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PRECISION DROUGHT STRESS IN ORCHARDS: ROOTSTOCK EVALUATION,
TRUNK HYDRATION AND CANOPY TEMPERATURE

by

Lance V. Stott

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Plant Science

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2017

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ABSTRACT

Precision Drought Stress in Orchards: Rootstock Evaluation,
Trunk Hydration and Canopy Temperature

by

Lance V. Stott, Doctor of Philosophy

Utah State University, 2017

Major Professor: Dr. Bruce Bugbee
Department: Plant, Soils and Climate

In many areas, over half of all diverted water is used for irrigation. Tree fruit crops use a lot of water, but water productivity can be increased using properly-timed precision water stress. In addition to water conservation, increases in water productivity arise from better fruit quality, increased storage life and reductions in pruning and maintenance. One major hurdle to applying precision water stress in orchards is the lack of a reliable, automated method of determining tree water status. However, the influence of physiological characteristics such as rootstock vigor on water productivity are also important. Selecting the most appropriate rootstocks and accurately determining the water status of orchard trees can increase water productivity.

Research has shown that some rootstocks can more effectively extract water from soil. In this research, the response to water stress of three different Gisela tart cherry dwarfing rootstocks was compared using a weighing lysimeter system. Gisela 12 and

Gisela 3 rootstocks recovered from drought stress more quickly and had higher trunk diameter growth rates than drought-stressed Gisela 5 rootstocks.

Two potential methods of determining tree water status were also evaluated. Trunk hydration was measured using electromagnetic sensors and canopy temperature changes were detected using infrared radiometry.

Electromagnetic techniques, including time domain reflectometry, can be used to determine the water content of wood. Until recently, the cost of this technology has inhibited its widespread use, but new affordable commercial electromagnetic soil moisture sensors have created renewed interest in this technique. In this research five different types of electromagnetic soil moisture sensors were inserted into the trunks of fruit trees and were monitored over two growing seasons. Maximizing exposure of waveguides to the sapwood increased the response of these sensors to changes in stem water potential.

Infrared measurements of canopy temperature have successfully been used with field crops. However, the heterogeneity of orchard canopies makes this technique more difficult in orchards. Here, the efficacy of aiming radiometers at single trees versus at entire orchards was compared over multiple growing seasons. Neither single tree measurements nor whole orchard techniques produced a sufficiently robust signal to recommend them for general use.

PUBLIC ABSTRACT

Precision Drought Stress in Orchards: Rootstock Evaluation,
Trunk Hydration and Canopy Temperature

Lance V. Stott

Tree fruit crops are of high value, but use a lot of water. Precision irrigation has the potential to save water while simultaneously improving crop quality. The timing and method of precision water stress in various tree fruit crops has been widely studied. However, in order to successfully employ precision irrigation methods in orchards, an accurate measurement of tree water status is required. Currently, stem water potential is the preferred indicator. However, this measurement is tedious and cannot be automated. Because measurements must be taken near solar noon (approximately 1:30 PM MDT in the summer in northern Utah), the number of measurements that can be recorded per day is limited. An automated, electronic measure of tree water status to replace stem water potential measurements is much sought after.

Numerous methods have been studied, including evapotranspiration models, soil water status and direct measurements of tree water use. Many of these techniques have demonstrated some level of utility, but none has been adopted for widespread use in orchards. The most widely studied include fluctuations in stem diameter, canopy temperature changes and sap flow measurements.

Canopy temperature measurements have great potential for determining tree water status. The main challenge with this technique in orchards is the heterogeneity of the

orchard canopy as compared to a field crop. Exploring various methods of measuring canopy temperature changes could provide the needed plant-based metric required to successfully employ precision water stress in orchards.

Measurements of trunk hydration using time-domain reflectometry have been studied for many years, but sensor cost prohibited the widespread use of this technique. The evolution of less expensive sensors has triggered a renewed interest in this technique. Still, much needs to be learned about the best methods to obtain accurate measurements of trunk hydration.

Should precision water stress production systems become more widely used, the influence of rootstock characteristics on drought-tolerance becomes increasingly important. This research provides evidence that some rootstocks are more drought-tolerant than others. The research also presents findings in regard to canopy temperature measurements using infrared thermometry and measurements of trunk hydration using electromagnetic moisture sensors.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Irrigation uses well over half of all diverted water in many areas (Fererer et al., 2003; D Goldhamer et al., 2003). Because water is increasingly scarce there is more competition for irrigation water and growers are under pressure to reduce irrigation volume (Costa et al., 2007). Evaluating irrigation efficiency is essential. Several studies have suggested a shift in the evaluation of efficiency to production per unit water consumed rather than production per acre (Fererer and Evans, 2006; Fererer et al., 2003; Pascual Romero et al., 2006a; P Romero et al., 2006b). Maximizing water productivity (WP) requires a knowledge of crop water needs, including genetic differences between crops and cultivars, and necessitates the scheduling of irrigation based on those needs rather than on fixed schedules (Fererer and Evans, 2006).

Maximum profit may be achieved by reducing irrigation costs through deficit irrigation (English, 1990; Fererer and Evans, 2006). Decisions about using deficit irrigation should be made based on whether land or water is limiting, how much rainfall contributes to the water supply and the total percentage of production costs that irrigation comprises (Hargreaves and Samani, 1984). Deficit irrigation is only economically feasible if the effects on crop yield and quality are insignificant or the savings in irrigation costs offset the lower yields or slightly reduced crop quality (Fererer et al., 2003).

Nearly 1.6 million hectares of orchards are found in the United States. The total production value from these orchards was nearly \$17 billion in 2015 (U.S. Department of

Agriculture, 2015). These high value crops require irrigation management to conserve water resources. Precision water stress has the potential to reduce water consumption, improve crop quality and limit nutrient leaching and runoff.

Moderate water stress of high value tree fruit crops results in higher fruit sugar content, but a reliable indicator of tree water status is required before precision water stress can be used. Measurements of soil moisture are unreliable because of the deep and extensive root systems of trees. Pressure bomb measurements of stem water potential are more reliable, but are labor intensive and cannot be automated. Infrared measurements of leaf-air temperature differences could be effective, but the heterogeneity of canopy architecture makes the measurements difficult. Determining trunk hydration with electromagnetic water content sensors inserted into fruit tree trunks could help determine tree water status. If successful, this method could have broad application in orchards worldwide.

1.2 Literature Review

Because of the direct relationship between water use and biomass, deficit irrigation does not work well when biomass is the end goal (Fereres and Soriano, 2007) or when growing annual vegetables (Costa et al., 2007). However, grapes and some tree crops are well-suited to deficit irrigation because economic return in these crops is tied to *quality* as well as biomass (Costa et al., 2007). Because of this, increases in crop quality may result in similar or even increased profits despite the likely decrease in biomass or change in biomass partitioning and potential decrease in yield that usually occurs under deficit irrigation.

Deficit irrigation can increase water productivity (mass of yield per volume of water used) through means other than reducing water consumption. As deficit irrigation has a greater effect on vegetative growth than on reproductive growth, orchards and vineyards can produce similar yields while using less irrigation water. Total biomass is usually reduced during deficit irrigation, but the effect seems to be greater on vegetative growth than on reproductive growth (Asín et al., 2007; Ballester et al., 2011; Boland et al., 2000a; Boland et al., 2000b; MM Chaves et al., 2010; M. M. Chaves et al., 2007; Joan Girona et al., 2003; González-Altozano and Castel, 1999; Intrigliolo and Castel, 2010; Lopez et al., 2008; Jordi Marsal et al., 2002; Mitchell et al., 1986). This makes deficit irrigation an effective means of controlling excess vegetative growth, which reduces pruning and maintenance costs, thereby increasing the water productivity of these crops.

