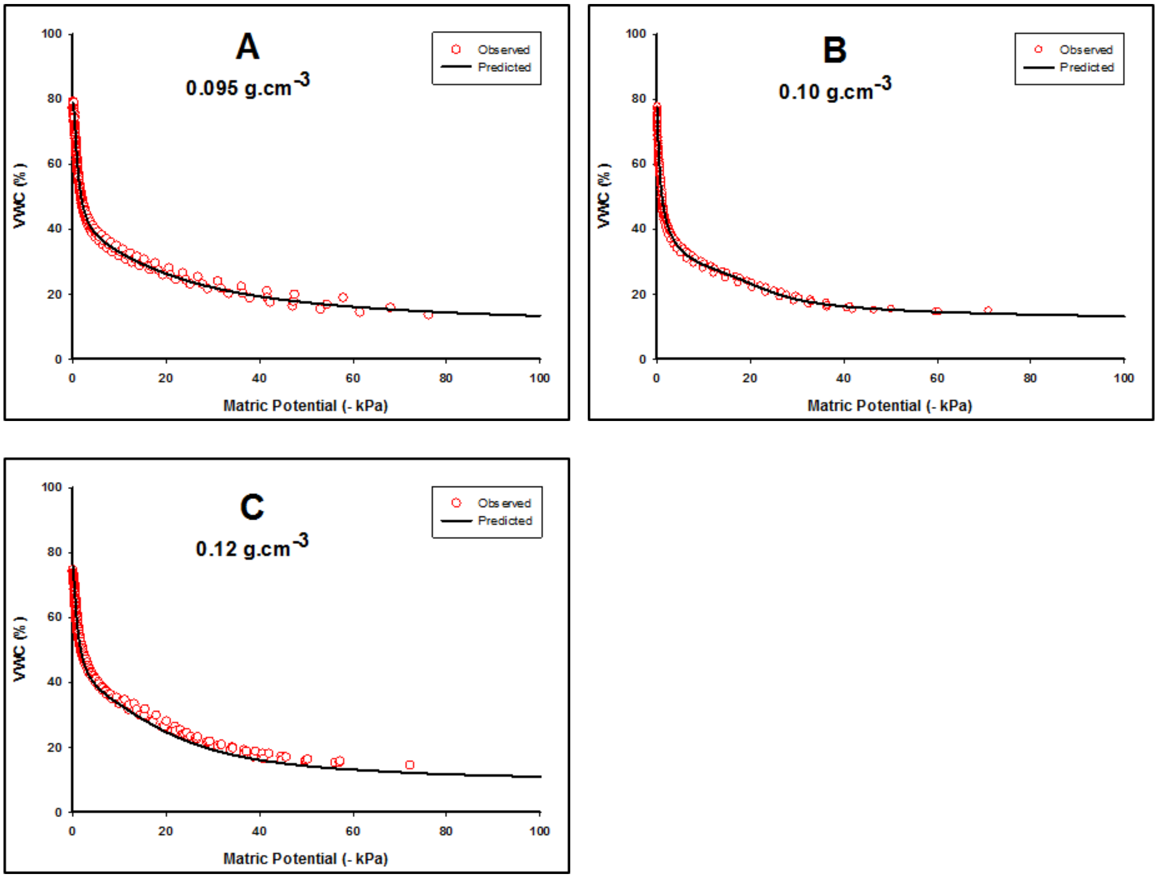


Table A.2. Comparisons between replicates of the three bulk densities of the LC1 substrate using the Kolmogorov-Smirnov two-sample test and Kruskal-Wallis rank sum test. Tests were based on water content data of replicates. The test statistic (KSa and χ^2) and corresponding P-values are provided.

