Investigating Effects of Environmental Treatments on Transpiration

Ying Yin

TU Delft

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by

Ying Yin

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Tuesday May 28, 2024 at 11:00 AM.

Student number:	5480264	
Thesis committee:	Marie-Claire ten Veldhuis,	TU Delft, supervisor
	Miriam Coenders,	TU Delft
	Judith Boekee,	TU Delft

Contents

SUMMARY

Transpiration is a crucial flux in greenhouses that directly affects plant growth. However, there are currently no direct measurements available. Sap flow is the most widely used method for quantifying transpiration, and calibration can enhance the accuracy of these estimates. Despite the existence of numerous recommendations for applying sap flow calibrations, few reports have employed them. Furthermore, plants frequently encounter various stressors during their growth and development, including drought, salinity, and reduced leaf area. These stressors can impede plant growth and, in extreme cases, can even result in plant death. Plant growth is contingent upon transpiration, and thus, stress conditions can also influence transpiration. However, there is a paucity of research on the effects of these stress conditions on transpiration.

The objective of this report is to calibrate the sap flow and subsequently investigate the effects of stresses, such as salinity, drought and leaf removal on transpiration in order to enhance irrigation strategies. Calibration was initially conducted by comparing daily sap flow with transpiration estimated by a water balance model using linear regression analysis. The corrected sap flow for the controlled and treated gutter was then compared to investigate the impact of stresses on transpiration.

The corrected sap flow coefficients were 2.30, 1.76, 1.64 and 3.58 for the controlled plants (1 and 2) and the treated plants (1 and 2), respectively. The corrected sap flow may be employed as an indicator of transpiration. It has been observed that salinity levels and a reduction in leaf area result in a decrease in transpiration, particularly when transpiration rates are already high. There was no significant difference in transpiration even when irrigation was reduced to 33% of the original amount. In the event of salinity, drought and leaf area reduction, it is recommended that the irrigation frequency be increased and the irrigation amount be reduced. Furthermore, it is recommended that salt leaching during the non-planting period be undertaken.

1

INTRODUCTION

Climate change, population expansion, and resource depletion have led countries worldwide to adopt sustainable development solutions. Improving water efficiency, addressing water scarcity, and tackling famine are among the key sustainable development challenges in the United Nations' 2030 Agenda (United Nations, n.d.-a). In response to this challenge, greenhouses are becoming increasingly prevalent.

Greenhouse cultivation has several advantages over traditional field methods. Yields per unit area in greenhouses can be up to ten times higher than those achieved in open field conditions (Vox et al., 2010). Additionally, greenhouse systems have the potential to reduce the needs of irrigation water by up to 90% compared to conventional open-field agriculture (Akrami et al., 2020). In addition, greenhouses provide a controlled environment that allows crops to be grown without being constrained by local environmental conditions, reducing the need for imports.

Water scarcity is a pressing issue in many regions and affects a significant number of people. Currently, 3.2 billion people live in agricultural areas that face high to very high water shortages, with 1.2 billion of them living in severely water-constrained agricultural regions (United Nations, n.d.-b). This issue is expected to worsen in the future due to the combined effects of climate change and a growing global population. The lack of water for irrigation is one of the most important environmental stresses that limit the growth and yield of crops.

Proper irrigation scheduling and water supply are crucial for improving water efficiency and increasing crop yields in greenhouses. Limited irrigation might induce water and nutritional stress and reduce plant production. On the other hand, the excessive application of water could lead to waste and promote nitrogen leaching. Furthermore, it stresses plants by disturbing the oxygen balance in the root zone and drowning the root system (Liu et al., 2019). Therefore, greenhouse growers have to put more emphasis on optimizing their irrigation strategies to meet the needs of crop, effectively reducing water consumption and ensuring production.

Transpiration (T), the evaporation of water from the aerial parts of plants such as leaves, stems and flowers, is one of the dominant fluxes in greenhouses. It directly affects plant growth and crop yield. The accurate determination of T is essential for improving greenhouse plant irrigation, as most of the plant's moisture is released into the air through transpiration.

Evapotranspiration, which includes evaporation and transpiration, can be estimated from the soil water balance in the field. Since the soil in the greenhouse is covered with plastic film and watered by drip irrigation, soil evaporation and intercepted evaporation are negligible and evapotranspiration can be considered as transpiration in the greenhouse. There are two limitations to this method: firstly, the temporal resolution is better chosen to a few days to reduce the effect of delay, and secondly, estimates of drainage and surface runoff are usually uncertain (Smith & Allen, 1996). The sap flow method, which represents transpiration only, is more advantageous than the water balance method for measuring transpiration from individual branches, tillers or whole plants because the sap flow method can be easily automated and provides a continuous record of plant water use with high temporal resolution. However, sap flow measurements can be affected by a number of potential errors. In a 2018 study, the sap flow method was found to underestimate transpiration by 37% (Peters et al., 2018). Some of these errors may be related to scaling sap flow from a sample of individual stems to a stand of the known area (Hatton et al., 1995), while others may be due to intrinsic limitations of this method or the way this method is applied (Flo et al., 2019). Calibration of sap flow is therefore vital to improve the accuracy of transpiration estimates.

The world is facing many changes that may affect plant transpiration. One of the most serious is water scarcity. Deficit irrigation has become a prevalent practice in areas where access to freshwater is difficult or expensive (Chand et al., 2020). The primary aim of deficit irrigation is to improve crop water use efficiency by eliminating irrigation that has little impact on yield (Kirda et al., 2002). The implementation of deficit irrigation requires a thorough understanding of its effects on transpiration. Greenhouse growers can therefore implement more water-efficient irrigation practices by determining the level of transpiration that can be tolerated without significant yield loss. However, there is a lack of studies analyzing the effects of water deficit on transpiration.

Not only is the amount of irrigation water a growing concern, but so is the quality of irrigation water. The use of saline groundwater for irrigation has become a widespread practice, particularly in areas of water scarcity. Furthermore, there is a growing trend in the use of recycled drainage and wastewater for irrigation (Ungureanu et al., 2020). Soil salinisation arising from these irrigation practices becomes one of the most serious land degradation problems affecting people all over the world. It is estimated that nearly 830 million hectares of land are affected by salinisation, increasing at a rate of 2 million hectares per year (Minhas et al., 2020). Elevated salinity in the irrigation water affects transpiration in several ways. Firstly, increased salinity in the soil water causes a decrease in water potential and makes it difficult for plants to absorb water from the soil. Secondly, high salinity levels can induce stomatal closure in plants. Thirdly, the infiltration of salt ions into the plant may lead to physiological changes in plants, which may affect their ability to maintain normal transpiration rates. A better understanding of the effects of salinity on transpiration may help to optimize irrigation practices and improve efficiency, which is particularly important in areas of poor water qualities. However, the effects of salinity on transpiration have rarely been investigated (Tian et al., 2020).

Reduced irrigation water and irrigation with saline water can result in reduced leaf growth (Tian et al., 2020). Leaves are organs of transpiration. Leaf area index (*LAI*), which represents the total leaf area per unit of ground area, is a key parameter in determining transpiration (Stanghellini, 1987). In general, a higher *LAI* implies a higher potential for water loss through transpiration. A comprehensive understanding of the effects of *LAI* on transpiration can provide opportunities to improve water use efficiency by adjusting leaf area. However, few studies have investigated the relationship between transpiration and *LAI*.

1.1. Aim of the Research

In short, this study has the following objective:

To investigate effects of environmental treatments, such as deficit irrigation, elevated salinity and leaf removal, on transpiration to improve irrigation strategies.

For that, the following sub questions will be addressed:

- Whether crop sap flow can be used as an indicator of transpiration?
- What are the effects of these three treatments on transpiration?
- What are the appropriate irrigation management practices to deal with salinity, drought and leaf area reduction in agriculture?

1.2. Thesis Outline

This thesis consists of a literature review (Chapter 2) that presents the current state of academic research into transpiration measurement and the effects of environmental treatments on transpiration. The subsequent chapter (Chapter 3) introduces the research methods used in this thesis. Chapter 4 presents the results and discussion, which first demonstrate the correction of the sap flow method. The relationship between transpiration and these environmental treatments is subsequently demonstrated. The significance of the results is also shown here. The conclusion (Chapter 5) presents the main findings and answers the research questions.

2

Literature Review

This chapter aims to provide an overview of the sap flow method used to estimate transpiration and the impact of stress conditions, such as salinity, drought, and reduced leaf area, on transpiration. Section 2.1 introduces the uncertainties in sap flow measurements and the correction of the sap flow method. Section 2.2 explains how stress conditions affect transpiration.

2.1. SAP FLOW MEASUREMENT

Sap flow measurement is a crucial technique for estimating transpiration rates. It provides continuous recordings of plant water use at high time resolution. Sap flow can be measured using two methods: heat pulse and constant heating approaches. These methods include four specific measurements: the stem balance method, the trunk heat balance method, the heat pulse method and the thermal dissipation method (Smith & Allen, 1996). Each method has its own advantages and limitations, which are influenced by factors such as design complexity, cost considerations, and the size and type of stem on which the sensors can be applied (Forster, 2017).

This section describes the thermal pulse method, the most commonly used sap flow measurement method. It then discusses the sources of error that can affect the accuracy of sap flow measurements using this method. Finally, it provides an overview of the current status of correction methods for sap flow measurements.

2.1.1. THE HEAT PULSE METHOD

Heat pulse methods are commonly used for measuring sap flow in greenhouses due to their low cost, low power requirements, and low maintenance. Typically, four sets of heat pulse probes are used to measure sap flow, with one set installed in each quadrant of the stem. Each set of heat pulse probes consists of one heater probe and two sensor probes, which are implanted in parallel holes drilled radially into the stem. The velocity of each pulse as it moves with the sap stream is measured by continuously monitoring the sensor probes while short pulses of heat are periodically released from the heat probe.

2.1.2. SOURCES OF ERROR

The heat-pulse method for measuring sap flow can be prone to several potential errors. There are four main sources of error:

Probe Misalignment

Heater and sensor probes are inserted into parallel holes drilled radially into the stem. When drilling the holes, the distance between the probes should be carefully measured using a jig. However, in practice, it is almost impossible to install the probes exactly parallel. Misalignment of probes can lead to large errors in the heat-pulse method due to its high sensitivity to the distance between the heater and sensor probes. In 2004, a study demonstrated that a spacing error of 2 mm resulted in a 100% error in sap flow estimations (Bleby et al., 2004).

Wounding

Wound reaction in stem tissue can have a significant impact on the accuracy of sap flow measurements. This reaction typically occurs 14-21 days after probe implantation and is believed to be caused by resin deposition in the xylem vessels or tracheas surrounding the implantation site, or possibly by cultivation. As the wound reaction develops, sap flow occurs further away from the sensor probes, leading to a serious impact on technique accuracy (Smith & Allen, 1996). In Michael's study, wounding resulted in sap flow underestimation ranging from 50% to 90% (Forster, 2017).

Thermal Inhomogeneity

Marshall analytically demonstrated that heat pulse velocity in stems differs from sap velocity (Marshall, 1958). The analysis showed that heat ascends the stem more slowly than sap due to the transfer of heat between the moving sap and the stationary interstitial tissue between xylem vessels or tracheids. Thus, heat pulse velocity measurements may not accurately calculate sap flow rates for thermally heterogeneous species with uneven distribution of conductive elements or large interstitial distances between elements, where the time required for thermal equilibration between sap flow and matrix is not negligible (Smith & Allen, 1996). This is the case with kiwifruit, which has large xylem vessels and a substantial interstitial area of woody matrix, affecting the thermal homogeneity of the sap flow. In the study conducted by Steve, the sap flow rates of kiwifruit were measured using the heat pulse method and found to be within 5 to 10% of the actual transpiration due to thermal inhomogeneity (Green et al., 2003).

Scaling from Plant to Stand

After measuring sap flow, it is often necessary to convert mass or volume flow rates for individual plants to estimates of transpiration per unit area of land. In uniform stands, where plants are of similar size and radiation and water availability are uniform, transpiration is unlikely to vary greatly. Therefore, transpiration can be calculated from plant density. However, this approach may not be satisfactory in reality. As plants come in various sizes, the correlation between ground area and transpiration may differ among individual plants. A study in 2007 has shown that when converting mass flow rates from individual plants to sap flow per unit area in the catchment, sap flow is 48% less than the actual transpiration if plant variation is ignored (Ford et al., 2007).

2.1.3. CORRECTION OF SAP FLOW MEASUREMENT

There are significant errors between sap flow measurements and actual transpiration, from underestimations of up to three times the actual transpiration to overestimations of up to 55% (Dix & Aubrey, 2021). Due to significant errors between sap flow measurements and actual transpiration, it is necessary to correct measured sap flow rates when using sap flow sensors to estimate transpiration. Previous studies have mentioned warnings and recommendations about calibrating sap flow. For example, in 2017, Michael A. Forster stated that '*sap flow sensors must be calibrated*' when whole plant water use or the amount of transpiration is the primary concern (Forster, 2017). However, despite numerous warnings and recommendations, calibration is not commonly performed in reports of sap flow measurements. Only 5.3% of studies from 2010 through 2018 conducted calibrations or applied previous calibration results to ensure or improve the accuracy of transpiration estimates (Dix & Aubrey, 2021). It is crucial to ensure accurate measurements in this field.

Sap flow calibration involves comparing the transpiration measured by sap flow sensors with independent reference transpiration data, typically obtained through gravimetric or photometric methods (Dix & Aubrey, 2021). Although achieving greater accuracy in transpiration estimates through calibration is beneficial, it poses a challenge for research due to the resource-intensive nature of the process.

2.2. EFFECTS OF STRESS CONDITIONS ON TRANSPIRATION

Plants often encounter abiotic stress during growth and development, such as drought, salinity, and reduction in leaf area. These conditions can delay growth, reduce productivity, and in extreme cases, cause plant death. Plant growth is dependent on transpiration; therefore, stress conditions that affect growth also affect transpiration. However, there is a lack of research on the impact of these stress conditions on transpiration.