Increases in water productivity in response to precision water stress have been reported in almond (Egea et al., 2013; Egea et al., 2010; García et al., 2004; Pascual Romero et al., 2006a), citrus (Domingo et al., 1996; García-Tejero et al., 2010; González-Altozano and Castel, 1999; P Romero et al., 2006b), apple (Einhorn and Caspari, 2003; Leib et al., 2006), grape (MM Chaves et al., 2010; M. M. Chaves et al., 2007) apricot (Alejandro Pérez-Pastor et al., 2007; Torrecillas et al., 1999), tart cherry, (Kylara Papenfuss, 2010), peach (Boland et al., 2000b; Dichio et al., 2007; J. Girona et al., 1993; Lopez et al., 2008), nectarine (A. Naor et al., 1999), prune (KA Shackel et al., 2000), olive (Gómez-del-Campo, 2013) and Asian pear (Horst W. Caspari et al., 1994). Reliably sensing plant water status is essential if growers are to effectively manage

deficit irrigation and realize the potential increases in water productivity without losing their crop or damaging their trees.

1.1.1 Methods of Sensing Water Status

Researchers have employed several methods to monitor tree water status (Hsiao, 1990). Fernández and Cuevas (2010) emphasized the importance of signal intensity and the signal to noise ratio in selecting an indicator of tree water status. Naor and Cohen (2003) also stressed that indicators must be evaluated by sensitivity and variability. Whatever the method, it must accurately quantify tree water stress so that precision water stress can be effectively applied to orchards (Lopez et al., 2008).

Plant-based Indicators. Plant-based indicators, including stomatal conductance, transpiration, photosynthesis, sap flow measurements, trunk diameter fluctuations, canopy temperature differences and plant water potentials have the greatest potential for precision irrigation scheduling (D. A. Goldhamer and Fereres, 2004; Intrigliolo and Castel, 2006; McCutchan and Shackel, 1992).

Water Potential. The most commonly-used method of determining plant water status is measuring water potential using a pressure chamber. This technique, originally referred to as hydrostatic pressure (Per F Scholander et al., 1964) or sap pressure (P. F. Scholander et al., 1965), uses a pressurized chamber to force sap back through a cut leaf petiole or stem. The pressure required is equal to the water potential of the system, but is of opposite sign. The three common methods of assessing plant water potential are predawn leaf water potential (LWP_{pd}), midday leaf water potential (LWP_{md}) and midday

stem water potential (SWP_{md}) and the three measurements are strongly correlated (McCutchan and Shackel, 1992; Williams and Araujo, 2002).

Some authors have found sufficient correlations between LWP_{pd} and soil volumetric water content to include LWP_{pd} as a suitable indicator of tree water status (David A. Goldhamer et al., 1999b; Pascual Romero et al., 2004a). Others have indicated that SWP_{md} is preferable to LWP_{pd} which is preferable to mid-day leaf water potential (LWP_{md}) in terms of sensitivity to plant water status (Domingo et al., 1996; J. Girona et al., 1993; McCutchan and Shackel, 1992; Amos Naor et al., 2006; A. Pérez-Pastor et al., 2009; Remorini and Massai, 2003).

The literature suggests that SWP_{md} is the preferable method of measuring plant water status because it is “robust, reliable and practical” and strongly correlated with vapor pressure deficit (VPD) (Ken Shackel, 2011). Others have recommended SWP as a good indicator of plant stress (McCutchan and Shackel, 1992; Amos Naor et al., 2006; A. Naor et al., 2001; A. Naor et al., 1999; A. Pérez-Pastor et al., 2009; KA Shackel et al., 2000; Kenneth A Shackel et al., 1997). Many have even used SWP as the standard to which other potential plant water status indicators, like canopy-air temperature differences (Wang and Gartung, 2010), trunk diameter variations (Intrigliolo and Castel, 2004) and sap flow measurements (J. E. Fernández et al., 2008), may be compared. Perhaps one reason for its preference is that SWP_{md} seems to be more sensitive to crop load than other indicators (A. Naor et al., 2001). Still, an indicator that can be continuously monitored is preferable because of the logistics involved in making SWP_{md} measurements (DavidA Goldhamer and Fereres, 2001).

Stem water potential can also be measured using heat dissipation or psychrometric methods. These methods have the advantage of being continuous and automated, but the complexity of the psychrometric technique has curtailed its widespread use. The measurement speed of the recently-introduced Campbell Scientific CR6 datalogger has renewed interest in this technique.

Early design of the thermocouple psychrometer is attributed to Spanner (Spanner, 1951). Much research has been devoted to improving the design of thermocouple psychrometers (Campbell, 1979; Millar, 1971), but current models are still often called Spanner-type thermocouples. Measurements of plant water potential using thermocouple psychrometers date back to the mid-1960s (S. L. Rawlins, 1966; Wiebe and Brown, 1970; Wiebe et al., 1971). Determining water potential using thermocouple psychrometry requires an understanding of the psychrometric principles involved (Stephen L Rawlins and Campbell, 1986).

Measuring stem water potential involves the detection of small voltages and requires extreme caution about temperature gradients (Boyer, 1995). Because of the extreme sensitivity of thermocouple psychrometers, user expertise is required to avoid experimental error (Brown and Oosterhuis, 1992; Martinez et al., 2011). Despite the complexity of this technique, it has been used to successfully monitor plant water status (Vogt, 2001; Wiebe and Brown, 1970).

One of the long-standing concerns is contamination of the thermocouple by sap, but Wiebe and Brown (1970) reported continuous function for six weeks in Juniper trees.

Still, it is possible that sap exudation from different species would vary so psychrometer contamination is still a primary concern.

Measuring stem water potential using heat dissipation sensors relies on the principle that heat is dissipated more quickly from a wet medium than from a dry one. Heat is applied continuously for 30 seconds to a hypodermic needle embedded in a porous ceramic cup, using a constant current controller. The temperature at the beginning of heating is subtracted from the temperature at the end of the heat cycle to find a temperature difference. Calibration methods then convert temperature differences to water potential. A custom calibration is required for each sensor (Campbell Scientific Inc., 2009). However, monitoring changes in the temperature differences may suffice if an exact water potential is not required. Installing this type of sensor in the trunk of a tree may be another electronic method of determining water status. Contamination of the porous ceramic cup by trunk exudates is a primary concern with this sensor as well.

Gas Exchange. Romero et al. (2004b) reported a lag in sensitivity which makes measurements of stomatal conductance, transpiration and photosynthesis problematic. In addition, measures of gas exchange are often less sensitive indicators of plant water status (A Goldhamer et al., 1999a; A. Moriana and Fereres, 2002; Ortuño et al., 2004). There is also danger in making measurements of small samples at specific times and extrapolating to the tree or orchard level on a seasonal basis. If a sufficient number of samples are taken, at repeated intervals, this technique could be effective in producing a model of tree water status, but would be laborious (Jarvis, 1976).

Sap Flow. Sap flow can be monitored by inserting two probes and a heater into a tree trunk, applying a heat pulse and measuring the time until each probe senses an equivalent temperature rise (Green et al., 2003). Kang et al. (2003) and Mpelasoka et al. (2001a) found that sap flow rates were sensitive to changes in plant water status. Conversely, Fernández et al. (2008) found sap flow rates unreliable in apple, grape, olive and Asian pear, indicating that they may not be the best indicator of plant water status, despite their ability to be continuously monitored.