Bulk Density ($g.cm^{-3}$)	**Replicates Compared**	**Kolmogorov-Smirnov**		**Kruskal-Wallis**	
		KSa	**P-value**	**χ^2**	**P-value**
0.095	Rep 1 v. Rep 2	0.853	0.461	1.174	0.279
	Rep 1 v. Rep 3	0.853	0.461	0.570	0.450
	Rep 2 v. Rep 3	1.066	0.206	1.993	0.158
0.10	Rep 1 v. Rep 2	0.213	1.000	0.130	0.718
	Rep 1 v. Rep 3	0.853	0.461	1.036	0.309
	Rep 2 v. Rep 3	0.640	0.808	0.570	0.450
0.12	Rep 1 v. Rep 2	0.426	0.993	0.027	0.870
	Rep 1 v. Rep 3	0.213	1.000	0.010	0.922
	Rep 2 v. Rep 3	0.426	0.993	0.010	0.922

Figure A.2. Observed water retention data (red circles) of three bulk densities of the LC1 substrate – 0.095 g.cm^{-3} (A), 0.10 g.cm^{-3} (B) and 0.12 g.cm^{-3} (C). The bimodal van Genuchten model of Durner (1994) was fitted to the observed data (black line).



Appendix B: Supplemental Material (Field Studies)

Figure B.1. MPS-6 sensor soil matric potential dynamics of the control and deficit irrigation treatments during treatment period of the field study in year 3 (n=4), and the daily precipitation received at the study site during the treatment period. Threshold matric potentials used to control irrigation treatments were -30 kPa (Cont.), -40 kPa (DI1), -50 kPa (DI2) and -60 kPa (DI3).

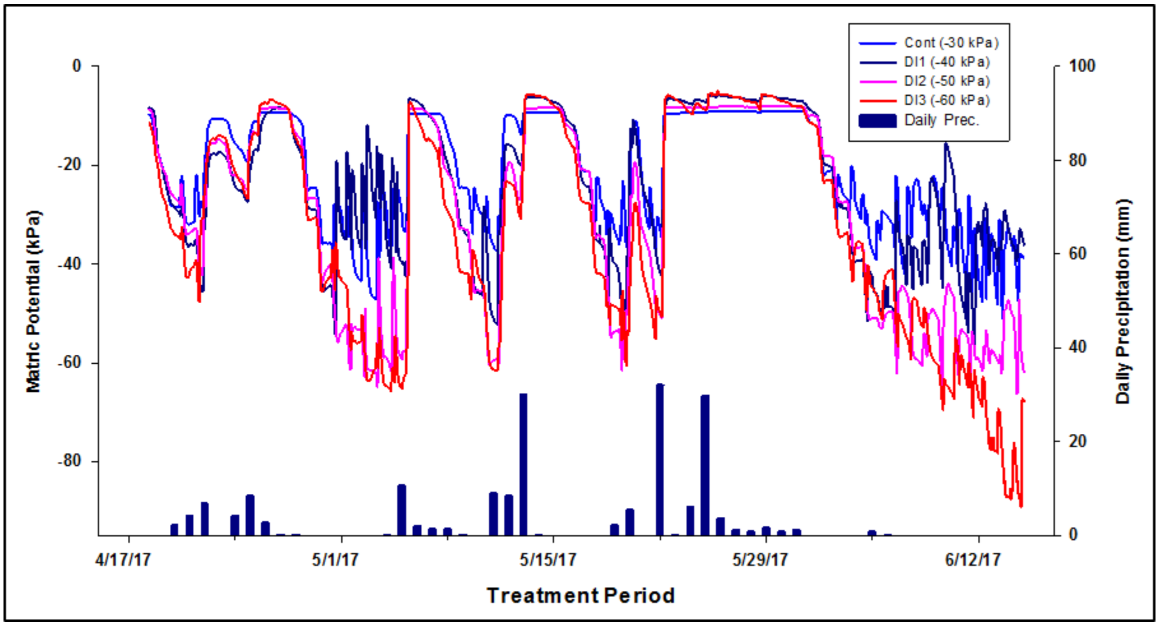


Figure B.2. Comparison of soil matric potential measurements of T8-field tensiometers (2 per treatment) and MPS-6 sensors (4 per treatment) for the control and deficit irrigation treatments during the field study in year 3. Threshold matric potentials used to control irrigation treatments were -30 kPa (Cont.), -40 kPa (DI1), -50 kPa (DI2) and -60 kPa (DI3).