Effect of Salinity on Transpiration

Numerous studies have shown that salinity has a significant impact on plant physiology across different plant species. High concentrations of soluble salts cause osmotic stress, ion toxicities, and imbalanced accumulation of specific ions, all of which negatively affect plant growth and productivity. As soil salt content increases, soil water potential decreases, hindering water uptake by plants and impeding their growth. Furthermore, salt concentrations can infiltrate plant tissues, resulting in leaf damage and growth inhibition (Minhas et al., 2020). These salt-affected plants with less growth in turn are able to transpire less. Salinity can therefore have a significant impact on transpiration. A 2019 study found that non-uniform salt accumulation in the soil profile results in spatial heterogeneity in transpiration (Tian et al., 2020). However, research on the impact of soil salinity on transpiration remains limited.

Effect of Leaf Area on Transpiration

Leaf Area Index (*LAI*) is a crucial parameter in vegetation studies as it represents the total leaf area per unit of ground surface area. *LAI* plays a significant role in regulating transpiration processes. Several studies have demonstrated a positive correlation between *LAI* and transpiration rates in vegetated ecosystems. As *LAI* increases, there is typically a corresponding rise in transpiration due to the greater leaf surface area available for water vapor exchange. This relationship is mainly attributed to the leaves' role as the primary site for transpiration. Higher *LAI* values indicate a larger leaf area available for moisture loss through stomatal openings. Additionally, changes in *LAI* can affect other physiological processes within plants, such as stomatal conductance and canopy structure, which can further affect transpiration rates (Stanghellini, 1987). The effect of *LAI* on transpiration in greenhouses is a significant research area as *LAI* is a crucial parameter for estimating transpiration rates in the greenhouse. However, there are few studies on the effect of leaf area on transpiration as the relationship between the two is largely determined by empirical models.

Effect of Irrigation Amount on Transpiration

Deficit irrigation is a water-conserving practice that involves irrigating plants with less water than their full requirement, either at specific growth stages or throughout the cultivation period. This technique induces water stress in plants, which can adversely affect their biochemical and physiological processes, ultimately reducing their photosynthetic capacity and growth. Moreover, under conditions of water stress, plants tend to close their stomata to preserve their water status, leading to a decrease in stomatal conductance. Typically, plants experiencing water stress transpire less. A 2022 study found that trends in alfalfa transpiration varied under different irrigation treatments (Liu et al., 2022). However, research on the impact of irrigation amount on transpiration is still limited.

3

METHODOLOGY

Sap flow methods can provide continuous records of plant transpiration with high time resolution. However, the original sap flow methods may not be reliable due to errors mentioned in the Section 2.1.2. Transpiration can also be estimated from the soil water balance. However, it is desirable to have a temporal resolution of a few days. To correct transpiration estimated by the sap flow method, the following methods are applied. Daily transpiration is estimated using both the sap flow method and soil water balance. A linear regression analysis is then conducted to compare the transpiration measured by both methods. A coefficient can be obtained to correct the sap flow method based on this relationship. To investigate the effect of environmental treatments on transpiration, the corrected transpiration measured by the sap flow method for the controlled and treated gutters are compared. A diagram of these is shown in Figure 3.1.

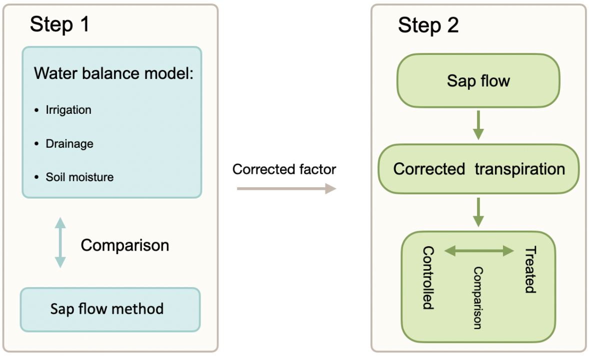

Figure 3.1: Diagram of the Research Method

This chapter presents the specific information and methods used in the study. Section 3.1 describes the experiment area, followed by section 3.2 which introduces the environmental treatments used in the experiment. Section 3.3 explains how to collect the required data. Finally, the method for correcting transpiration measured by the sap flow method is introduced in Section 3.4.

3.1. SITE DESCRIPTION

The experiment took place at the Delphy Improvement Centre in Bleiswijk, South Holland from October 2022 to September 2023. The high-tech soilless greenhouse used rockwool as the planting medium. Merlic tomato plants, one of the main varieties grown in the Netherlands, were grown in this greenhouse.

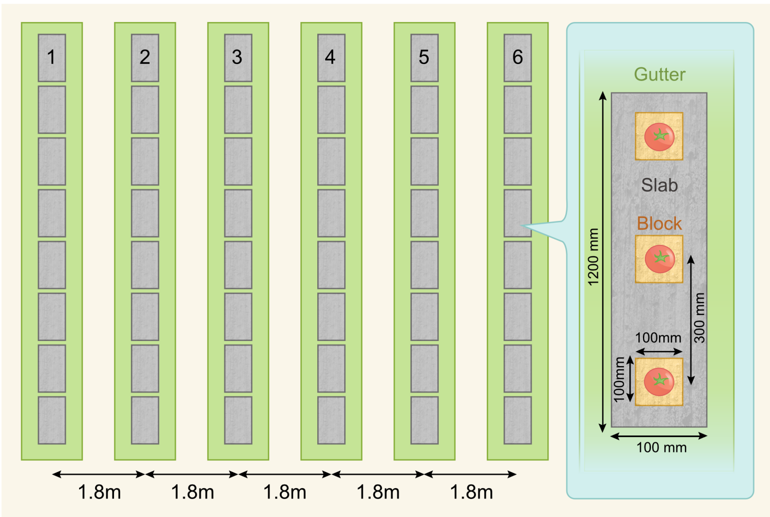

Figure 3.2: Greenhouse Layout

As shown in Figure 3.2, the greenhouse is rectangular in shape. There are 6 suspended gutters with a distance of 1.8 *m* between the centres of adjacent gutters. Each gutter contains 8 slabs. The size for a slab is 120 *cm* in length, 10 *cm* in width and 15 *cm* in height. The distance between neighbouring slabs is 30 *cm*. A slab is toppped by three blocks measuring 10 x 10 *mm* and each block is planted with a tomato plant.

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3.2. ENVIRONMENTAL TREATMENTS

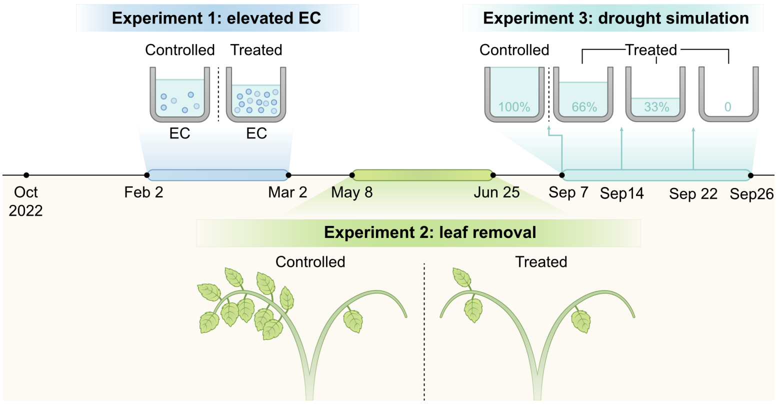


Figure 3.3: Timeline of the Environmental Treatments

As shown in Figure 3.3, three experiments were conducted during the experimental period period, namely the elevated salinity experiment, the drought simulation experiment and the leaf area reduction experiment. Gutter 2 was used as the controlled gutter and gutter 5 was used as the treated gutter.

The elevated electrical conductivity experiment was conducted from 2 February to 2 March 2023. The EC of the irrigation water in the treated gutter was increased compared to the controlled gutter. The exact value of the increase in EC values varied from day to day.

The leaf area reduction experiment was carried out from 8 May to 25 June 2023. Leaves from plants in the treated gutter are partially removed each week. The percentage of leaves that were removed decreased as the number of weeks went on. Compared to the controlled gutter, 34% of the leaves in the treated gutter were removed in week 19 (8 May - 14 May), 21% of the leaves in the treated gutter were removed in week 21 (22 May - 28 May), 15% of the leaves in the treated gutter were removed in week 23 (5 June - 11 June) and no leaves are removed in week 25 (19 June - 25 June).

The drought simulation experiment was conducted from 7 September to 26 September 2023. From 7 September to 14 September, the amount of irrigation water in the treated gutter was reduced to 66% of that in the controlled gutter. From 14 September to 22 September, irrigation in the treated gutter was reduced to 33% of that in the controlled gutter. From 22 September to 26 September, there was no irrigation water in the treated gutter.

3.3. DATA COLLECTION

Irrigation and Drainage Data

Irrigation and drainage were measured by Priva water sensors. The cumulative irrigation and drainage values in the unit of L/m^2 were automatically recorded every 5 minutes for the whole greenhouse. Furthermore, the irrigation and drainage values were reset on a new day. In this study, irrigation was recorded from 3 November 2022 to 26 September 2023 and drainage from 9 December 2022 to 26 September 2023 was recorded.

Soil Moisture Content

Soil moisture content was measured for 4 slabs in each gutter, with soil moisture sensors installed approximately halfway along the slab. In the study, the volumetric soil moisture, expressed in cubic meters of moisture per cubic meters of soil volume, was measured and automatically recorded every 5 minutes from 15 October 2022 to 26 September 2023.

Slab Weight

The weight of the two slabs was measured with a weighing balance (Zemic Europe, Type 1B-S Miniature Sensor) and recorded automatically every 5 minutes from 3 January to 26 March 2023, 1 April to 20 July 2023 and 10 August to 26 September 2023. The weight of the slabs is given in the unit of kilograms (kg).

Sap Flow

For sap flow measurements of plants in the controlled and treated gutter, 2 plants were selected from each gutter and sap flow was measured from both branches of each plant. The measured sap flow rates were recorded every 5 minutes in grams per hour (g/h). Sap flow was recorded between 16 November 2022 and 26 September 2023.

The recorded time is displayed on Figure 3.4.

3.4. METHODS FOR SAP FLOW CORRECTION

This section describes the process methodology for correcting sap flow. Firstly, it outlines the method for processing the collected data to eliminate error and converting it to the desired units. Next, the method for obtaining transpiration is introduced. How to calibrate transpiration measured by sap flow sensors is then explained. Finally, error metrics that can be used to analyse the accuracy of the correction is described.

The difference in irrigation and drainage between the treated and controlled gutters is unclear as the irrigation and drainage data were collected for the entire greenhouse. To estimate transpiration based on the soil water balance, data collected during periods

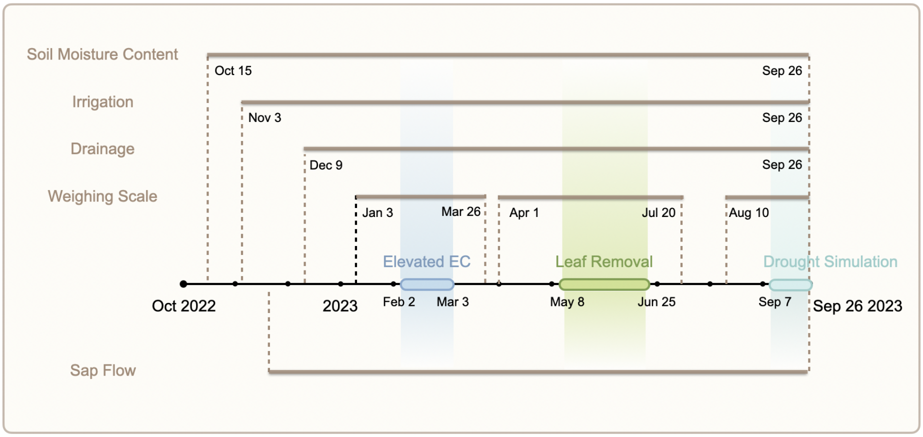


Figure 3.4: Recorded Time for Collected Irrigation, Drainage, Soil Moisture Content, Weighing Scale and Sap Flow

without environmental treatments were used. During these normal periods, plant water use is unlikely to vary significantly between the controlled and treated gutter and it can be assumed that both gutters irrigate and drain at the same rate. Continuous monitoring of irrigation, drainage, soil moisture, scale and sap flow is also required to correct for sap flow. Taking all these characteristics into account, three periods of data were chosen to correct the sap flow measurements: 4 January to 1 February, 3 March to 22 March, and 26 June to 17 July.

3.4.1. DATA PROCESSING

In order to mitigate the effects of delay, a temporal resolution of one day was chosen for the correction of the sap flow measurement.

Irrigation and Drainage Data

The daily maximum values (indicating the total cumulative irrigation or drainage volume for the day) are selectively identified for subsequent analysis. These daily maximums are in the unit of $L/m^2/d$.

Soil Moisture Content Data

The volumetric soil content is automatically measured and recorded. However, data errors may occur during the recording process due to sudden changes in temperature and humidity or by nearby electronic equipment, which can affect the accuracy of the measurements.. To improve the accuracy of soil moisture content measurements, it is necessary to eliminate these errors. Specific steps for eliminating errors are shown in **Appendix**. The soil moisture in a given slab can be calculated based on the following equation.

$$S_{SM} = \frac{\theta}{100} \times V_{slab} \tag{3.1}$$

With:
S_{SM} = moisture in the soil measured by the soil moisture content (m^3)
θ = soil moisture content for a slab (%)
V_{slab} = volume of the slab (0.018 m^3)

3

It is essential to calculate the surface area of each slab to determine the soil moisture per unit area. As there are 6 gutters in the investigated greenhouse, and each gutters has 8 slabs., all slabs are assumed to share the same surface area, which is expressed as $\frac{150}{6\times8}$ m^2.

$$S_{sm} = \frac{S_{SM}}{A_{slab}} \times 10^3 \tag{3.2}$$

With:
S_{sm} = soil moisture per unit of area (mm)
A_{slab} = surface area of each slab (m^2)

Weighing Balance Data

The weighing balance records the weight of the two slabs in kg. The surface area for each weighing scale can be approximated as $\frac{150}{6\times4}$ m^2, as there are (6 × 8) slabs in the greenhouse. The following equation is employed to compute the weight per unit of area.

$$M_{wb} = \frac{M_{WB}}{A_{WB}} \tag{3.3}$$

With:
M_{wb} = mass per unit of area (kg/m^2)
M_{WB} = mass measured by the weighing balance (kg)
A_{WB} = surface area of each weighing balance (m^2)

Sap Flow Data

From 5 May to 27 May, sap flow values for plant 1 in gutter 5 were hundreds higher than those for plant 2, which may be result from errors in data recording. Values for this period are therefore removed.