Trunk Diameter. Diurnal changes in trunk diameter have been studied extensively and can be continuously monitored. Generally, a linear voltage displacement transducer (LVDT) is used to monitor daily changes in trunk diameter. These devices can be automated and are precise (Ortuño et al., 2010). Maximum daily shrinkage (MDS)—the difference between daily maximum and minimum trunk diameter—is commonly used to determine the water status of orchard trees (Cohen et al., 2001; A Goldhamer et al., 1999a).

One potential advantage compared to other methods is that trunk diameter variations show sensitivity to water stress sooner (Cohen et al., 2001; Fereres and Goldhamer, 2003; David A. Goldhamer et al., 1999b; Ortuño et al., 2004; Remorini and Massai, 2003). Many studies suggest that MDS is more variable than stem water potential (SWP) (Ginestar and Sánchez, 1996; A Goldhamer et al., 1999a; D. A. Goldhamer and Fereres, 2004; A. Naor and Cohen, 2003), but some still recommend using MDS because it is automatable and continuous and has a greater signal to noise ratio than SWP (Fereres and Goldhamer, 2003; David A. Goldhamer et al., 1999b; A.

Moriana and Fereres, 2002). Intrigliolo and Castel (2006) concluded that pre-dawn leaf water potential (LWP_{pd}) and SWP_{md} are preferable water stress indicators in plum despite the fact that trunk diameter fluctuations can be continuously monitored. Perhaps this is because MDS becomes less sensitive than trunk growth rate post-harvest (Intrigliolo and Castel, 2004) or because MDS is less sensitive under very dry conditions (Huguet et al., 1992). Ortuño et al. (2010) also pointed out that MDS doesn't work well in trees with fast growth rates.

Infrared Thermometry. Infrared thermometry can detect differences in canopy temperature as plant water status changes. Infrared thermometry could even be employed from space, but the lack of spatial and temporal resolution of satellites has inhibited widespread adoption of this method (Bastiaanssen et al., 2006; Berni et al., 2009). Stagakis et al. (2012) demonstrated the potential of using unmanned aerial vehicles (UAVs) equipped with multispectral (IR and near-IR) cameras to characterize citrus orchard water status. Similarly, Berni et al. (2009) combined data from an airborne hyperspectral scanner (AHS) on a UAV with crop water stress index (CWSI) data to characterize olive orchard water status. Sepulcre-Cantó et al. (2006) compared data from UAV-borne AHS to land-based infrared measurements with strong correlation ($r^2 = 0.45-0.57$). Their AHS data also correlated reasonably with mid-day leaf water potential (LWP_{md}) ($r^2 = 0.25-0.62$).

Chlorophyll fluorescence monitored with high spectral resolution spectrometers has also shown promise for detecting plant water status (Pérez-Priego et al., 2005). Further, despite the implicit limitations of point measurements described by Berni et al.

(2009), Wang and Gartung (2010) obtained a strong correlation ($r^2 = 0.67-0.70$) between canopy to air temperature differences (ΔT) and SWP_{md} using land-based IRT.

Time Domain Reflectometry and Other Electromagnetic Techniques. Time domain reflectometry has primarily been used to determine soil water content. A good review of the principles of this technique can be found here (Černý, 2009; Robinson et al., 2003). Beginning in the early 1990s, TDR was also used to determine the water content of wood. Kumagai et al. (2009) found that amplitude domain reflectometry (ADR), a technique similar to TDR, could also determine the water content of wood based on the apparent dielectric permittivity. Use of these ADR sensors bolstered predictions of stomatal conductance, indicating that they may be of use in monitoring tree water status.

Still, most research using this system focused on stem water storage (Constantz and Murphy, 1990; NM Holbrook and Sinclair, 1992; Irvine and Grace, 1997; Kravka et al., 1999; Wullschleger et al., 1996). Other work evaluated xylem cavitation (Sparks et al., 2001). Nadler suggested that TDR could be used to monitor tree water status, but concluded that TDR was too expensive for managing orchard irrigation (2006; 2003).

With the advent of less expensive TDR and other electromagnetic soil moisture sensors, interest in this technique has resurfaced. Some studies continue to use TDR systems to determine stem water content (Young-Robertson et al., 2016), but others have shown that lower frequency electromagnetic sensors such as the Decagon Devices GS3 can determine the water content of wood (Garrity, 2014; Matheny et al., 2015) and

monitor xylem embolism (Hao et al., 2013). Most recently, Saito et al. (2016) used this sensor to monitor invasive species in arid regions.

There are several challenges in determining trunk hydration using electromagnetic techniques, such as temperature sensitivity, ideal wave guide length (N Michele Holbrook et al., 1992) and calibration (N Michele Holbrook et al., 1992; A Nadler et al., 2006). In spite of these challenges, measuring the permittivity of tree trunks shows potential as an automated, plant-based indicator of tree water status.

Considering the complexity of measuring any one of these plant-based indicators, it is no surprise that many have tested other techniques—even though a plant-based method might be preferable. Both modeling evapotranspiration and characterizing soil water content are widely described in the literature.

Evapotranspiration Models. Evapotranspiration (ET) models are commonly used to predict plant water use and schedule irrigation. In fact, most studies about deficit irrigation or partial root zone drying use ET models to establish the rates of irrigation for the controls upon which the water stress treatments are based. ET models, which use weather data to predict plant water use, have been used to predict irrigation needs in fruit trees (Jordi Marsal et al., 2002; J. Marsal et al., 2000).

Goldhamer and Fereres (2001) suggested that, in the past, modeling was considered more reliable than direct plant measurements—even though the latter would be preferable—because weather instrumentation developed more rapidly than plant-stress-sensing instrumentation.

One drawback of modeling ET is site-to-site variability. The crop coefficients (K_c) associated with ET are not universal and need to be adjusted to local conditions and cultural practices (Jordi Marsal et al., 2002). Models are difficult to use in young orchards because of the large soil surface evaporation component (Testi et al., 2004). Marsal and Stöckle (2012) used a crop growth model (CropSyst) to forecast plant water potential for irrigation and found strong correlation with stem water potentials. They reported that CropSyst produced relevant information for periods shorter than 40 days, but longer simulations were less accurate. Acevedo-Opazo (2010) indicated that weather-based models tended to recommend excessive irrigations (6 to 23 fold more), which limits their usefulness.

Soil Water Content. Soil water potential seems to be an obvious choice for an indicator of water stress, but the fact that soil water content has been found to vary within plots makes this metric more complicated (McCutchan and Shackel, 1992). Romero et al. (2004a) suggested that the strong correlation found between volumetric soil water content and pre-dawn LWP (LWP_{pd}) measurements ($r^2 = 0.69$ and 0.70) made both a useful tool for scheduling irrigation. These findings are similar to those reported by Natali et al. (1984), Girona et al. (1993) and Pérez-Pastor (2001). But, while citing soil moisture sensors as a “useful tool,” Intrigliolo and Castel (2004) indicated the need for a large number of soil moisture sensors to accurately characterize the soil moisture profile—particularly if sensor precision is in question.

Boland et al. (2000b) reported that it takes longer to stress trees with large root systems which could explain why soil matric potential never indicated plant water stress

despite obvious reductions in yield (Intrigliolo and Castel, 2006). This apparent discrepancy could be explained by soil depth since a restricted root environment made RDI more effective at reducing excessive vegetative growth (Joan Girona et al., 2003). Acevedo-Opazo et al. (2010) also found soil water content ineffective due to the great depth of soil in their study and emphasized that soil heterogeneity and uncertainty about root depth and distribution limit the utility of soil water potential as an indicator of tree water status.