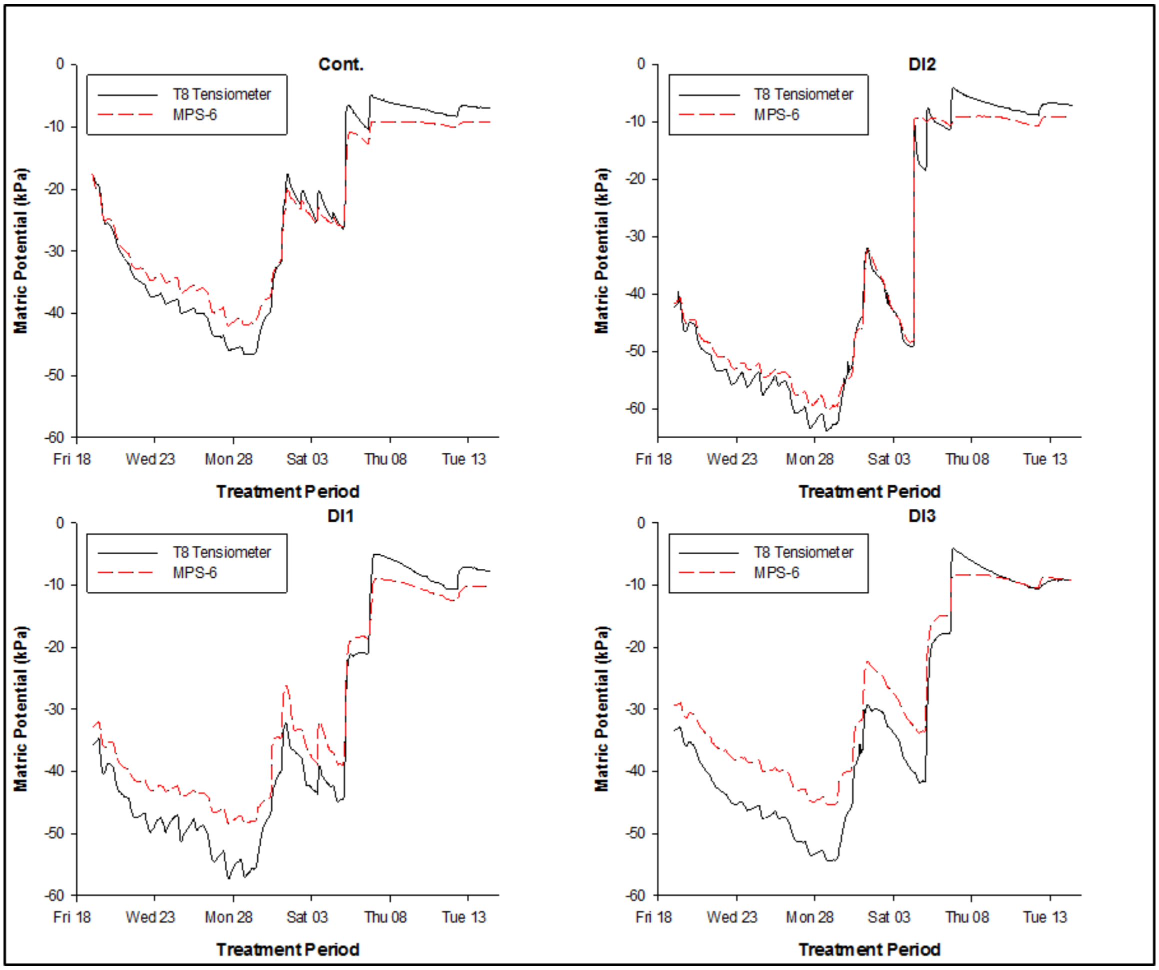


Figure B.3. T8 tensiometer soil matric potential dynamics of the control and deficit irrigation treatments during the treatment period of the field study in year 2 (n=2), and the daily precipitation received at the study site during the treatment period. Threshold matric potentials used to control irrigation treatments were -30 kPa (Cont.), -40 kPa (DI1), -50 kPa (DI2) and -60 kPa (DI3).