The process of converting the sap flow from grams per hour (*g/h*) to grams per day (*g/d*) is as follow. First, an average sap flow is calculated on an hourly basis. Next, these hourly values are summed up to obtain a cumulative daily sap flow.

3.4.2. ESTIMATION OF TRANSPIRATION

As mention in Chapter 1, there are two kinds of methods that can be used to estimate transpiration: the soil water balance method and the sap flow method.

SOIL WATER BALANCE METHOD

Water balance relies on the principle of mass conservation. However, conservation of volumes is employed in our research as the difference of the two is negligible.

The tomato plants grown in the slab were covered with plastic film to reduce or prevent water evaporation from the soil. Soil evaporation is not considered in the research. In addition, the irrigation system uses drip irrigation, which means that interception evaporation can be disregarded. As a result, some of the irrigation water is drained directly, some is absorbed by the plants, and the rest is stored in the soil, as shown in Formula 3.4.

$$\frac{dS_{soil}}{dt} = I - D - U \tag{3.4}$$

With:
$\frac{dS_{soil}}{dt}$ = the rate of change of soil water storage over time (mm/d)
I = irrigation (mm/d)
D = drainage (mm/d)
U = water uptake by the plant (mm/d)

Changes in soil water storage can be assessed through two methods. One uses a weighing balance. The change is first determined by subtracting the weight per unit of area on day (t+1) from that of day t. Since the alteration in weight is attributed to water inflow and outflow, the weight change is subsequently divided by the density of water (1000 kg/m^3) and multiplied by 1000 to facilitate the conversion of unit to mm. The other method is to use soil moisture content. Soil moisture is first calculated and then the moisture at time (t+1) is subtracted from the moisture at time t to calculate the change.

Part of the water taken up by plants is used for transpiration, which contributes to the plant's cooling and nutrient transport. While the other part is stored to support plant growth.

$$\frac{dS_{plant}}{dt} = U - T_{WB} \tag{3.5}$$

With:
$\frac{dS_{plant}}{dt}$ = the rate of plant water storage over time (mm/d)
T_{WB} = transpiration estimated by the water balance model (mm/d)

The amount of water stored in the plant is relatively small, up to 90% of the water taken by roots is lost through transpiration (Lumenwaymaker, n.d.). Water stored in plants is therefore ignored, and transpiration can be calculated using the following equation:

$$T_{WB} = I - D - \frac{dS_{soil}}{dt} \tag{3.6}$$

3

SAP FLOW METHOD

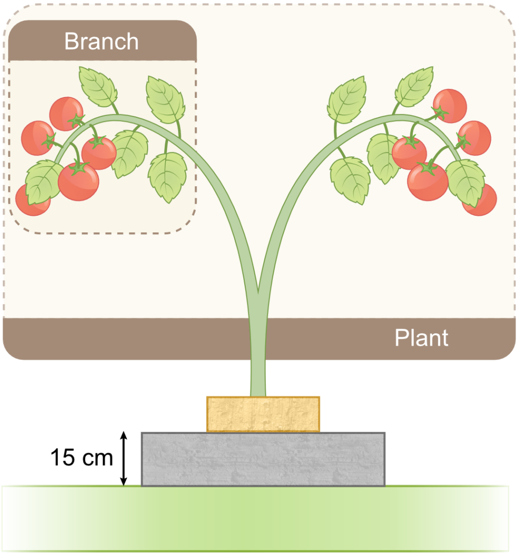


Figure 3.5: Example of Plant Grown on the Slab

As shown in Figure 3.5, plant has two stems and sap flow is measured for one stem. The sap flow of each stem is then converted to transpiration per unit of area using the following formula. Two assumptions are used here. Firstly, sap flow was assumed to be the same for both stems in a plant. Secondly, each stem covers the same area.

$$T_{SF} = \frac{1}{\rho_{water}} \times \frac{f}{A} \times 2 \tag{3.7}$$

With:
f = sap flow (g/d)
A = area covered by each stem ($\frac{150}{6\times8\times3}$ m^2)

ρ_{water} = water density ($1000\ g/L$)
T_{SF} = transpiration estimated by the sap flow method (mm/d)

3.4.3. SAP FLOW CALIBRATION

Sap flow calibration is the comparison of independent reference transpiration with transpiration measured by sap flow sensors. In this study, independent reference transpiration is estimated by the soil water balance model. Transpiration estimated by sap flow measurements are then calibrated by linear regression analysis.

3

$$T_{WB} = \beta \times T_{SF} \tag{3.8}$$

With:
β = slope of the linear regression line

3.4.4. ESTIMATED ERROR

Root mean square error (RMSE) and correlation coefficient (CC) are used further to analyze the accuracy of the sap flow calibration.

$$RMSE = \sqrt{\frac{1}{n}\sum_{1}^{n}\left(y_i - \hat{y}_i\right)^2} \tag{3.9}$$

With:
n = number of measured sap flow
$\hat{y}_i$ = predicted transpiration using the linear regression line (corrected sap flow), which is corresponds to the ith sap flow (mm/d) y_i = actual transpiration estimated by the soil water balance, which is corresponds to the ith sap flow (mm/d)

$$CC = \frac{\sum_{i=1}^{n}(x_i - \bar{x})\left(y_i - \bar{y}\right)}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=a}^{n}\left(y_i - \bar{y}\right)^2}} \tag{3.10}$$

With:
x = the ith transpiration estimated by the sap flow method (mm/d)
y = the ith transpiration estimated by the soil water balance (mm/d)
$\bar{x}$ = the mean value of transpiration estimated by the sap flow method (mm/d)
$\bar{y}$ = the mean value of transpiration estimated by the soil water balance (mm/d)

RMSE is a measure of the difference between corrected sap flow and the actual transpiration estimated by the soil water balance. It quantifies the deviation in units of *mm*/*d*, with lower values indicating better performance. The correlation coefficient measures the strength and direction of the linear relationship between corrected sap flow and transpiration estimated by the water balance model. It ranges from -1 to 1, where 1 indicates a perfect positive linear relationship, -1 indicates a perfect negative linear relationship, and 0 indicates no linear relationship.

4

Result and Discussion

This chapter presents the research findings. Section 4.1 displays the transpiration results estimated by the water balance model, while Section 4.2 shows the transpiration results corrected by the sap flow method. Sections 4.3, 4.4, and 4.5 demonstrate the effects of salinity, leaf area, and water availability, respectively.

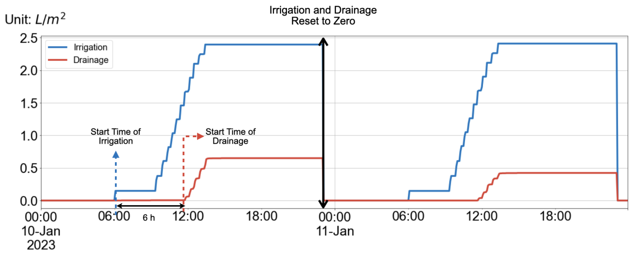
4.1. Estimation of Transpiration by the Water Balance Model

Transpiration can be estimated using the water balance model based on Equation 3.7. In this study, transpiration was estimated for three time periods: from 4th January to 1st February 2023, from 3rd to 22nd March 2023 and from 26th June to 17th July 2023, as introduced in Section 3.4. This section describes the changes in irrigation, drainage and soil moisture, which are important components of the water balance model and provides estimates of transpiration for the three periods.

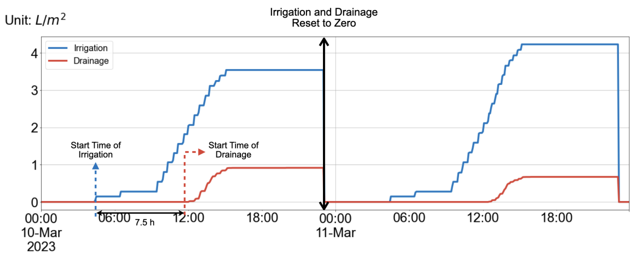
For the sake of simplicity, data collected between 4th January and 1st February are referred to as January data, data collected between 3rd March and 22nd March are referred to as March data and data collected between 26th June and 17th July are referred to as July data.

4.1.1. Changes in Irrigation and Drainage

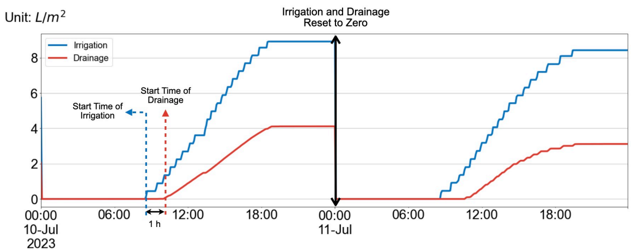
Figure 4.1 illustrates the cumulative values of irrigation and drainage over a two-day period. The volume of irrigation is higher in July than in January and March. As shown in Figure 4.1a, irrigation starts at 6:00 with a small volume and continues at a relatively



(a) From 10th to 11th January



(b) From 10th to 11th March

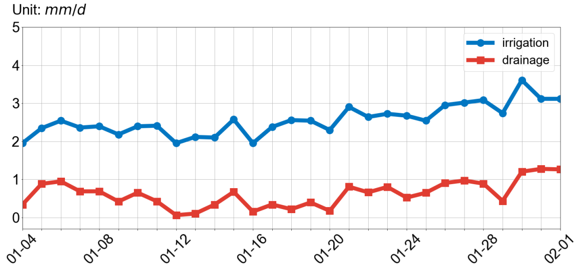


(c) From 10th to 11th July

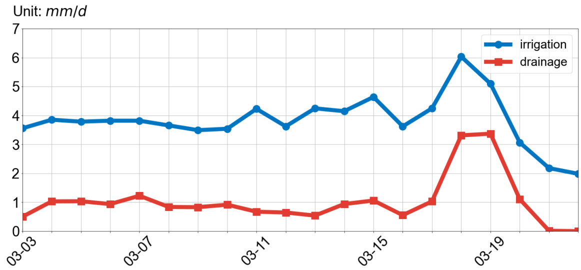
Figure 4.1: Cumulative Value of Irrigation and Drainage in a Day

constant rate every five minutes between 9:00 and 13:30. Drainage starts at 12:00 and finishes around 13:30. Irrigation and drainage return to 0 around 23:00. Figure 4.1b is similar to Figure 4.1a. Irrigation starts with a small volume at around 4:30. From 9:00 to 15:00, irrigation is relatively constant and continuous. Drainage is recorded from 12:00 to 15:10. At 23:00, irrigation and drainage goes back to 0. Figure 4.1c shows that irrigation occurs between 9:00 and 18:30, with similar amounts of irrigation recorded every five minutes, while drainage is recorded from 10:00 and ends at 19:00. Irrigation and drainage values are set to zero at 0:00. Irrigation and drainage are reset to zero at the beginning of each day. Therefore, any irrigation or drainage that occurs on one day will not affect the subsequent day's irrigation and drainage.

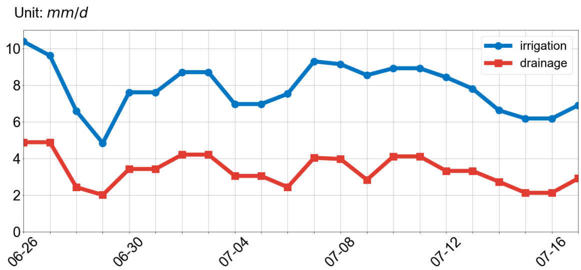
The time interval between the start time of recorded irrigation and drainage is approximately 6 hours in January, 7.5 hours in March and 1 hour in July. The longer time intervals in January and March may be attributed to the difference in the filling of soil moisture. Increased irrigation in July can saturate the soil more quickly, leading to earlier drainage. In order to reduce the effect of the delay in the estimation of transpiration using the water balance model, daily values are used for subsequent calculations.



(a) From January 4th to February 1st



(b) From March 3rd to March 22nd



(c) From June 26th to July 17th

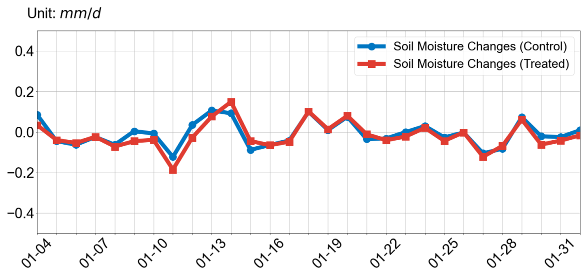
Figure 4.2: Time Series of Irrigation and Drainage

Figure 4.2 illustrates the variation in irrigation and drainage during the three periods. Discharge is dependent on the volume of irrigation. Additionally, the values for irrigation and drainage are higher in July compared to March and January. In January, irrigation ranged from 1.95 to 3.61 *mm/d* with a mean value of 2.56 *mm/d*, while drainage varied from 0.06 to 1.28 *mm/d* with a mean value of 0.61 *mm/d*. In March, the irrigation levels ranged from 1.98 to 6.03 *mm/d*, with a mean value of 3.81 *mm/d*. Similarly, the drainage levels varied from 0.00 to 3.37 *mm/d*, with a mean value of 1.03 *mm/d*. In July, irrigation ranged from 4.84 to 10.38 *mm/d* with a mean value of 7.84 *mm/d*, and drainage varied from 2.01 to 4.89 *mm/d* with a mean value of 3.35 *mm/d*.