The ability of tree root systems to grow toward locations of high moisture content may also hinder the application of this technique (Amos Naor et al., 2006). For these reasons, plant-based measures of water status would be preferable to soil-based measures—particularly on deep soils (Acevedo-Opazo et al., 2010; Intrigliolo and Castel, 2006). Further, peach yield was more highly correlated with mid-day stem water potential (SWP_{md}) than soil water potential (A. Naor et al., 1999) and, since SWP_{md} is independent of soil moisture measurements, it seems to be a better indicator of plant water status (McCutchan and Shackel, 1992; Kenneth A Shackel et al., 1997). Characterizing tree water status alone is insufficient as the method and timing of deficit irrigation also influence the water productivity of an orchard.

1.1.2 Deficit Irrigation Methods

Various deficit irrigation techniques can be used. All reduce orchard water use. Some are applied continuously and others are applied only at specific stages. Timing will be discussed in more detail in the next section, but research has shown that different species vary in their tolerance to water stress based on their physiological development

stage. For example, stone fruits like peaches and cherries progress through three stages of ripening (Li et al., 1989). Stage I consists of reproductive cell division, while Stage II is known as a lag period where the pit hardens. Stage III is where rapid expansion of fruit cells occurs (Joan Girona et al., 2012; Kylara Papenfuss, 2010). Stage II has been shown to be the period where stone fruits are the most tolerant of water stress.

Regulated, Sustained and Continuous Deficit Irrigation. Regulated deficit irrigation (RDI) is applying less water during certain stages of the growing season (Chalmers et al., 1981). Egea et al. (2013) differentiated SDI (sustained deficit irrigation) from RDI in terms of duration. SDI is applied during the entire growing season while RDI is applied only during certain parts of the growing season. Others have referred to SDI as continuous deficit irrigation (CDI) (Vera et al., 2013). Caspari et al. (1994) described LDI (late deficit irrigation) as deficit irrigation during rapid fruit growth. Some researchers have suggested applying drought stress in non-bearing years of alternate-bearing pistachio (Stevenson and Shackel, 1998) and olive trees (“AYI”) (Alfonso Moriana et al., 2003). Another technique is on/off cycles where every other irrigation is skipped, but this method resulted in smaller fruits and/or reduced yield (Horst W Caspari et al., 2001; Bussakorn S Mpelasoka et al., 2000).

SDI has been found to be advantageous over RDI in some cases. Ben Mechlia et al. (2001) found that peach yield was less affected by continuous deficit irrigation than with deficits during particular stages. Lampinen (2001; 2004) reported similar findings in prune. A mild SDI treatment that avoids severe stress in any one physiological stage

may have an advantage by allowing trees to adapt gradually to water deficits as Goldhamer et al. (2006) found in almonds.

When water stress does occur, researchers have emphasized the need for rapid stress alleviation. When water stress could not be alleviated quickly, water stress persisted into stage III or rapid fruit growth. Perhaps this is why Goldhamer et al. (2006) found that mild SDI was preferable to RDI. If water stress persisted into the rapid fruit growth stage, it would most likely affect fruit growth (J Marsal et al., 2003) and, indeed, did with peaches on deep California soils where infiltration was reduced (J. Girona et al., 1993).

Delays in the onset and recovery of plant water stress may occur on deep soils because of the large reservoir of water available to trees (J Marsal et al., 2003). Monitoring plant water status during the entire growing season may help to avoid possible yield reductions from overshooting with RDI (J Marsal et al., 2003). Another possible reason for the conflicting results in peach yield under RDI during stage II could be the difficulty in detecting the shift from stage II to stage III (DA Goldhamer et al., 2001). When recovery from water stress is rapid, mild SDI may not have any advantage over RDI (DavidA Goldhamer and Fereres, 2001; Alfonso Moriana et al., 2007; Pascual Romero et al., 2004b).

Partial Root Zone Drying. Partial root zone drying (PRD), originally attributed to Goodwin (1992; 1990), is another technique that has been successfully employed to save irrigation water (Abrisqueta et al., 2008; Horst W Caspari et al., 2001; Egea et al., 2010; Einhorn and Caspari, 2003; Kang et al., 2003; Leib et al., 2006; Spreer et al.,

2007). In partial root zone drying, water is applied to only one part of a tree's root zone, allowing the other part to dry out. This differential drying of the root system induces both a hydraulic and a chemical signal (most likely ABA) that modifies plant growth (Dodd et al., 1996; Dry and Loveys, 1998). The chemical signal can occur even before turgor is affected by the lack of soil moisture (Gollan et al., 1992; Schurr et al., 1992). Partial root zone drying may be preferred to RDI in some cases because root production ceases when the soil is dry (Abrisqueta et al., 2008), likely because the ABA signal is lost. Accordingly, some have suggested the alternate applying of water to each side of the trees or alternate partial rootzone drying (APRD) to maintain this signal.

Alternate Partial Root Zone Drying. Alternating wet and dry sides of the root system (APRD) could help alleviate this potential problem and maintain the ABA signal, but, twice the irrigation infrastructure is required for this system, so APRD may have no economic advantage over RDI (Vera et al., 2013). It is also unclear whether alternating dry and wet sides of the root system stimulates root production and, thus, increases water uptake (Abrisqueta et al., 2008), or whether there is no benefit to alternating sides (JE Fernández et al., 2006). Fruit size and yield were less affected by PRD than by RDI in grapes (M. M. Chaves et al., 2007) and mango (Spreer et al., 2007). The same was true for apples in some cases (Horst W Caspari et al., 2001; Leib et al., 2006), but the opposite was true in other cases (Lombardini et al., 2002). Still others found no difference between RDI and PRD when similar total amounts of irrigation were applied (Egea et al., 2010; DA Goldhamer et al., 2001). Perhaps RDI is preferable for some crops and/or locations while PRD is preferable in others.

1.1.3 Timing of Deficit Irrigation

Whatever the method, the appropriate level of water stress must be applied at the correct time. The sensitivity of fruit/nut trees to water stress varies by time of year and by species. Deficit irrigation applied during periods that are less-sensitive generally produces minimal effect on fruit size and yield.

Much evidence suggests that stage II is the optimal time to apply precision water stress to stone fruits. In peaches, deficit irrigation during stage II had minimal effects on yield, whereas post-harvest deficit irrigation exacerbated excess vegetative growth and decreased the following year's bloom (Joan Girona et al., 2003; J. Girona et al., 1993) and yield (Vera et al., 2013). Perhaps this is because maximum root growth has been found to occur post-harvest (Abrisqueta et al., 2008). Dichio et al. (2007) found that peach quality and yield were unaffected when regulated deficit irrigation was applied to peaches post-harvest. Deficit irrigation during stage I *and* II reduced peach size but deficit irrigation during stage II *only* had less of an effect (DA Goldhamer et al., 2001). Others have also indicated that stage II was the optimal time to apply DI to peaches in terms of yield (Gelly et al., 2004; Lopez et al., 2008; J Marsal et al., 2003). Pérez-Pastor et al. (2009; 2007) suggested that early post-harvest and rapid fruit growth (stage III) were critical periods for apricots and suggested targeting regulated deficit irrigation of apricots to “non-critical” periods. Tart cherry quality and yield may be maintained with a 30% reduction in annual irrigation, if deficit irrigation is applied during pit hardening (stage II) (Kylara Papenfuss, 2010; Kylara A Papenfuss and Black, 2010).

RDI before rapid fruit growth did not reduce Asian pear fruit growth or yield (Asín et al., 2007; Horst W. Caspari et al., 1994). However, RDI during stage I reduced yield by 9% in Asian pears (J. Marsal et al., 2000), while RDI during stage II had little effect (Jordi Marsal et al., 2002).