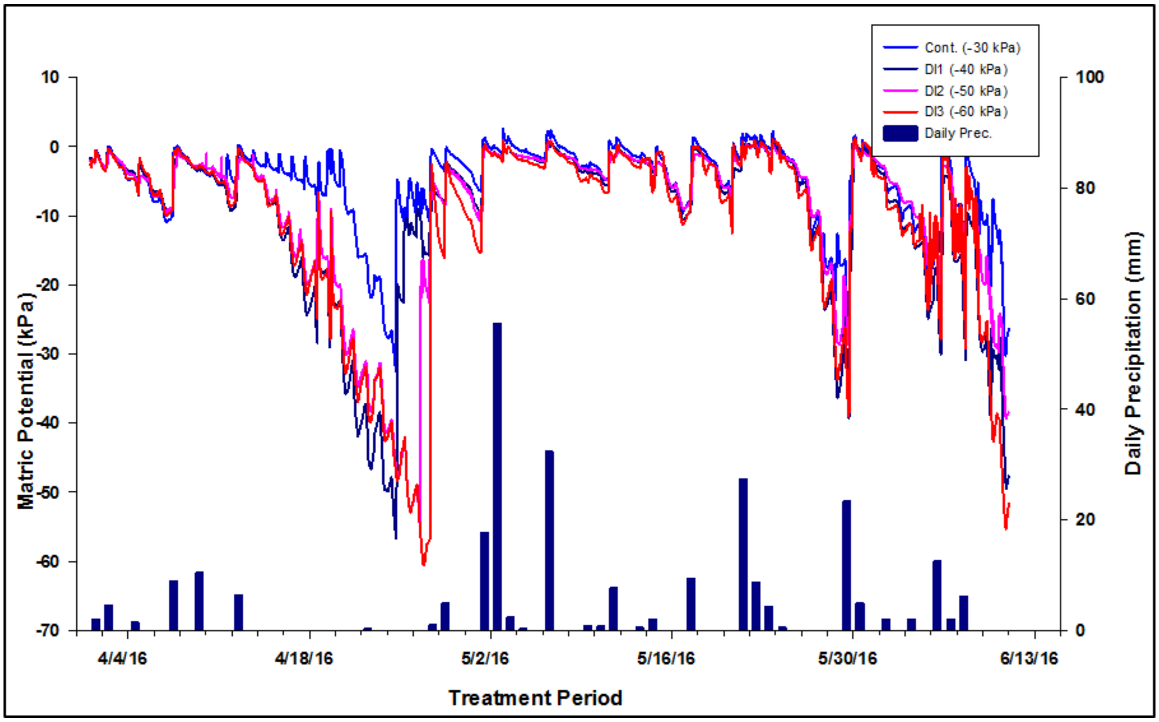


Table B.1. Fruit yield, number of fruit per plant, individual fruit mass, irrigation application per plant and water use efficiency (WUE) of the control and deficit irrigation treatments in the field study in year 2. Threshold matric potentials used to control irrigation treatments were -30 kPa (Cont.), -40 kPa (DI1), -50 kPa (DI2) and -60 kPa (DI3). Values indicated are mean ± SEM. Means followed by different letters within columns are significantly different (P<0.05).

Treatment	**Fruit Yield (g/plant)**	**Number of Fruits per Plant**	**Individual Fruit Mass (g)**	**Irrigation Application (L/Plant)**	**WUE (g/L)**
Cont.	410.9±15.1	45.7±1.4	9.0±0.1	26.5±0.4a	15.8±1.1
DI1	385.0±21.8	43.1±3.0	9.0±0.7	20.4±0.2b	16.9±0.9
DI2	341.9±19.3	36.8±2.0	9.3±0.1	19.6±0.3b	20.3±0.8
DI3	334.1±11.8	38.6±5.2	8.7±0.2	15.2±0.1b	23.7±1.4

Table B.2. Stomatal conductance (g_s) of 'Chandler', 'Sweet Charlie' and 'Camarosa' for the control and deficit irrigation treatments during the spring treatment period of the greenhouse study in year 2. Measurements were conducted on April 5 (g_s1), April 10 (g_s2), April 20 (g_s3) and April 23 (g_s4). Threshold volumetric water contents used to control irrigation treatments were 40% (Cont.), 30% (DI1), 20% (DI2) and 15% (DI3). Values indicated are mean ± SEM. Means followed by different letters in columns are significantly different within cultivars (P<0.05).