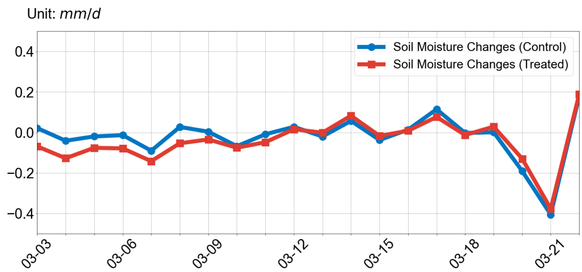
The seasonal variation of drainage to irrigation ratio is evident. In January, drainage accounts for around 24% of irrigation. In March, drainage is 29% of irrigation. While in July, drainage represents 43% of irrigation.

4.1.2. Changes in Soil Moisture

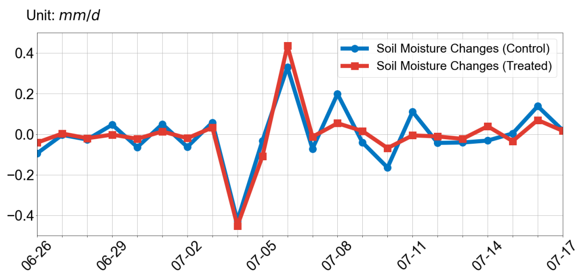
As introduced in 3.4.2, two methods were used to measure soil moisture in the controlled plants in gutter 2 and treated plants in gutter 5: one using the soil moisture content and the other using the weighing scale.



(a) From January 4th to February 1st



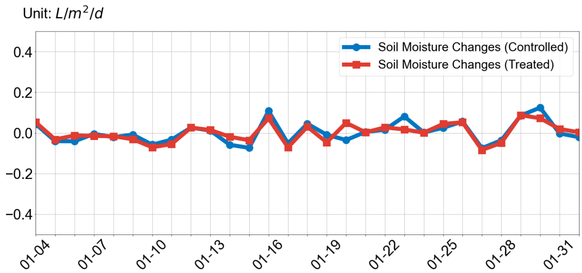
(b) From March 3rd to March 22nd



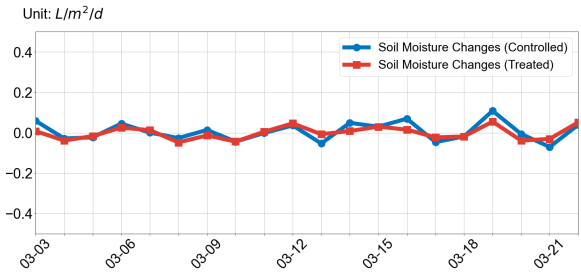
(c) From June 26th to July 17th

Figure 4.3: Changes in Soil Moisture by the Soil Moisture Content

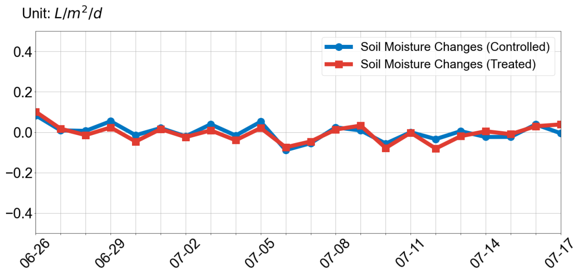
Figure 4.3 illustrates the variation in soil moisture, as measured by the soil moisture content, for the two gutters at three different time periods. In January, soil moisture ranged from -0.12 to 0.11 *mm/d* for the controlled gutter and -0.19 to 0.15 *mm/d* for the treated gutter (Figure 4.3a). In March, soil moisture varied from -0.40 to 0.18 *mm/d* for the control gutter and -0.38 to 0.19 *mm/d* for the treated gutter (Figure 4.3b). In July, soil moisture ranged from -0.43 to 0.33 *mm/d* for the control gutter and from -0.45 to 0.44 *mm/d* for the treated gutter (Figure 4.3c).



(a) From January 4th to February 1st



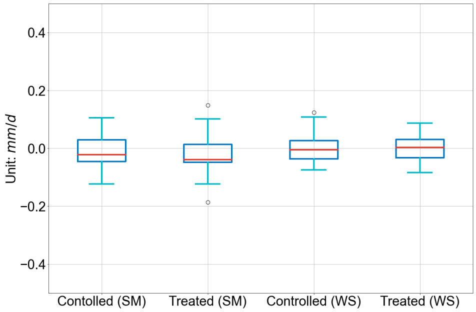
(b) From March 3rd to March 22nd



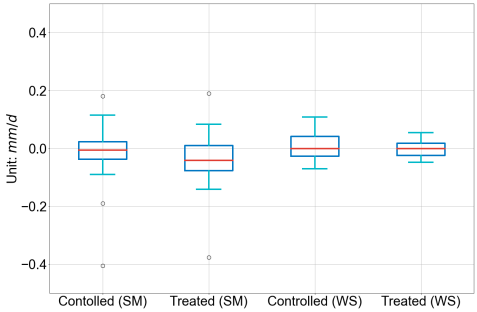
(c) From June 26th to July 17th

Figure 4.4: Changes in Soil Moisture by the Weighing Scale

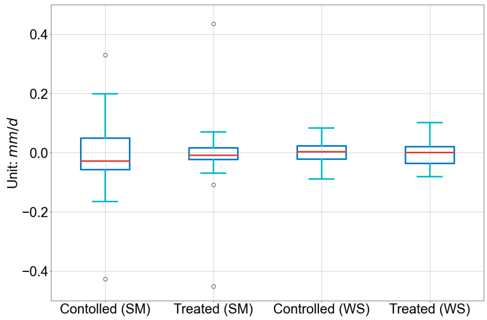
Figure 4.4 shows the variation in soil moisture measured by the weighing scale for both gutters during the three periods. Figure 4.4a shows the moisture changes varied from -0.07 to 0.12 *mm/d* for the controlled gutter and from -0.08 to 0.09 *mm/d* for the treated gutter in January. Figure 4.4b shows that in March, soil moisture ranged from -0.07 to 0.11 *mm/d* for the controlled gutter and from -0.05 to 0.05 *mm/d* for the treated gutter. In July, the soil moisture were between -0.09 and 0.08 *mm/d* for the control gutter and between -0.08 and 0.10 *mm/d* for the treated gutter, as shown in Figure 4.4c.



(a) From January 4th to February 2nd



(b) From March 3rd to March 22nd



(c) From June 26th to July 17th

Figure 4.5: Boxplot of Soil Moisture Changes (SM: measured by soil moisture content, WS: measured by weighing scale)

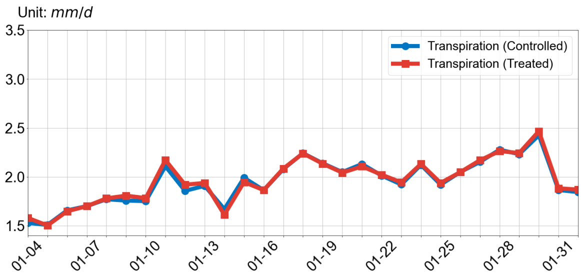
As can also be seen from Figure 4.5, the variation in soil moisture is typically greater when measured by then soil moisture content than by the weighing scale. The difference in soil moisture measurement methods may be attributed to two factors. Firstly, the weighing method measures soil moisture indirectly by detecting the change in mass, whereas soil moisture content measurements are usually derived by measuring the ratio of the volume of moisture in the soil to the total volume of the soil, and thus more directly reflect changes in soil moisture. Secondly, the soil moisture content method boasts greater sensitivity and can detect even small changes in soil moisture that may not be accurately measured by weighing scales.

The disparity is more pronounced in July than in January and March. This is probably due to the higher temperatures, which cause increased irrigation and evaporation, resulting in greater fluctuations in soil moisture.

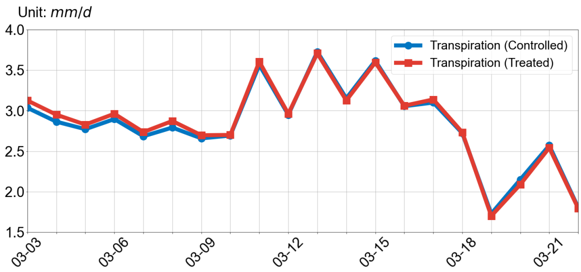
The soil moisture content method can be more accurate than the weighing scale method, especially in higher temperature conditions. As a result, soil moisture measured using the soil moisture content method is better used for further calculations.

Figure 4.5 also shows that there is only a slight difference in the changes in soil moisture between the controlled and treated gutter when the same measurements are used. This supports the assumption presented in Section 3.4 that when the environmental conditions in the greenhouse are the same, the water distribution is uniform throughout the greenhouse.

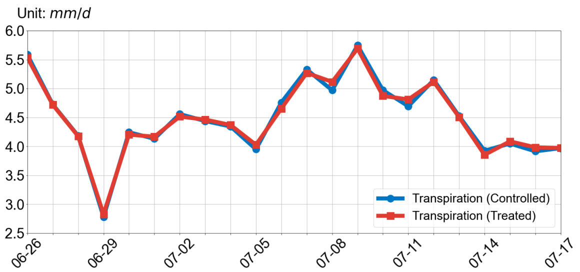
4.1.3. ESTIMATION OF TRANSPIRATION USING THE WATER BALANCE MODEL



(a) From January 4th to February 1st



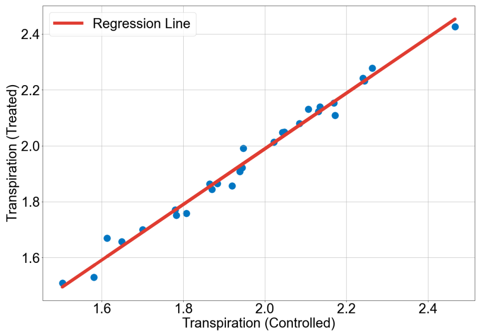
(b) From March 3rd to March 22nd



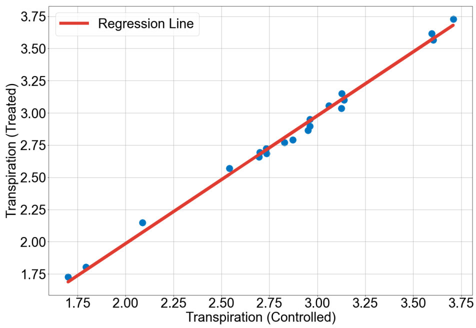
(c) From June 26th to July 17th

Figure 4.6: Transpiration estimated by the Water Balance Model

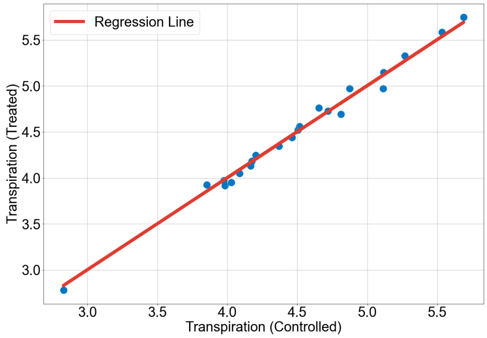
Figure 4.6 displays the transpiration estimated by the water balance model for the three periods. In January, transpiration ranged from 1.51 to 2.43 *mm/d* for the controlled gutter and from 1.50 to 2.47 *mm/d* for the treated gutter. In March, transpiration ranged from 1.73 to 3.73 *mm/d* for the controlled gutter and from 1.70 to 3.71 for the treated gutter *mm/d*. In July, transpiration rates were between 2.78 and 5.75 *mm/d* for the controlled gutter and between 2.83 and 5.69 *mm/d* for the treated gutter.



(a) From January 4th to February 1st



(b) From March 3rd to March 22nd



(c) From June 26th to July 17th

Figure 4.7: Scatter Plot of Estimated Transpiration for the Controlled and Treated Gutter

The regression lines for transpiration in the controlled and treated gutter are displayed in Figure 4.7. The upward slope of the fitted line suggests a positive correlation between the two sets of transpiration data.

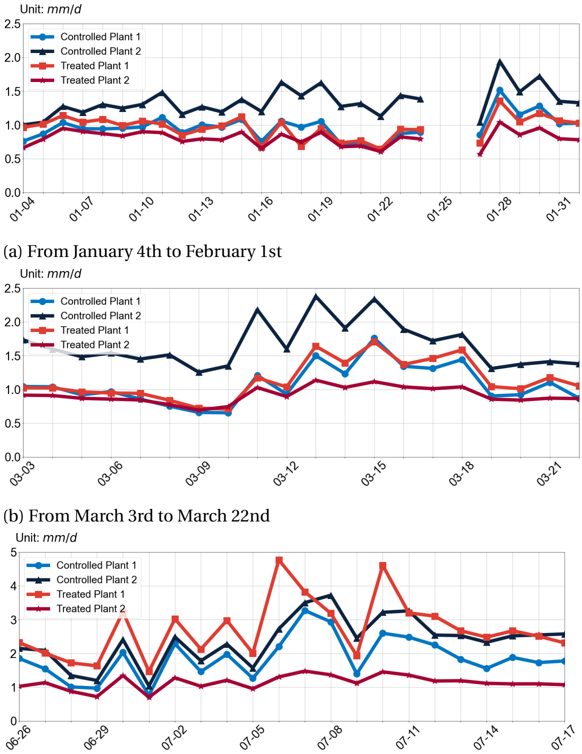
The table presents the correlation coefficient (*CC*) and root mean square error (*RMSE*). All three periods show a strong positive correlation between the variables, as the correlation coefficient is close to 1. The *RMSE* values are also close to 0, indicating that transpiration in the controlled gutter is similar to that in the treated gutter. The difference in transpiration estimation for both gutter is attributed to the difference in soil moisture changes. The high *CC* and low *RMSE* values suggest that transpiration is primarily influenced by irrigation and drainage, with soil moisture changes having minimal impact.