For apples, water deficit later in the season had little impact on fruit weight (Mills et al., 1996). The fact that RDI early *or* late in the growing season had little effect on apple yield suggests that apples have a drought sensitive period (Bussakorn S Mpelasoka et al., 2000).

Deficit irrigation treatments in July and August did not reduce citrus yield or fruit quality, but deficit irrigation applied in September and October significantly reduced fruit size and increased peel creasing (González-Altozano and Castel, 1999). Deficit irrigation during fruit-growth reduced citrus fruit size; deficit irrigation at flowering reduced fruit number; and deficit irrigation near maturity mainly affected fruit quality (García-Tejero et al., 2010). Summer likely is the correct time to apply deficit irrigation to mandarins (Ballester et al., 2011; González-Altozano and Castel, 2000; P Romero et al., 2006b) and other citrus crops.

RDI of olive trees from massive pit hardening (July) to just before fruit ripening (the end of September) did not significantly reduce oil yield (Alegre et al., 2000; Motilva et al., 2000). Moriana et al. suggested two critical phases for adequate irrigation in olive: around full bloom (2003; 2007) and during oil accumulation (2007). Gómez-del-Campo et al. (2013) also suggested that olive is most drought resistant during the summer period as it has evolved in and is well-adapted to a Mediterranean climate.

The timing of deficit irrigation affected the early-splitting of pistachios, with June being the season where deficit irrigation had the least effect on early-split nuts (Doster et al., 2001). A 28% reduction in irrigation during almond kernel filling resulted in only a 7% reduction in yield (García et al., 2004), while a 45% irrigation reduction during kernel-filling *and* post-harvest reduced yield by 17% (García et al., 2004).

Chaves et al. (2010) reviewed the stages of grape ripening and suggested differences in sensitivity to water stress for different stages. Acevedo-Opazo et al. (2010) suggested timing grape regulated deficit irrigation treatments between post-setting and harvest. In addition, different rootstocks may be better-suited for deficit irrigation than others because they are more efficient at soil water extraction (Pérez-Pérez et al., 2010; Pérez-Pérez et al., 2008; P Romero et al., 2006b).

It is clear that there are differences in sensitivity from one crop stage to another for different species of orchard and vineyard crops. But, the appropriate level of irrigation stress must be applied at the appropriate time and via the appropriate method in order to reap the benefits of precision water stress.

1.1.4 Benefits of Deficit Irrigation

The most obvious benefit of deficit irrigation is water savings. In almond, water productivity increased 123% with deficit irrigation during kernel filling, but yield was “somewhat reduced” (Egea et al., 2010). In another study, deficit irrigation during kernel filling reduced yield by 7%, but water use was reduced 45% (Pascual Romero et al., 2006a). García et al. (2004) also reported that the water savings of deficit irrigation outweighed the 7% yield reduction. In apricots, up to a 22% reduction in irrigation

resulted in similar yields (A. Pérez-Pastor et al., 2009), while irrigation reductions over 25% reduced apricot yields (Torrecillas et al., 1999). Einhorn and Caspari (2003) reported water savings from 25-75% without negative impacts on apple fruit size.

Irrigation water savings of 25-75% (Einhorn and Caspari, 2003), 45-50% (Leib et al., 2006) and 50% (Lombardini et al., 2002) have been reported in apples with no significant difference in yield or fruit size. Asian pear size and yield were similar with an 8% water savings when deficit irrigation was applied before rapid fruit growth (Horst W. Caspari et al., 1994). Forty percent irrigation savings have been reported with “minor consequences” on peach size and yield (Joan Girona, 1989; J. Girona et al., 1993). Papenfuss (2010) reported irrigation savings of 30% while maintaining tart cherry yield and fruit quality. Water savings from 6 to 22 percent have been reported for citrus without significant reductions in yield, fruit quality or profitability (Ballester et al., 2011; Domingo et al., 1996; González-Altozano and Castel, 1999). García-Tejero et al. (2010) reported a 10-12% citrus yield reduction, but 1000 cubic meters of water were saved per hectare (100 mm depth equivalent), resulting in an overall WP increase of 24%. Similar trends have been observed in grape (MM Chaves et al., 2010; M. M. Chaves et al., 2007), olive (Alegre et al., 2000; Gómez-del-Campo, 2013), pistachio (Doster et al., 2001) and prune (Intrigliolo and Castel, 2010; BruceD Lampinen et al., 2001; KA Shackel et al., 2000).

In other cases, water productivity was greatly increased with only minor reductions in yield or fruit quality of citrus (García-Tejero et al., 2010; García et al., 2004) and almond (Egea et al., 2010; Joan Girona et al., 2003; Pascual Romero et al.,

2006a). Even when total yield or fruit size was slightly reduced, many have reported that deficit irrigation techniques have resulted in fruit quality improvements and/or improvements in management efficiency in many crops which make deficit irrigation preferable.

Deficit irrigation reduced berry size, increased skin-pulp ratio and anthocyanin content in wine grapes (Acevedo-Opazo et al., 2010). Increased skin-pulp ratio and anthocyanin concentration are directly related to better wine color, flavor and aroma (Koundouras et al., 2006; Williams and Matthews, 1990). Deficit irrigation in grapes also helps to control excessive vegetative vigor and improve light reception (MM Chaves et al., 2010; M. M. Chaves et al., 2007).

In apple, deficit irrigation increased total soluble solids, sugar concentration, flesh firmness, dry matter concentration and aroma volatiles while hastening maturity and reducing shriveling during storage (Leib et al., 2006; Mills et al., 1996; B. Mpelasoka et al., 2001a; Bussakorn S Mpelasoka et al., 2000; Bussakorn S Mpelasoka et al., 2001b; Bussakorn S. Mpelasoka and Behboudian, 2002). Deficit irrigation can reduce salt accumulation in soils from poor quality irrigation water and apples grown under these circumstances have improved °Brix (sugar content to liquid) measurements (Nasr and Ben Mechlia, 2000).

Deficit irrigation also reduced shoot length/extension and summer pruning weights and increased return bloom in pears (Asín et al., 2007; Jordi Marsal et al., 2002; Mitchell et al., 1986). Pears may even produce higher yields when grown with the Tatura trellis system and deficit irrigation (Mitchell et al., 1986; Mitchell et al., 1989).

Appropriately-timed deficit irrigation in olive hastened ripening, increased the amount of extracted oil (Alegre et al., 2000; Alfonso Moriana et al., 2003), oil stability, color, pigment content (Motilva et al., 2000) and pulp-pit ratio (Gómez-del-Campo, 2013). When timed correctly, RDI reduced excess vegetative growth and improved citrus titratable acid and soluble solids concentration (Ballester et al., 2011; González-Altozano and Castel, 1999). In almond a pre-harvest RDI reduced hull rot (David A. Goldhamer and Viveros, 2000) while, June DI in pistachio reduced early-split nuts (Doster et al., 2001). Partial root zone drying in mango resulted in fruits with a higher harvest index (Spreer et al., 2007).

Total soluble solids, dry matter content and fruit chroma increased in tart cherry with RDI during stage II (Kylara Papenfuss, 2010; Kylara A Papenfuss and Black, 2010). RDI also seemed to make trunks more resistant to mechanical shaker damage. Plums, too, developed more soluble solids under RDI (Intrigliolo and Castel, 2010). RDI in plum triggered a shift from vegetative to reproductive growth and resulted in sweeter fruits (Intrigliolo and Castel, 2010). Less dry mass dropped from prunes; side cracking was reduced; and less post-harvest drying was required because of lower fruit hydration ratios (BruceD Lampinen et al., 2001; KA Shackel et al., 2000). Fewer apricots were lost to fungal attacks and shriveling during storage when RDI was applied during production (Alejandro Pérez-Pastor et al., 2007).