Cultivar	**Trt.**	**g_s1 ($mol.m^{-2}s^{-}$)**	**g_s2 ($mol.m^{-2}s^{-}$)**	**g_s3 ($mol.m^{-2}s^{-}$)**	**g_s4 ($mol.m^{-2}s^{-}$)**
Chandler	Cont.	0.403±0.044	0.488±0.043a	0.499±0.037	0.489±0.020
	DI1	0.465±0.046	0.458±0.042ab	0.327±0.018	0.511±0.036
	DI2	0.362±0.012	0.202±0.020b	0.289±0.010	0.402±0.033
	DI3	0.255±0.018	0.185±0.021b	0.158±0.011	0.398±0.028
Sweet Charlie	Cont.	0.373±0.014	0.554±0.030a	0.585±0.007a	0.624±0.041
	DI1	0.403±0.039	0.400±0.025ab	0.344±0.026ab	0.498±0.049
	DI2	0.308±0.024	0.397±0.011ab	0.224±0.015b	0.439±0.033
	DI3	0.297±0.040	0.240±0.023b	0.143±0.017b	0.388±0.025
Camarosa	Cont.	0.360±0.032	0.661±0.084a	0.352±0.009b	0.703±0.025a
	DI1	0.380±0.035	0.500±0.035ab	0.503±0.035a	0.515±0.022b
	DI2	0.390±0.037	0.304±0.022ab	0.349±0.002b	0.419±0.018b
	DI3	0.451±0.021	0.176±0.017b	0.334±0.016b	0.539±0.020b

Table B.3. Leaf water potential (ψ_{leaf}) of ‘Chandler’, ‘Sweet Charlie’ and ‘Camarosa’ for the control and deficit irrigation treatments during the spring treatment period of the greenhouse study in year 2. Measurements were conducted on April 5 (ψ_{leaf}1**)**, April 10 (ψ_{leaf}2**)**, April 20 (ψ_{leaf}3**)** and April 23 (ψ_{leaf}4**)**. Threshold volumetric water contents used to control irrigation treatments were 40% (Cont.), 30% (DI1), 20% (DI2) and 15% (DI3). Values indicated are mean ± SEM. Means followed by different letters in columns are significantly different within cultivars (P<0.05).

Cultivar	**Treatment**	**ψ_{leaf}1 (-MPa)**	**ψ_{leaf}2 (-MPa)**	**ψ_{leaf}3 (-MPa)**	**ψ_{leaf}4 (-MPa)**
Chandler	Cont.	1.8±0.03	1.4±0.04	1.7±0.02	1.7±0.10
	DI1	1.9±0.04	1.6±0.03	1.70.02	1.8±0.04
	DI2	1.8±0.04	1.7±0.03	1.8±0.02	1.7±0.06
	DI3	1.9±0.05	1.9±0.06	1.8±0.03	1.8±0.05
Sweet Charlie	Cont.	1.7±0.05	1.5±0.02	1.6±0.02	1.6±0.13
	DI1	1.70.05	1.6±0.05	1.6±0.05	1.8±0.07
	DI2	1.8±0.05	1.8±0.05	1.8±0.03	2.0±0.07
	DI3	1.9±0.03	1.6±0.08	1.9±0.08	2.0±0.03
Camarosa	Cont.	1.8±0.07	1.6±0.04	1.8±0.03	2.0±0.03
	DI1	1.9±0.01	1.7±0.07	1.6±0.03	2.1±0.03
	DI2	2.0±0.10	1.7±0.06	1.7±0.04	2.0±0.04
	DI3	2.0±0.07	1.8±0.09	1.9±0.03	2.2±0.05

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