Table 4.1: Correlation Coefficiant and Root Mean Square Error for Transpiration in Gutter 2 and Gutter 5

	Correlation Coefficient	Root Mean Square Error (mm/d)
January	0.99	0.03
March	1.00	0.04
July	1.00	0.06

4.2. CORRECTION OF SAP FLOW

As discussed in Section 2.1.2, sap flow measurement is subject to several uncertainties that can compromise the reliability of the results. Therefore, calibration is necessary. This section first explains the variation of sap flow and then outlines the result of calibrating sap flow using estimated transpiration.



(a) From January 4th to February 1st

(b) From March 3rd to March 22nd

(c) From June 26th to July 17th

Figure 4.8: Transpiration estimated by the Water Balance Model

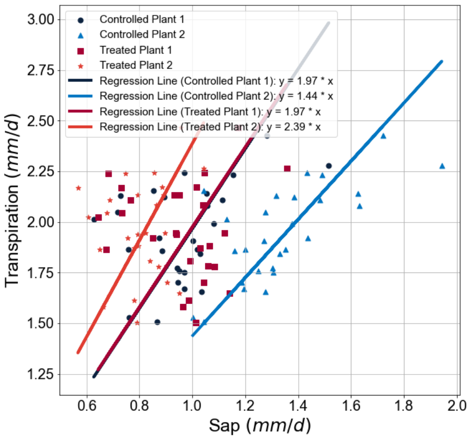
4.2.1. Variations of Sap Flow

Figure 4.8 displays the variation of sap flow during three periods. Even in the same environment, different plants may have different sap flow rates due to variability in plant physiology and response to environmental factors. In January, the sap flow of controlled plant 1 ranged from 0.63 to 1.52 *mm/d*, and for controlled plant 2, it ranged from 1.00 to 1.94 *mm/d*. In the treated gutter, the sap flow of plant 1 ranged from 0.64 to 1.36 *mm/d*, and for plant 2, it ranged from 0.57 to 1.04 *mm/d*. In March, the sap flow of plant 1 in the controlled gutter ranged from 0.65 to 1.76 *mm/d*, and for plant 2, it ranged from 1.26 to 2.38 *mm/d*. In the treated gutter, the sap flow of plant 1 ranged from 0.71 to 1.70 *mm/d*, and for plant 2, it ranged from 0.69 to 1.14 *mm/d*. In July, the sap flow rates were between 0.76 and 3.27 *mm/d* for controlled plant 1, and between 1.04 and 3.73 *mm/d* for controlled plant 2. The sap flow of treated plant 1 varied from 1.47 to 4.77 *mm/d*, and for plant 2, it varied from 0.70 to 1.48 *mm/d*.

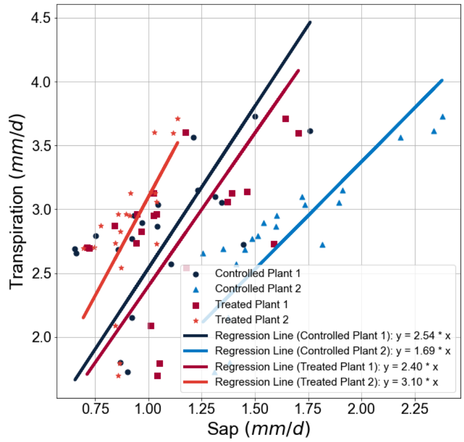
Figure 4.8a and Figure 4.8b show that all four plants have similar trends in sap flow over time. However, there is a slightly higher sap flow for controlled plant 2 compared to the other plants. This difference may be due to individual variations among the plants.

Figure 4.8c illustrates that sap flow is higher in July. Although plants still exhibit similar trends of sap flow over time, the difference in sap flow between controlled and treated gutter is relatively high. Treated plant 1 exhibits higher sap flow values than the controlled plants, whereas treated plant 2 displays relatively lower sap flow values than the plants in controlled gutter.

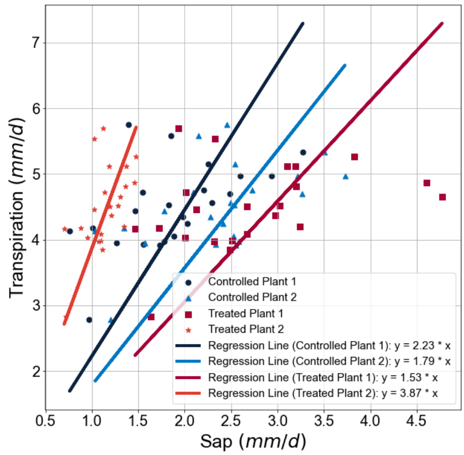
4.2.2. CALIBRATION OF SAP FLOW WITH ESTIMATED TRANSPIRATION



(a) From January 4th to February 1st



(b) From March 3rd to March 22nd



(c) From June 26th to July 17th

Figure 4.9: Scatter Plot for the Estimated Transpiration and Sap Flow

Figure 4.9 shows the fitted line for sap flow of all plants and transpiration during three periods. Specific details can be found in the Table below.

Table 4.2 first displays the proportional relationship between sap flow (x) and transpiration (y). Different plants may have different relationships between sap flow and transpiration even in the same environment due to variability in plant physiology and response to environmental factors. The table also shows the correlation coefficient (*CC*) and the Root Mean Square Error (*RMSE*). *CC* values are relatively low for both treated plants in January. *RMSE* is higher in July and this is due to the dispersion of points in both the control plants and the treated plant 2 in July, as shown in Figure 4.9c.

Table 4.2: Relationship between Sap Flow and Transpiration (x=sap flow, y=transpiration)

		Relationship	RMSE (mm/d)	CC
January	Controlled Plant 1	y=1.97x	0.34	0.41
	Controlled Plant 2	y=1.44x	0.22	0.70
	Treated Plant 1	y=1.97x	0.42	-0.06
	Treated Plant 2	y=2.39x	0.33	0.11
March	Controlled Plant 1	y=2.54x	0.57	0.63
	Controlled Plant 2	y=1.69x	0.30	0.84
	Treated Plant 1	y=2.40x	0.64	0.47
	Treated Plant 2	y=3.10x	0.41	0.61
July	Controlled Plant 1	y=2.23x	1.21	0.53
	Controlled Plant 2	y=1.79x	1.06	0.54
	Treated Plant 1	y=1.53x	1.05	0.40
	Treated Plant 2	y=3.87x	0.69	0.55

The correlation coefficients between estimated transpiration and sap flow are low for treated plants in January, with treated plant 1 even showing a negative correlation coefficient, indicating that transpiration decreases as transpiration increases. Looking at the time series of transpiration and sap flow (Figure 4.10), there appeared to be an opposite trend between estimated transpiration and sap flow in boxes. For instance, sap flow for both plants decreased on 9 January, whereas transpiration increased on 9 January.

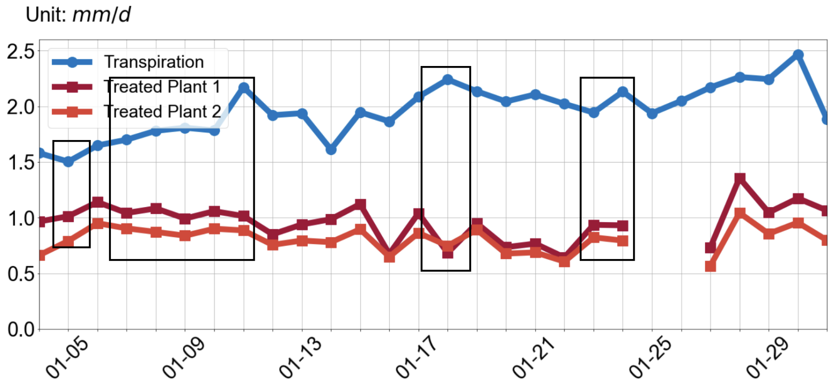


Figure 4.10: Time Series of Sap flow and Transpiration in January

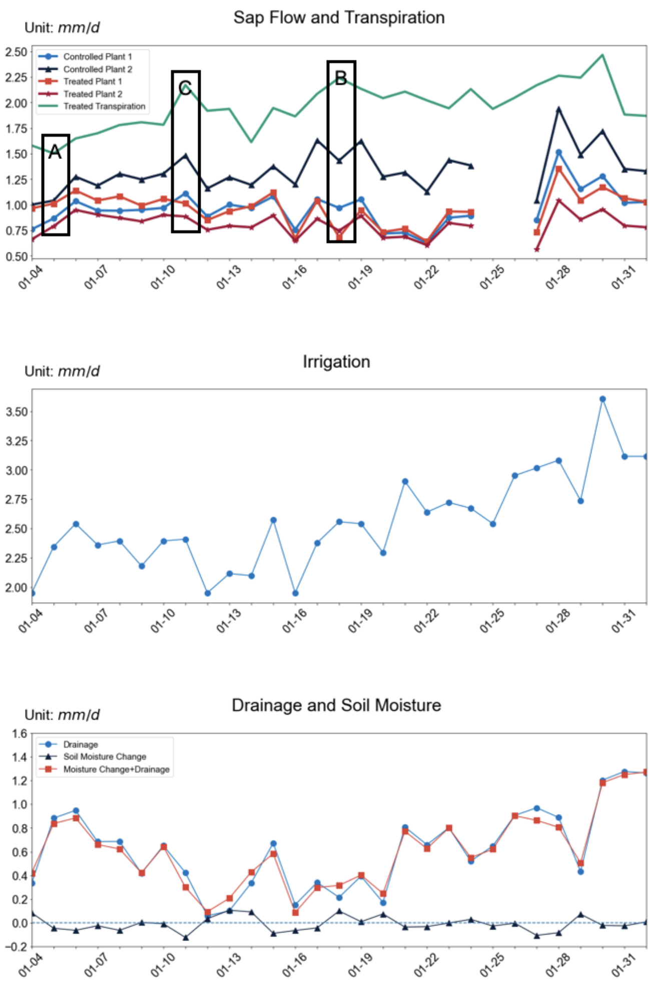


Figure 4.11: Time Series of the Components in the Estimation of Transpiration

Figure 4.11 presents changes over time in sap flow in treated plants and changes over time in components in transpiration estimates. In Box A, although irrigation may not fully satisfy the plant's water requirements, plants can still absorb water from the soil to maintain sap flow (negative soil moisture changes) due to their relatively low water requirement. In Box B, irrigation may exceeds the required value. Water supersaturation in the soil may limit water uptake capacity, therefore reducing sap flow rates. In January, plants appear to be more sensitive to soil moisture. Sap flow sensors can directly measure changes in water movement within the plant to accurately capture the plant's response to changes in soil moisture. In contrast, the water balance model is not as sensitive to changes in soil moisture, which is also stated in Section 4.1.3. In Box C, the controlled and treated plants exhibited opposite changes in sap flow. This could be attributed to unreliable measurements taken at low sap flow rates. Hence, sap flow measurements taken in January may be unreliable, and as a result, they were not taken into account in subsequent calculations.

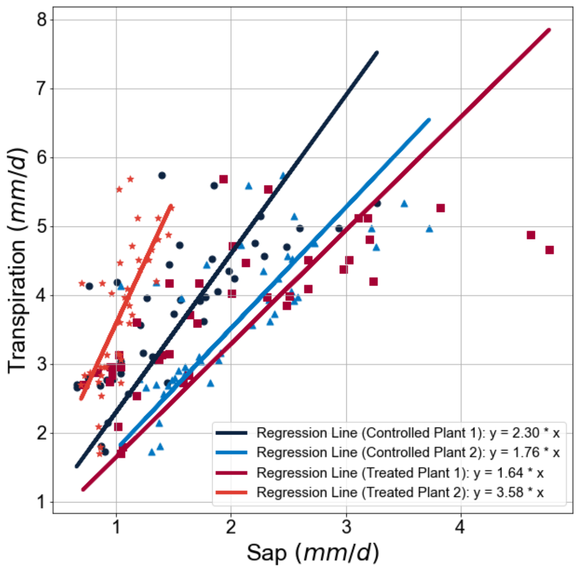


Figure 4.12: Scatter Plot for the Estimated Transpiration and Sap Flow in March and July

To enhance data reliability, the data for March and July were combined for analysis. The scatter plot in Figure 4.12 displays the relationship between the plant sap flow and estimated transpiration for both gutter in March and July. Details can be seen in Table 4.3. The combined months' CC value is higher than the value calculated for each individual month. Therefore, these relationships can be used further to calibrate the sap flow.

Table 4.3: Relationship between Sap Flow and Transpiration in March and July (x=sap flow, y=transpiration)

		Relationship	RMSE (mm/d)	CC
January	Controlled Plant 1	y=2.30x	0.98	0.76
	Controlled Plant 2	y=1.76x	0.80	0.74
	Treated Plant 1	y=1.64x	0.80	0.80
	Treated Plant 2	y=3.58x	0.72	0.72

The slopes of the relationships for all plants are greater than 1. This may be due to the assumption that the area covered by each stem is $\frac{150}{6\times8\times3}$ m^2 when converting the mass flow rate of individual stems to estimated transpiration per unit area of land. It is assumed that plant leaves cover the entire greenhouse and that the leaf coverage of two stems of the same plant overlap. In reality, there are parts of the greenhouse that are not covered by leaves, such as the roads between the two gutters. Therefore, the assumed area covered by each stem is larger than in reality, resulting in a smaller measured transpiration through sap flow than in reality.

4.3. EFFECT OF SALINITY ON TRANSPIRATION

This section presents the impact of elevated electrical conductivity on transpiration. It displays the variations in electrical conductivity throughout the experiment and compares it with transpiration to determine any correlation between the two, while considering other factors that may affect transpiration. Finally, this study presents the time series results of transpiration in control and treated gutters to examine the effect of increased salinity on transpiration, excluding other factors affecting transpiration.

The experiment was conducted from 2 February to 2 March. Plants from gutter 2 were used as the control plants, while plants from gutter 5 as the treated plants.