For peaches, RDI reduced vegetative growth by as much as 70% but maintained productivity (Boland et al., 2000a; Boland et al., 2000b; Joan Girona et al., 2003; Lopez et al., 2008). RDI during stage II also reduced fruit drop (Joan Girona et al., 2003) and

improved flower bud production when applied during the critical period of induction (Li et al., 1989). Total dry matter, soluble solids, acid ratio and fruit sugar content improved (Ben Mechlia et al., 2001; Gelly et al., 2004; Li et al., 1989) and peach fruit were softer and developed more reddish color with deficit irrigation (Gelly et al., 2004).

Observations that fruit grown under DI developed more trichomes and a thicker cuticle resulting in lower fruit water loss potential (Crisosto et al., 1994) may help to explain improvements in cold storage quality (Gelly et al., 2004).

In some cases, yield and grade are not affected by reduced irrigation while fruit quality is simultaneously improved (Einhorn and Caspari, 2003; Gelly et al., 2004; KA Shackel et al., 2000)

Reductions in yield or fruit quality have also been reported as a result of deficit irrigation. Improper timing, too great of severity and inaccurate plant water status measurements could all contribute to problems. Crop load also affects the degree of water stress and confounds the effects of deficit irrigation (Berman and DeJong, 1996). Drought stress persisting into late summer increased the number of double fruits in peaches (Johnson et al., 1992) because drought stress at this stage in peaches damages the differentiating carpels (Handley and Johnson, 2000; Tufts and Morrow, 1925). Keeping orchards too wet can also reduce flower bud initiation, anthesis, fruit set and fruit growth (Kozłowski, 1997). It is plausible that these yield and quality reductions are the result of incorrect technique or the improper application of it. It is clear from the literature that there is more consensus regarding the appropriate timing and method of deficit irrigation

for specific tree fruit crops than there is regarding a reliable indicator of tree water status. Research about potential indicators of plant water status is abundant.

1.1.5 Need for More Reliable Indicator

Despite the plethora of potential methods for evaluating plant water status, the need for an automated, plant-based indicator to take the place of SWP_{md} is abundantly evident (Ballester et al., 2011; Fereres and Evans, 2006; Fereres and Soriano, 2007; A Goldhamer et al., 1999a; D. A. Goldhamer and Fereres, 2004; David A. Goldhamer et al., 1999b; J. Marsal and Stöckle, 2012; Ortuño et al., 2004). Continuously measured indicators are more immediate and sensitive than discretely measured indicators (Ortuño et al., 2004).

Plant water status indicators based on oscillations are more sensitive than discrete measures (A Goldhamer et al., 1999a). Oscillations in plant water status could potentially be monitored by inserting soil volumetric water content sensors into the trunks of trees. Diurnal cycles and seasonal changes have been detected using water content sensors in mature birch (*Betula papyrifera*) trees using such a technique (Hao et al., 2013). Matheny et al. (2015) showed similar evidence of detecting both diurnal cycles and season-long changes in red oak (*Quercus rubra*) and red maple (*Acer rubrum*). This technique is also likely to be able to detect these trends in fruit trees.

1.3 Objectives and Hypotheses

Tart cherries, apples and peaches made up over 90% of the production from approximately 2630 hectares of orchards in Utah. The total dollar value of production for

these three orchard crops was in excess of \$28 million in 2015 (U.S. Department of Agriculture, 2015). Because of this, these are the preferred species to study. One objective for this research is to compare the drought tolerance of different rootstocks using weighing lysimeters. The second objective for this research is to evaluate automated, plant-based methods of determining tree water status in order to find a suitable replacement for stem water potential measurements.

The following hypotheses will be tested:

1. Recovery after drought stress will differ among rootstock cultivars.
2. Daily transpiration rates will differ between rootstock cultivars.
3. Growth under drought stress will differ among rootstock cultivars.
4. Trunk hydration as indicated by permittivity will be correlated with stem water potential in tart cherries, peaches and apples.
5. Provided that the IR sensor field of view contains mostly leaves, canopy to air Delta T will be strongly correlated with mid-day stem water potential (SWP_{md}) after filtering for wind speed, solar radiation and vapor pressure deficit.

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CHAPTER 2
THE INFLUENCE OF ROOTSTOCK ON
DROUGHT RESISTANCE

2.1 Abstract

Since crop irrigation uses much water and water supplies are limited, growing tree fruit crops with less water is important. The Gisela series of dwarfing rootstock are popular because they induce precocity, disease resistance and compact growth that enables high density production. However, aside from anecdotal evidence, research is absent into the drought tolerance of these rootstocks. This important factor cannot be ignored in designing and implementing precision water stress orchard systems. This research compares the drought tolerance of Gisela 5 rootstocks to Gisela 3 and Gisela 12 rootstocks using a weighing lysimeter system. Gisela 12 and Gisela 3 recovered more quickly from water stress and were able to sustain a higher growth rate over several dry-down cycles than Gisela 5. These studies indicate that Gisela 3 and Gisela 12 are more drought tolerant rootstocks than Gisela 5 and may be more appropriate for precision water stress orchard systems.

2.2 Introduction

Irrigation uses well over half of all diverted water in many areas (Fererres et al., 2003; Goldhamer et al., 2003). Because water is increasingly scarce there is more competition for irrigation water and growers are under pressure to reduce irrigation volume (Costa et al., 2007). Maximizing water productivity requires a knowledge of

crop water needs and the scheduling of irrigation based on those needs rather than on fixed schedules (Fererer and Evans, 2006). Some tree crops are well-suited to deficit irrigation because economic return in these crops is tied to quality as well as biomass (Costa et al., 2007). Accordingly, increases in crop quality may result in similar or even increased profits despite the likely decrease in biomass and potential decrease in yield that usually occurs under deficit irrigation.

There are more than 1.6 million hectares of orchards in the United States. The total production value from these orchards was in excess of \$13 billion in 2015 (U.S. Department of Agriculture, 2015). These high value crops require irrigation management to conserve water resources. Precision water stress has the potential to reduce water consumption, improve crop quality and limit nutrient leaching and runoff.

Multiple studies indicate that precision water stress has a greater effect on vegetative growth than on reproductive growth in fruit trees (Boland et al., 2000a; Boland et al., 2000b; Mitchell et al., 1989). This technique reduces pruning costs and saves water. Orchards and vineyards can produce similar yields while using less irrigation water, thereby increasing water productivity (Fererer and Soriano, 2007). Increases in water productivity resulting from appropriately timed water stress have been reported for many orchard crops including tart cherries (Kylara Papenfuss, 2010; Kylara A Papenfuss and Black, 2010), peaches (Joan Girona, 1989; J. Girona et al., 1993) and apples (Einhorn and Caspari, 2003; Leib et al., 2006).

Some rootstocks may be better-suited for precision water stress than others because they are more efficient at soil water extraction (Pérez-Pérez et al., 2010; Pérez-Pérez et al., 2008; Romero et al., 2006).

The Gisela® Series rootstocks were produced in Giessen, Germany (Callesen, 1997) and are clonal rootstocks that produce dwarf trees. Gisela® 5 (G.5) is a triploid hybrid of *Prunus cerasus* ‘Schattenmorelle’ and *Prunus canescens* (Franken-Bembenek, 1997). Gisela® 3 (G.3) is a sibling to G.5 (Franken-Bembenek, 2002). Gisela® 12 (G.12) is a hybrid of *P. canescens* and *P. cerasus* (Lang, 2000). G.5 produces a tree that is 50 to 65% of one grown on a Mazzard rootstock while G.12 produces a tree that is 65 to 80% of a Mazzard (Lang, 2000). G.3 produces a tree slightly smaller than G.5 (Franken-Bembenek, 2002). These rootstocks have shown particular promise for high density cherry production for both sweet and tart cherries. They are particularly useful because they have many important pathogen resistances and they induce precocious bloom (Andersen et al., 1999; Callesen, 1997).

However, some dwarfing rootstocks (including G.5) seem to have less extensive root systems (Black et al., 2010) and are thus more sensitive to water stress than Mazzard and Mahaleb (Beckman and Lang, 2002). Santos and Gonçalves (1999) reported that G.5 showed greater drought resistance than *P. avium*, ‘Maxma 14’, ‘Edabriz’ and ‘Cab 11E’. However, Lang (2000) reported that inadvertent irrigation problems indicated that Gisela 5 is “fairly” drought sensitive (Lang, 2000). In a later study, Gonçalves (2003) reported that G.5 rootstocks led to increased sensitivity to water stress compared to more deeply-rooted rootstocks. In addition, Vercammen (2002) found that Gisela 5 has moderate to

weak vigor and in dry circumstances can have small fruit, but that irrigation alleviated the problem. However, it is not clear from these anecdotal observations whether the reduced drought tolerance is simply a function of a smaller root system exploring less root volume, or if the roots are less able to adapt to dry cycles.

Despite anecdotal evidence that it may be more susceptible to drought, G.5 is widely recommended for use in high density plantings. Though less information about G.3 and G.12 is found in the literature, a study of the response of these three dwarfing rootstocks to water stress is essential if any is to be used successfully for precision water stress during high density tart cherry production.

2.3 Materials and Methods

2.3.1 Study 1: Gisela 5 versus Gisela 12

Thirty dormant G.5 and thirty dormant G.12 tart cherry rootstocks (*Prunus* x, ProTree Nursery, Brentwood, California) were planted in peat:vermiculite soilless media and grown for 30 days in 1.3 L containers. Plants were micropruned often to maintain shape and size by pinching off the apical meristems. After 30 days, eight uniform trees of each cultivar were selected and transplanted into 22 L plastic containers in a mixture of peat moss/sandy loam topsoil. Three parts peat moss and seven parts sandy loam topsoil (by volume) were hand mixed and amended with 5 g of slow release fertilizer (Polyon 15-6-11, 1 to 2-month release, Pursell Industries, Sylacauga, Alabama).

The containers with dry soil were each placed on a weighing lysimeter with an electronic load cell (ESP-35, Transducer Techniques, Temecula, California). A detailed

description of the lysimeter system can be found here (Chard et al., 2004). (See Fig. 2.3.1)

Immediately after transplanting, the media was wetted using two drip emitters. Water was applied for 15 seconds out of every minute until water dripped from drain tubes inserted into the side of the plastic containers near the bottom. After saturating the media, water was allowed to drain completely from the bottom in response to gravity. After no more water was dripping from the drains, a vacuum pump was attached to ceramic cups inserted into the side of the containers near the bottom and on the opposite side from the drains. Water removed from each container by the vacuum system was captured in flasks and measured.

After growing for 30 days, the rootstocks were again watered and the vacuum system was used to remove excess water from each container. About 200 mL of water was extracted from each container. After vacuum extraction, the mass of each container was recorded to use as a baseline mass when re-wetting the



Fig. 2.3.1. Gisela 5 and Gisela 12 rootstocks on weighing lysimeters.

media in the containers during water stress. Finally, a 2 cm layer of perlite was added to the top of each container to minimize evaporation from the media surface. Daily transpiration totals were determined and used as an indicator of water stress. Irrigation was withheld until daily transpiration rates decreased from around 700 grams per day to less than 250 grams per day per tree. Once daily transpiration rates approached 250 grams per day, containers were re-wetted until the container mass equaled the baseline mass recorded prior to applying water stress.

After the first two irrigations, each container was stressed independently and automatically using datalogger control. The datalogger calculated daily transpiration rates by detecting changes in mass over time. Once the total daily transpiration was less than 250 g per tree, that tree was irrigated. Irrigations took place between midnight and 8:00 AM to minimize the amount of transpiration data lost as water was added.

Each container was subjected to at least 6 dry-down and irrigation cycles over a period of 81 days. Beginning on the 25th day of water stress, the diameter of each rootstock was measured regularly using a digital micrometer. Regular micropruning continued throughout the experiment.

Despite careful plant selection and media preparation, two common problems with lysimeter studies are inherent variability in plant size and media water-holding capacity. Irrigating based on calendar date results in variability in the level of stress each plant receives. However, irrigating based on stress level results in variability in the frequency of irrigation for each plant. The latter is preferable, but to compare drought stress recovery, the data must be normalized. Data was normalized to the irrigations by

assigning the day before irrigation to be the reference (Day 0). Transpiration and trunk diameter measurements for each consecutive day followed as days after the irrigation (Day 1, Day 2, etc.). When the next irrigation occurred, it was used as the new reference. The maximum length of a dry-down cycle in this study was 11 days. Once days were organized by dry-down cycle, the data were combined to return the data to a time-series format which we termed normalized Julian date (See Figs. 2.4.3 and 2.4.6).

The rootstocks were harvested on day 82. Two samples of leaves (15-20) were removed from each plant, weighed immediately and then passed through a leaf area meter. The fresh mass of all leaves was measured and then the leaves were dried to a constant mass and weighed again to determine total leaf dry mass. The ratio of dry mass to leaf area of these two samples was used to estimate the total leaf area of each plant based on total dry mass of leaves. Plant stems were cut off at the surface of the perlite, cut into small pieces, weighed, dried to a constant mass and then weighed again. Rootballs were removed from containers, shaken to remove media and visually evaluated.

2.3.2 Study 2: Gisela 3 versus Gisela 5

A similar procedure was followed to compare Gisela 3 and Gisela 5 rootstocks. There were a few differences in the procedure. The most important difference is that, rather than using a mixture of peat and soil, the containers were filled with a sandy loam soil. In order to equalize the mass of moist soil in each container, the media was wetted before planting the rootstocks in the containers. To avoid compacting the wet soil, a section of PVC pipe just larger than the rootball of the rootstocks was taped on both ends

and placed in the top of each container to make a space for the rootstock. Once the soil was wetted, moist soil was either subtracted or added from each container to equalize the mass of moist soil in each container. The PVC pipe was then removed and the rootstock planted in the hole that the pipe had reserved.

By equalizing the starting mass of each container, we hypothesized that the rootstocks would transpire at similar rates and, thus, require irrigation at more similar and regular intervals. Despite these efforts, transpiration rates still differed and each container was monitored and irrigated independently after the first irrigation. Each container was irrigated when the daily total transpiration was less than 250 g per tree.

The rootstocks were harvested on day 109. Harvest methods were identical to the first study, with the exception that all leaves were measured to determine leaf area rather than using subsamples to predict leaf area.

2.4 Results and Discussion

2.4.1 Study 1: Gisela 5 versus Gisela 12

Despite continued micropruning, G.12 trees were larger at harvest than G.5 trees (Fig. 2.4.1). There were no visual differences between G.5 and G.12 rootballs (Fig. 2.4.2). At harvest, leaf area was significantly greater for G.12 rootstocks than for G.5 rootstocks ($P < 0.02$). Leaf dry mass was not significantly different between the rootstock varieties ($P < 0.06$). There was no significant difference between trunk diameter at the beginning of the study (both were 11.2 mm), but, at harvest, G.12 trunk diameter averaged 14.2 mm and was significantly greater than G.5 trunk diameter (13.5 mm) ($P = 0.01$). The slope of the increase in trunk diameter was also significantly

greater for G.12 than for G.5 (58.7 $\mu\text{m}/\text{day}$ vs. 44.1 $\mu\text{m}/\text{day}$) ($P < 0.01$). However, the dry mass of the trunks was not different between the cultivars. The difference in leaf area per trunk cross sectional area (TCSA) was not significant (Table 2.4.1).