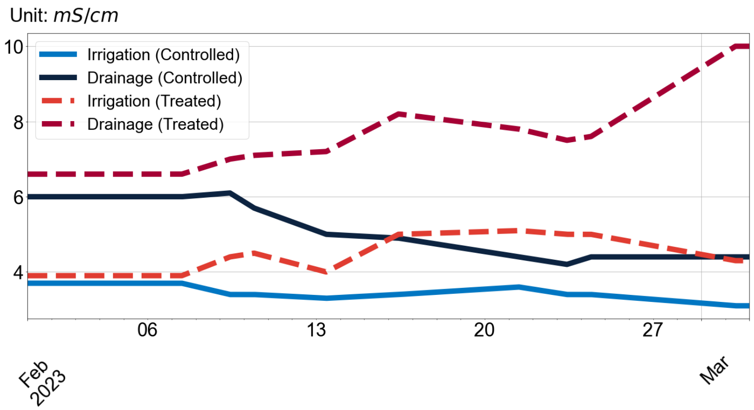


Figure 4.13: Time Series of Electrical Conductivity

4.3.1. ELECTRICAL CONDUCTIVITY

The change in conductivity conductivity (*EC*) over time is shown on Figure 4.13. The *EC* in the irrigation water for the control plants ranges from 3.1 to 3.8 *mS/cm* and for the treated plants from 3.9 to 5.1 *mS/cm*. The *EC* in the drainage water is between 4.2 and 6.1 *mS/cm* for the controlled plants and between 6.6 and 10.0 *mS/cm* for the treated plants. The *EC* of the drainage water is consistently higher than that of the irrigation water both for the controlled plants and for the treated plants, suggesting that there is an accumulation of dissolved salts in the soil, leading to an increase in salt concentration in the drainage water. Soil salinisation may continue to limit root growth and reduce soil water availability.

For the controlled gutter, the difference in *EC* between drainage and irrigation decreases over time. This means there was a reduction in the accumulation of soil salts during the experiment period. The reasons are as follows: Firstly, the *EC* content in the irrigation water was not high enough to cause further accumulation of soil salts; secondly, the plants absorbed some of the nutrients; and finally, the salts in the soil were leached out with the drainage of the system. On the other hand, the difference in *EC* increases over time for the treated plant. This is due to the increased salt content of the irrigation water, which leads to further accumulation of soil salts.

4.3.2. COMPARISON BETWEEN ELECTRICAL CONDUCTIVITY AND TRANSPIRATION

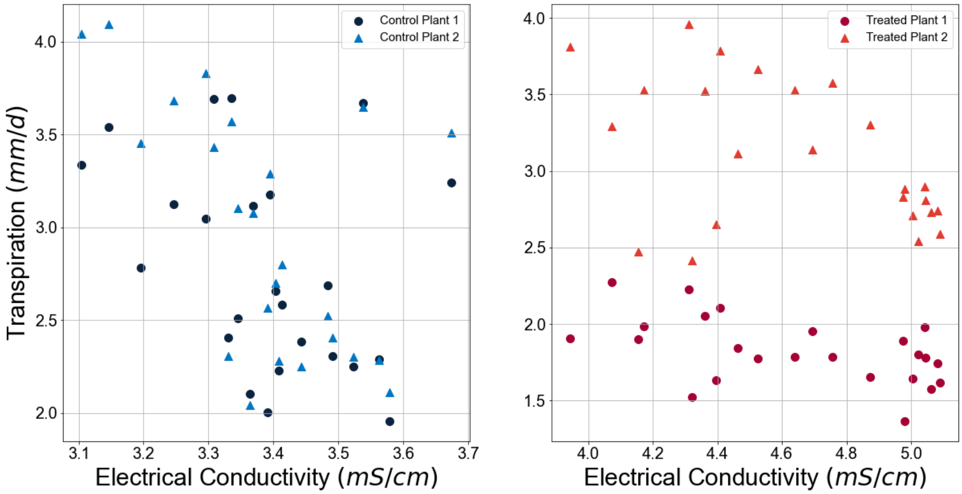


Figure 4.14: Scatter Plot of Electrical Conductivity and Transpiration

Figure 4.14 displays scatter plots of the electrical conductivity and transpiration for both the controlled and treated plants. It appears that there is a decreasing trend in which transpiration decreases as the electrical conductivity increases. However, from this analysis alone, it is not completely conclusive whether salinity directly reduces transpiration rate, as other factors such as temperature, radiation, humidity, and irrigation methods also affect transpiration rate.

The rate of transpiration decreased less in the treated plants compared to the control plants, indicating that the treated plants were more tolerant to salinity. This suggests that the plants may have developed some adaptation to high salinity conditions.

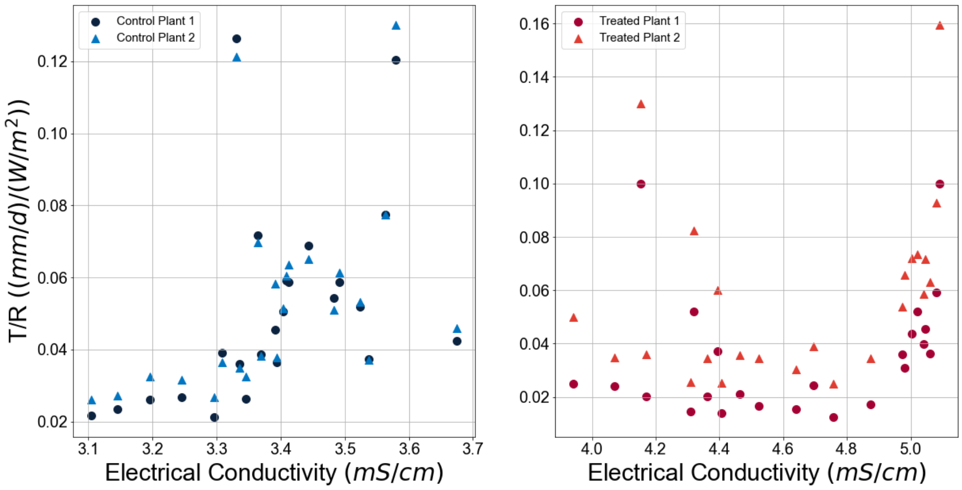


Figure 4.15: Scatter Plot of Electrical Conductivity and Transpiration/Radiation

Previous studies have indicated that transpiration is primarily influenced by radiation. Figure 4.15 displays scatter plots of the electrical conductivity and transpiration/radiation *(T/R)* for both the controlled and treated plants. For the controlled gutter, *T/R* values increased progressively with an increase in electrical conductivity. For the treated gutter, as electrical conductivity increases, there is more dispersion of *T/R* values. Radiation values are relatively high compared to transpiration values. The effect of radiation on the *T/R* ratio was more pronounced due to the relatively high radiation values. Although increased salinity may reduce transpiration, this reduction is insignificant in the presence of high radiation values. Consequently, larger values of radiation make changes in transpiration have less effect on the ratio of *T/R* ratios, leading to an increase in *T/R* ratios as electrical conductivity increases.

4.3.3. TIME SERIES OF THE TRANSPIRATION RATE AT DIFFERENT SALINITY LEVELS

The temporal variation of daily transpiration during the experimental period are shown in Figure 4.16. After February 7 (the start time for recording increases in EC of irrigation for the treated gutter), the transpiration rates of treated plant 2 were generally lower than those of the controlled plants and treated plant 1. This suggests that transpiration decreases as salinity increases. On sunny days (high transpiration rates for the controlled plants), the difference in transpiration rates between treated plant 2 and the other plants was more pronounced. This observation suggests that high transpiration rates may exacerbate the effect of salinity on transpiration.

In Figure 4.16, the daily transpiration was relatively higher on the 13th and lower on the 23rd, so these two days were chosen to observe the variations within a day. Figure

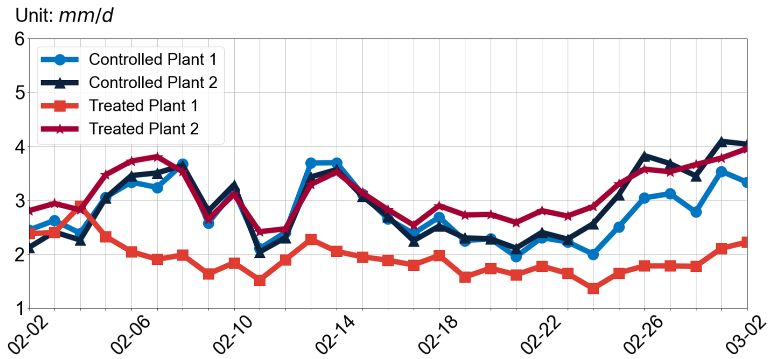


Figure 4.16: Time Series of Transpiration during Elevated Salinity Experiment

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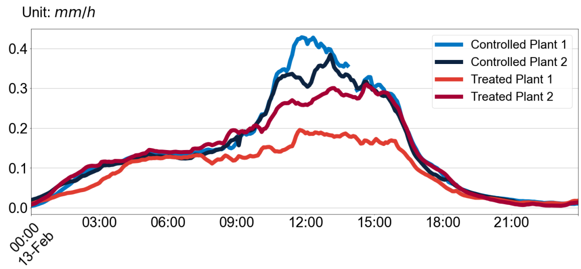
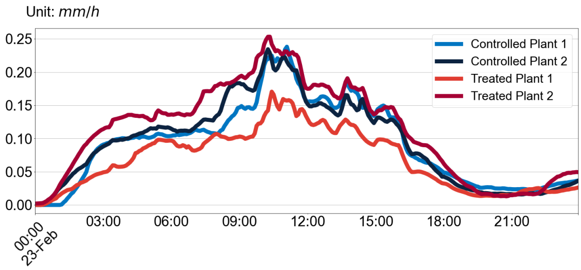
4.17 shows the variation in transpiration over the course of the day. This graph shows that there is a peak in the transpiration rate, which increases in the morning and gradually decreases in the evening. On 13 February, the maximum peaks occurred between 11:45 and 14:40, with peaks of 0.43, 0.38, 0.20 and 0.31 *mm/h* for the controlled plant 1 and 2 and the treated plant 1 and 2, respectively. On 23 February, the maximum peaks were between 10:15 and 11:05, with peaks of 0.24, 0.23, 0.17 and 0.25 *mm/h* for the controlled plants 1 and 2 and the treated plants 1 and 2. These results indicate that, when many other environmental conditions are held constant, there is a decrease in transpiration rate as soil salinity increases at high transpiration rates. And at low transpiration rates, there is no significant variation in transpiration rate with soil salinity.

Previous studies have shown that salinity can lead to reduced water uptake and growth, resulting in smaller plants with less leaf area and root growth. It also causes stomatal closure. As a result, these salt-affected plants would transpire less. Our results are consistent with these findings, showing a significant effect of salinity on transpiration under high transpiration conditions. However, under conditions of low transpiration, the effect of salinity on transpiration is less significant. This could be attributed to the fact that the plants require less water. Furthermore, the physiological activity of the plants may slow down during periods of low transpiration, leading to less noticeable or delayed responses to salinity. Furthermore, the crop's ability to tolerate soil salinity may increase in conditions of reduced transpiration. This is due to the fact that environmental factors, such as temperature and humidity, which regulate transpiration needs, also impact the salinity of the soil directly beneath the roots (Minhas et al., 2020).

There was no significant difference in transpiration between treated plant 2 and the control plants. This observation may be explained by 2 factors, including differences in growth conditions, and variations in plant tolerance to salinity. Firstly, as discussed in the Section 4.3.1, salt accumulates in the soil, and salt salinity may not be uniformly distributed (Minhas et al., 2020). This non-uniform distribution of salt could lead to differences in plant growth even under similar environmental conditions. Therefore, treated plant 2 may be larger than treated plant 1. Secondly, treated plant 2 may suggest



(a) On February 13



(b) On February 23

Figure 4.17: Variation of the Transpiration in a Day under Different Salt Stress Treatments

a higher tolerance to salinity. This aligns with the second reason, as larger plants often possess greater adaptive capabilities.

Elevated salinity can reduce transpiration, especially during periods of high transpiration demands. Therefore, smaller irrigation inputs may suffice to meet crop water needs. To mitigate soil salinization caused by salinity in irrigation water, more frequent irrigation may be recommended. Furthermore, it is advisable to implement salt leaching during non-crop periods to prevent salt accumulation in the greenhouse soil. Salt leaching can be achieved by applying excess water to the soil to flush out accumulated salts.

4.4. Effect of leaf area on Transpiration

This section presents the impact of reduced leaf area on transpiration. It first shows the variations in leaf area index throughout the experiment and then compares it with weekly transpiration to determine any correlation between the two, while considering other factors that may affect transpiration. Finally, this study presents the time series results of transpiration in control and treated gutters to examine the effect of reduced leaf area index on transpiration, excluding other factors affecting transpiration.

Week 19 is between 8 and 14 May, week 21 is between 22 and 28 May, week 23 is between 5 and 11 June and week 25 is between 19 and 25 June.

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4.4.1. LEAF AREA INDEX

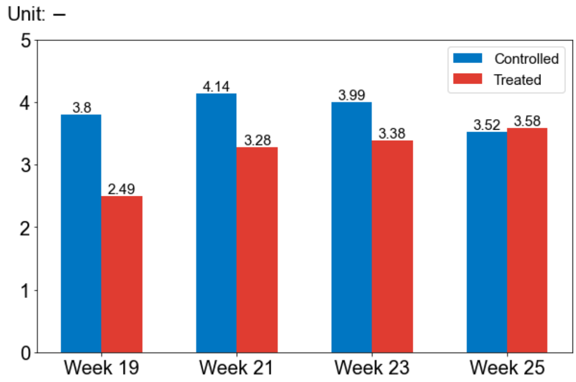


Figure 4.18: Time Series of Leaf Area Index

The leaf area index (*LAI*) was measured weekly after manually removing the leaves. Figure 4.18 illustrates the variation in leaf area index between the controlled and treated gutters over several weeks. As the number of weeks increased, the difference in leaf area index between the two became smaller until there was little disparity.

4.4.2. COMPARISON BETWEEN LEAF AREA INDEX AND TRANSPIRATION

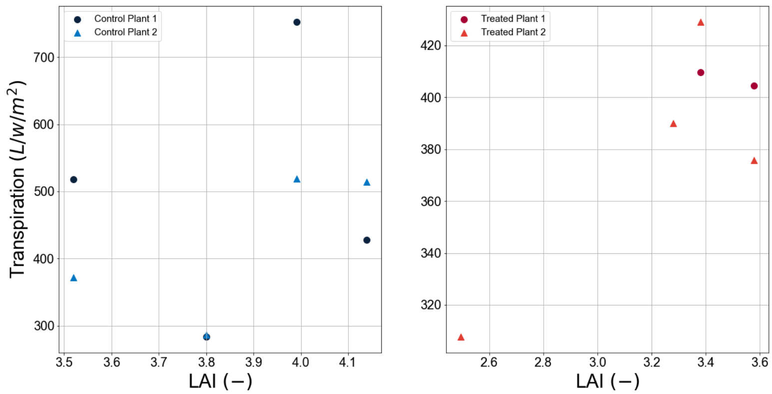
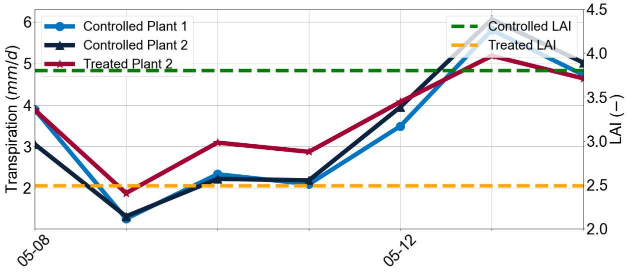


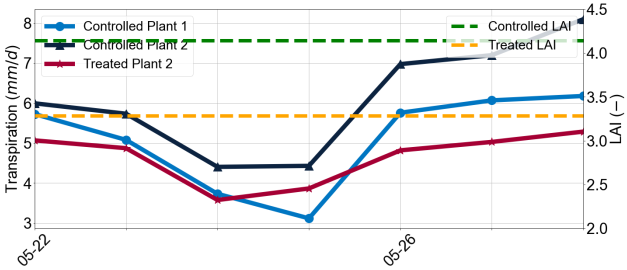
Figure 4.19: Scatter Plot of Leaf Area Index and Transpiration

The scatter plot in Figure 4.19 displays the relationship between leaf area index and weekly transpiration. However, the relationship is not clearly visible due to two possible reasons. Firstly, transpiration is influenced by other factors such as irrigation, radiation, and temperature. Secondly, the small number of data points can not provide a reliable relationship.

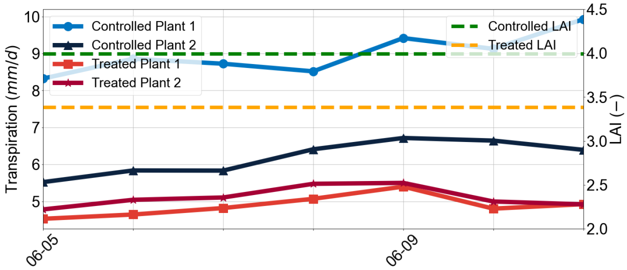
4.4.3. TIME SERIES OF THE TRANSPIRATION RATE AT DIFFERENT LEAF AREAS



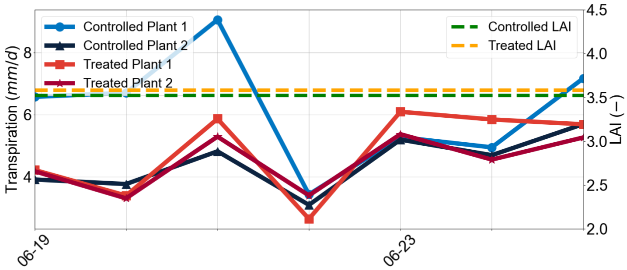
(a) 8-14 May



(b) 22-28 May



(c) 5-11 June



(d) 19-25 June

Figure 4.20: Time Series of the Transpiration under Different Leaf Area Index

The variation of daily transpiration under different leaf areas were shown in Figure 4.20. As the sap flow sensor recorded unusually high values from May 5 to May 22 for treated plant 1, which were deemed unreliable, sap flow data for treated plant 1 during this period were removed. In week 19, transpiration rates for controlled plant 1 ranged from 1.26 to 5.81 *mm/d*, transpiration rates for controlled plant 2 ranged from 1.32 to 6.07 *mm/d*, and transpiration rates for treated plant 2 ranged from 1.88 to 5.18 *mm/d*. There was no significant difference in transpiration between the controlled and treated plants. Prior to May 12, transpiration in treated plant 2 was marginally higher than that of the controlled plants. However, after May 12, transpiration in treated plant 2 was slightly lower than that of the controlled plants. During week 21, the transpiration rates of controlled plant 1 ranged from 3.12 to 6.18 *mm/d*, while those of controlled plant 2 ranged from 4.40 to 8.10 *mm/d*. The transpiration rates of treated plant 2 ranged from 3.57 to 5.29 *mm/d*, and were slightly lower than those of the controlled plants, except for May 25. During week 23, the transpiration rates of control plant 1 were between 8.32 and 9.93 *mm/d* and those of control plant 2 were between 5.52 and 6.72 *mm/d*. On the other hand, the transpiration rates of treated plant 1 were between 4.53 and 5.40 *mm/d* and those of treated plant 2 were between 4.78 and 5.50 *mm/d*. It is evident that the transpiration rates of the treated plants are lower than those of the controlled plants. During week 25, the transpiration rates of control plant 1 ranged from 3.43 to 9.96 *mm/d*, and those of control plant 2 ranged from 3.09 to 6.09 *mm/d*. In contrast, the transpiration rates of treated plant 1 ranged from 2.64 to 6.09 *mm/d*, and those of treated plant 2 ranged from 3.30 to 5.37 *mm/d*. The transpiration rates for the treated plants and control plant 2 were quite similar. However, before May 22, control plant 1 had a much higher transpiration rate than the other plants. There is no direct positive correlation between transpiration and leaf area index.

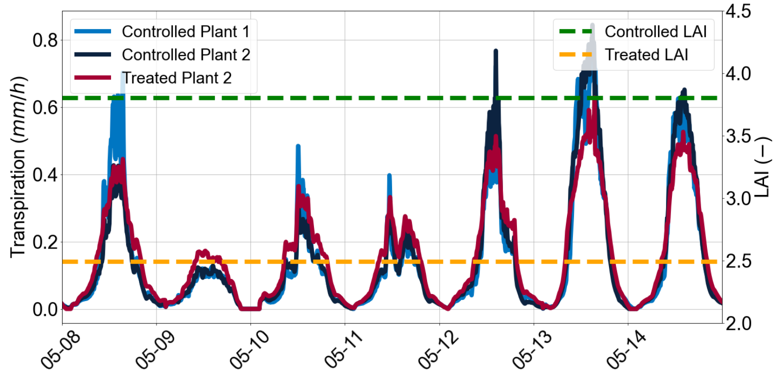


Figure 4.21: Variation of the Transpiration in a Day under Different Leaf Area (Week 19)

Figure 4.21 displays the transpiration variation per 5 minutes in week 19. Prior to May 12, the transpiration rate was relatively low, with peak values lower or equal to 0.4. There was no difference in transpiration between the controlled and treated plants. After May 12, there was still not much difference when the transpiration rate was low. However, around peak values (transpiration rate larger than 0.4), the treated plants exhibited lower transpiration rates than the controlled plants.

During weeks 19 and 21, only one sap flow measurement was available for the treated plants. This limited the ability to verify the accuracy of the sap flow data for treated plants.

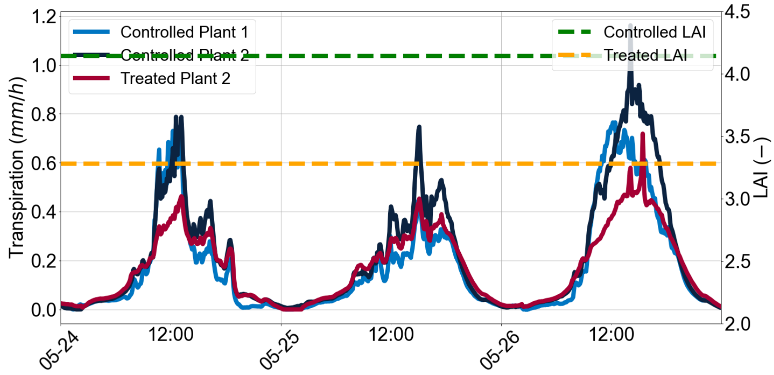


Figure 4.22: Variation of the Transpiration in a Day under Different Leaf Area (24-26 May)

Figure 4.22 shows the transpiration variation every 5 minutes from 24 to 26 May. It indicates that the treated plants had lower transpiration rates than the controlled plants during periods of high transpiration, similar to the results shown in Figure 4.19. On May 25, the transpiration rate for controlled plant 1 was relatively low, so it did not differ significantly from the transpiration of the treated plants.

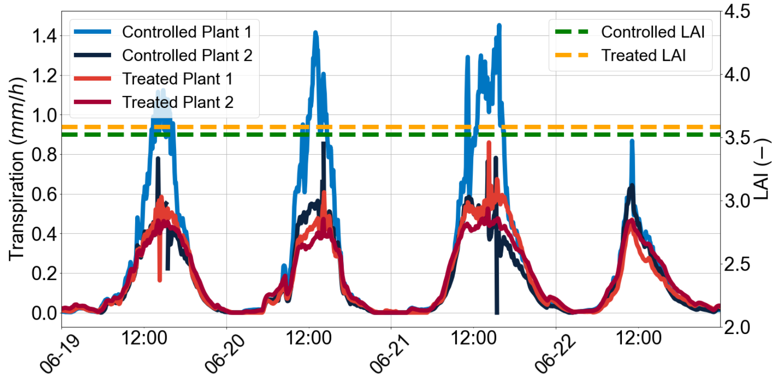


Figure 4.23: Variation of the Transpiration in a Day under Different Leaf Area (19-22 June)

Figure 4.23 shows the transpiration variation every 5 minutes from 19 to 22 June. In week 25, there was little difference in leaf area index between the controlled and treated plants, with the treated plants even having a slightly larger LAI. However, prior to June 22, controlled plant 1 transpired more than the other plants during the midday. The reasons for this difference may be as follows. In week 23, the leaf area index of the controlled plants was higher. In week 25, some leaves were manually removed from the controlled plants. It is possible that the leaves of controlled plant 1 were not removed before 22 June, which may have resulted in a higher transpiration rate at midday compared to the other plants.

When transpiration was low, the Leaf Area Index (LAI) did not have an effect on it. However, when transpiration was high, it increased with an increase in LAI. It appears that there is a threshold for transpiration, beyond which the leaf area index can significantly impact plant transpiration rates. During periods of low transpiration, such as in the morning or evening, plant water use is low and the leaf area provides a sufficient surface for water vapour exchange, transpiration is mainly influenced by other factors such as air temperature, humidity, and soil moisture, rather than being directly affected by the LAI. However, an increase in LAI can significantly increase transpiration rates during mid-day hours when the plant is in a higher transpiration state. This is because more water vapour exchange surface and more stomata are required at that time.

Reducing leaf area can decrease transpiration, especially during periods of high demand. Therefore, smaller irrigation inputs may be sufficient to meet crop water requirements.

4.5. EFFECT OF WATER AVAILABILITY ON TRANSPIRATION

From September 7 to September 14, the amount of irrigation water in the treated gutter was reduced to 66% of that in the controlled gutter. Subsequently, from September 14 to September 22, it was further reduced to 33% of the controlled amount. Finally, from September 22 to September 26, no water was provided for the controlled gutter.

As the sap flow sensor provided unreliable values for treated plant 2 from September 7 to September 26, data for this plant during this period has been removed.

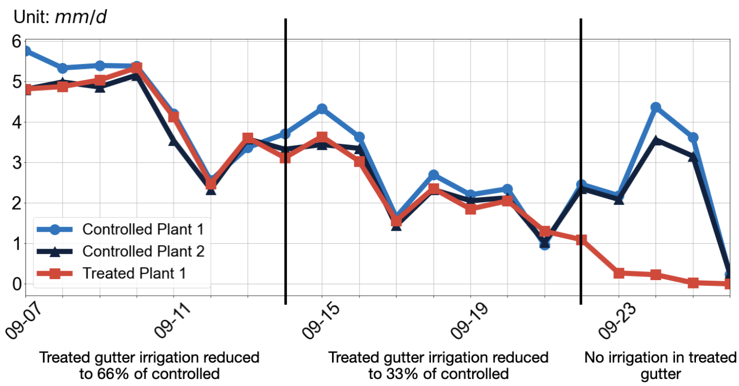


Figure 4.24: Time Series of the Transpiration under Different Water Supply Conditions

Figure 4.24 illustrates that there was little difference in transpiration between the controlled and treated plants prior to September 22. This suggests that even if the irrigation amount is reduced to 33% of the original amount, there may not be a significant difference in transpiration.

The ability of treated plants to maintain stable transpiration under limited water conditions may be due to three reasons. Firstly, treated plants increase water use efficiency by regulating stomatal opening to adapt to the lack of water. Secondly, treated plants may adaptively adjust to diminished water availability by decelerating growth and reallocating resources to the root system to enhance water uptake. Thirdly, it is possible that the drought may have a delayed effect, as there is a clear effect on transpiration after 22 September.

Reducing irrigation to even 33 percent of its original level had no effect on transpiration, indicating that the plants may be receiving more irrigation water than required. Therefore, it is highly recommended to reduce irrigation in practice.

5

CONCLUSION

The aim of this report was to analyse the effects of environmental treatments, such as elevated salinity, reduced leaf area, and insufficient water availability on transpiration. To do so, the daily transpiration measured by the sap flow method was first compared with the daily transpiration estimated by the soil water balance to correct the transpiration measured by the sap flow method. The study then compared transpiration estimates from the sap flow method for the controlled and treated gutters to investigate the effects of environmental treatments on transpiration. Finally, recommendations were provided for irrigation to meet the plants' exact requirements.

The correlation between daily transpiration estimated by the soil water balance model and sap flow method is good, as evidenced by the high correlation coefficient and low root mean square error. Therefore, the corrected transpiration measured by the sap flow method is a reliable indicator of transpiration. The corrected coefficients for controlled plants 1 and 2, and treated plants 1 and 2 are 2.30, 1.76, 1.64, and 3.58, respectively. These corrected coefficients can be used to improve the accuracy of the sap flow method when measuring transpiration in this greenhouse.

The comparison of transpiration between control and treatment gutters in three experiments revealed that increased salinity and reduced leaf area decreased transpiration, particularly during periods of high transpiration demand. Additionally, reducing the amount of water available in the greenhouse to 33% of the original amount did not have a significant effect on transpiration, while no irrigation gradually reduced transpiration to 0.

The irrigation recommendations below aim to accurately meet the crop's water requirements. Firstly, it is recommended to increase the frequency of irrigation and reduce the amount of irrigation water when salinity increases. During the non-planting period, salting out is recommended to reduce the accumulation of salts in the soil. Additionally, when the leaf area decreases, the required amount of irrigation water can be appropriately reduced. In this greenhouse, irrigation can be reduced by up to 66% as the original amount is excessive for the plants.

This study have mainly concentrated on the effect of environmental treatments on plant transpiration, with irrigation recommendations primarily focused on meeting the transpiration needs of plants. However, irrigation practices should also consider the growth requirements of plants to improve water use efficiency. In future studies, it is recommended to investigate the impact of environmental treatments on water use efficiency to further refine irrigation strategies. Furthermore, in light of the possibility that drought may have a delayed effect on transpiration, further research is required to determine the extent to which irrigation water is being reduced.

6
Appendix

6.1. Removal of Data Error

This section introduces the removal of data errors for soil moisture content and sap flow.

6.1.1. Moisture Content

The moisture content in the soil significantly influences the water availability to plant roots, consequently exerting an impact on transpiration. Therefore, achieving a precise determination of soil moisture content is essential for accurate transpiration estimation. In this study, the measurement of soil moisture content is executed using soil moisture probes at Delphy, which provide values in volumetric contents. These probes are sensitive to local soil conditions and therefore need to be calibrated for specific soils to ensure accuracy and reliability of measurements. Calibrations are assumed to be done in this experiment.

Despite the implementation of soil-specific calibrations, various errors still exist for continuous measurements. These errors may arise from probe-soil contact discontinuities and expected small-scale environment variations. As illustrated in Figure 6.1 to Figure 6.5, measurement errors can be divided into five different scenarios from January 5th to January 31st and from July 1st to July 19th.

Scenario A

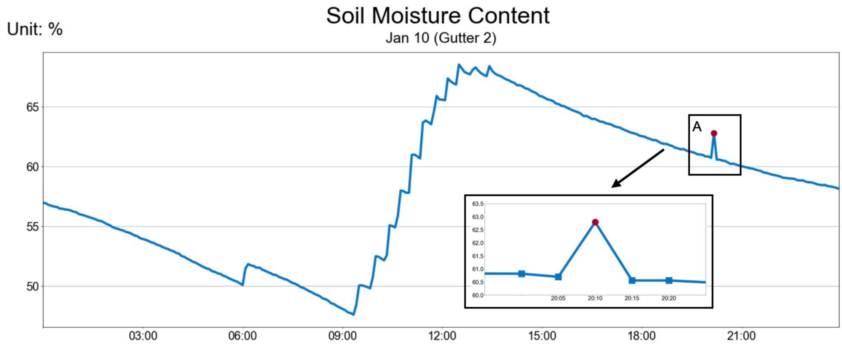


Figure 6.1: Error in Moisture Content Measurement (Scenario A)

Scenario B

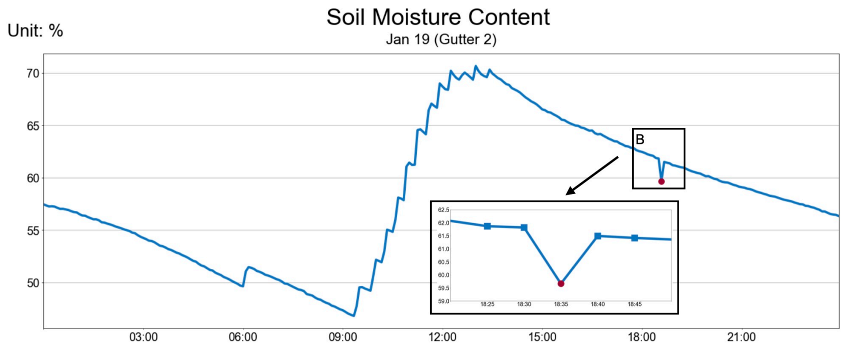


Figure 6.2: Error in Moisture Content Measurement (Scenario B)

Scenario C

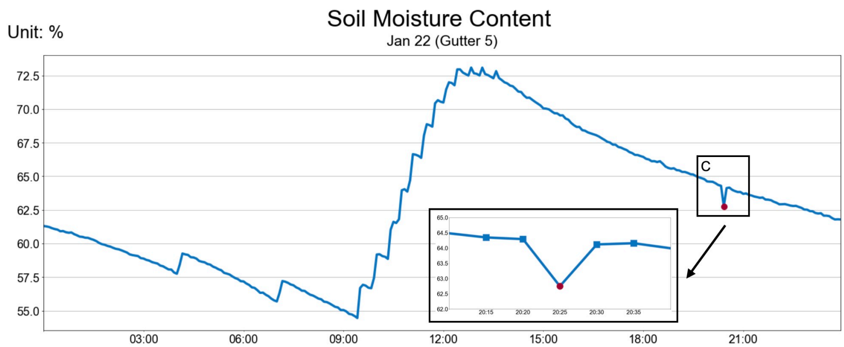


Figure 6.3: Error in Moisture Content Measurement (Scenario C)

Scenario D

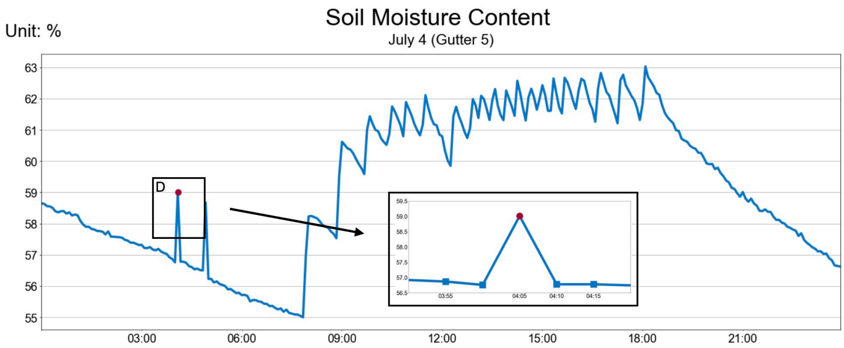


Figure 6.4: Error in Moisture Content Measurement (Scenario D)

Scenario E

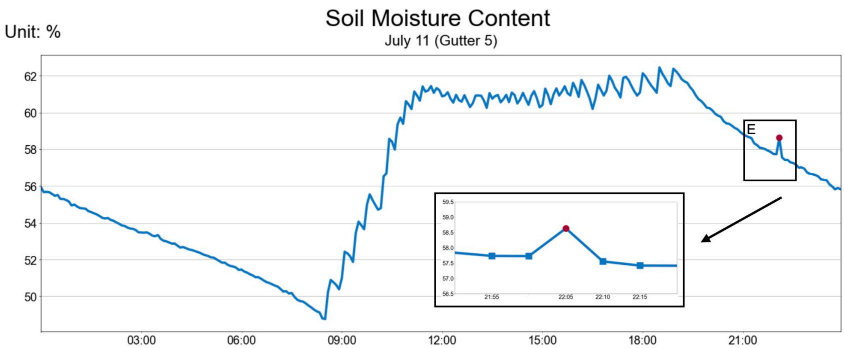


Figure 6.5: Error in Moisture Content Measurement (Scenario E)

The moisture content is automatically measured every 5 minutes and the change in moisture content over five minutes should remain below 1%. By comparing the change in water content at five adjacent points, the above-mentioned scenarios can be translated into the mathematical expression shown below, which provides a quantitative framework for eliminating errors in soil moisture content measurement.

Scenario A

There is a sudden upward point in the overall downward trajectory. The following are the mathematical expressions for this scenario:

$$MC_{t-1} - MC_{t-2} \leqslant 0$$

$$MC_{t+2} - MC_{t+1} \leqslant 0$$

$$MC_t - MC_{t-1} \geqslant 1$$

$MC_t - MC_{t+1} \geqslant 1$

Scenario B

There is a point of rapid descent throughout the failing trajectory. The following are the mathematical expressions for this scenario:

$MC_{t-1} - MC_{t-2} \leqslant 0$

$MC_{t+2} - MC_{t+1} \leqslant 0$

$MC_t - MC_{t-1} \leqslant -1$

$MC_t - MC_{t+1} \leqslant -1$

Scenario C

A concave point suddenly appears in a process that is otherwise stable and continuous. The mathematical expression for this situation is detailed below:

$-1 \leqslant MC_{t-1} - MC_{t-2} \leqslant 0$

$0 \leqslant MC_{t+2} - MC_{t+1} \leqslant 1$

$MC_t - MC_{t-1} \leqslant -1$

$MC_t - MC_{t+1} \leqslant -1$

Scenario D

A sudden bump appears in a process that is otherwise stable and continuous. The mathematical expression for this situation is detailed below:

$-1 \leqslant MC_{t-1} - MC_{t-2} \leqslant 0$

$0 \leqslant MC_{t+2} - MC_{t+1} \leqslant 1$

$MC_t - MC_{t-1} \geqslant 1$

$MC_t - MC_{t+1} \geqslant 1$

Scenario E

There is another case of bump. The mathematical expressions for this scenario are shown below:

$0 \leqslant MC_{t-1} - MC_{t-2} \leqslant 1$

$-1 \leqslant MC_{t+2} - MC_{t+1} \leqslant 0$

$MC_t - MC_{t-1} \geqslant 1$

$$MC_t - MC_{t+1} \geqslant 1$$

With:
MC_t: Moisture Content at time t (%)

6.1.2. SAP FLOW MEASUREMENT

As depicted in Figure 6.6, sap flow measurements are automatically taken at five-minute intervals. Between 5 May and 31 May, there was a significant increase in sap flow for plant 1 in gutter 5 compared to the other plants. This could be due to the data recording error. As a result, the value for plant 1 in the treated was removed first.

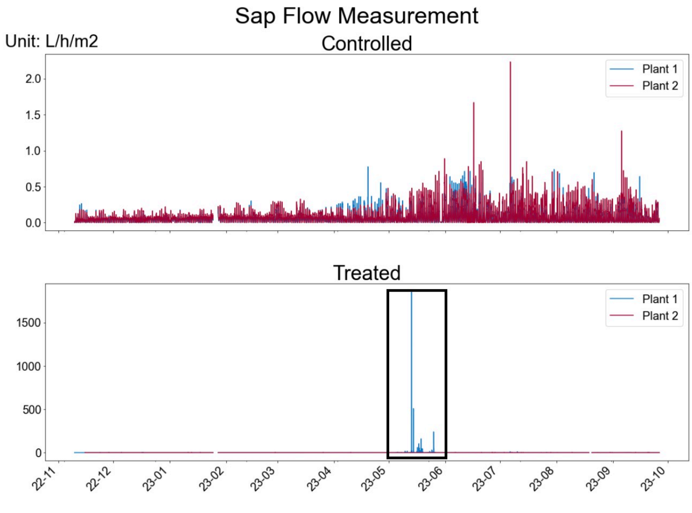


Figure 6.6: Sap Flow Measurement Throughout the Year

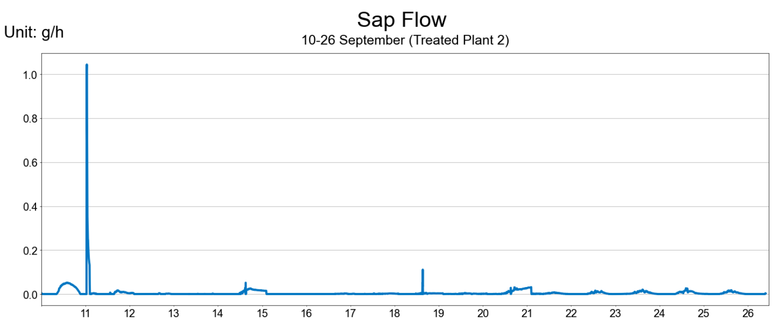


Figure 6.7: Sap Flow of Treated Plant 1 from 10-26 September

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Sap flow typically follows a pattern of increasing in the morning, peaking in the afternoon, and decreasing in the evening. However, there was no such change in sap flow between 10 September and 26 September. Thus, the sap flow variation of treated plant 2 was deemed unreliable between 10-26 September, and as a result, the values for this period were excluded.

6.1.3. WEIGHING SCALE VALUES

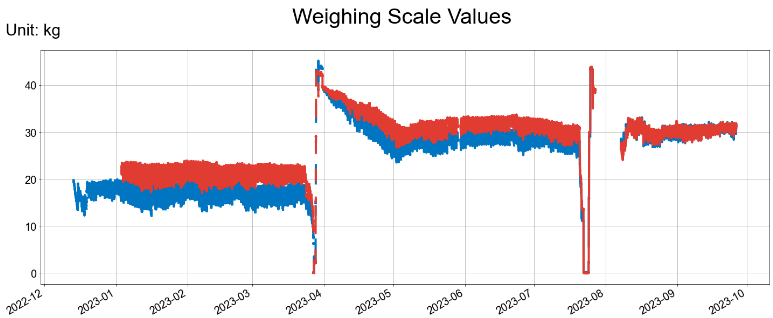

Figure 6.8: Weighing Scale Values Throughout the Year

During the experiment, sudden jumps occurred which may have been caused by slab replacement or extrusion. Data from 27 to 31 May and 21 July to 9 August were thus removed.

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