There was no significant difference in the recovery of transpiration for Gisela rootstocks after the first or second irrigation. However, beginning with the third irrigation, G.5 rootstocks recovered more slowly during the three or four days immediately following irrigation than did G.12 rootstocks. G.5 trees also never fully regained their pre-stress transpiration levels. After five days, transpiration rates between the two rootstocks did not differ (Fig. 2.4.3).



Fig. 2.4.1. Gisela 12 (left) and Gisela 5 (right) rootstocks near the end of the study. Despite continuous micropruning, G.12 trees appear larger than G.5 trees.



Fig. 2.4.2. Gisela 5 (bottom) and Gisela 12 (top) rootballs post-harvest. There were no visible differences between the rootstocks of the two cultivars.

Table 2.4.1. Growth metrics for Gisela 5 and Gisela 12 rootstocks. Though not different initially, G.12 rootstocks had greater trunk diameter at harvest than G.5 rootstocks. They also had greater leaf area and trunk dry mass.

	Leaf Fresh Mass	Leaf Dry Mass	Leaf % Dry Mass	Leaf Area	Specific Leaf Mass	Beginning Trunk Diameter	Ending Trunk Diameter	Leaf Area/ TCSA	Trunk Dry Mass
	(g)	(g)	(%)	(cm ²)	(g/m ²)	(mm)	(mm)	(cm ² /cm ²)	(g)
Gisela 5	93.4	42.4	45.7	3449	123	11.2	13.5	2435	71
Gisela 12	109.1	48.0	44.3	4106	117	11.2	14.2	2613	75
<i>P-Value</i>	<i>0.01</i>	<i>0.06</i>	<i>n.s.</i>	<i>0.02</i>	<i>0.04</i>	<i>n.s.</i>	<i>0.01</i>	<i>n.s.</i>	<i>n.s.</i>

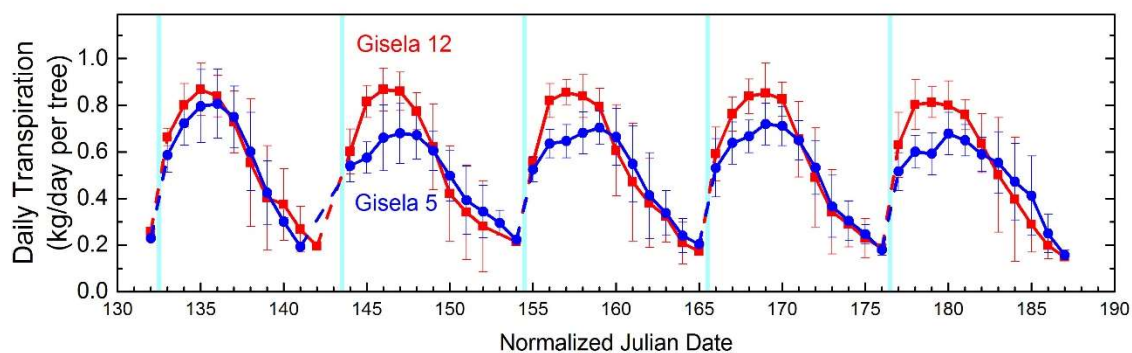


Fig. 2.4.3. Gisela 5 and Gisela 12 rootstock transpiration recovery following irrigations. Beginning at the second irrigation, G.12 transpiration rates recovered more quickly from drought stress than those of G.5.

When the last four dry-down cycles were pooled, transpiration rates were not significantly different between cultivars the day before irrigation. G.12 trees had significantly greater transpiration for the first five days after irrigation, but not all differences were significant at the 0.05 level (Fig. 2.4.4).

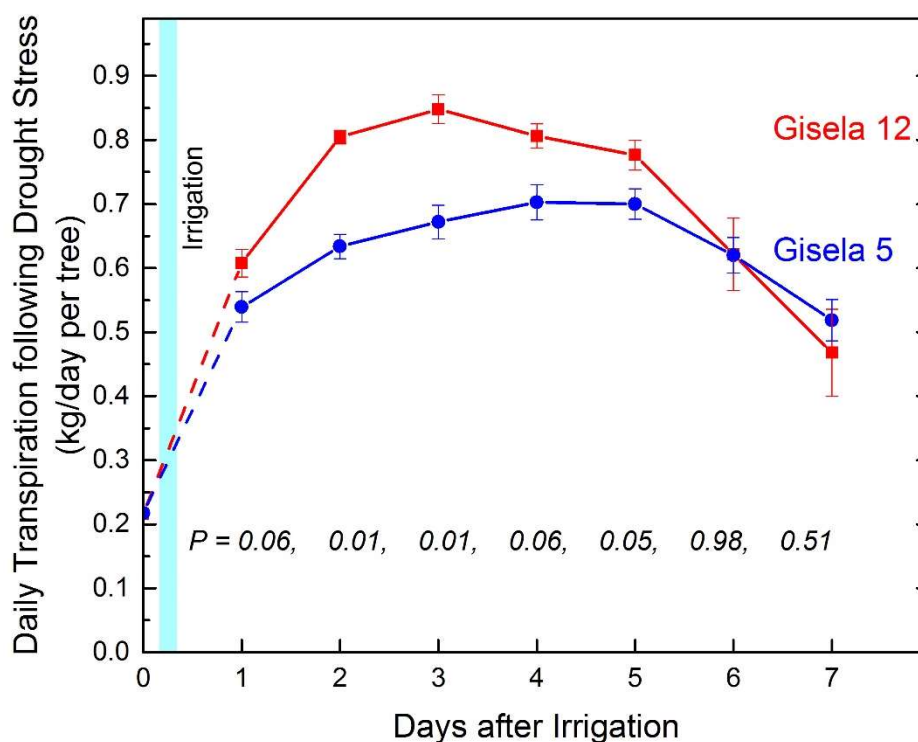


Fig. 2.4.4. Gisela 5 and Gisela 12 rootstock mean transpiration for seven days after the last four irrigations. G.12 transpiration recovered more quickly and completely for the first 5 days after irrigation. Beyond 5 days, the rates did not differ.

2.4.2 Study 2: Gisela 3 versus Gisela 5

At harvest, no size difference could be visually detected between G.3 trees and G.5 trees. There was also no visible difference between their rootballs (Fig. 2.4.5).

Leaf area of G.3 averaged 1796 cm² which was significantly greater than the average of 1312 cm² for G.5 ($P < 0.01$). Leaf dry mass was significantly greater for Gisela 3 than for Gisela 5 (19.0 g versus 16.2 g) ($P = 0.01$). There was no significant difference between trunk diameter at the beginning of the study—G.3 averaged 5.6 mm while G.5 averaged 5.9 mm. At harvest, G.3 trunk diameter averaged 11.3 mm and was significantly greater than Gisela 5 trunk diameter (9.3 mm) ($P < 0.01$). The slope of the increase in trunk diameter was also significantly greater for G.3 than for G. 5 (58.8 $\mu\text{m}/\text{day}$ vs. 33.2 $\mu\text{m}/\text{day}$) ($P < 0.01$). Total trunk biomass was significantly greater (33 g for G.3 and 28 g for G.5) ($P < 0.01$), but the difference in leaf area per TCSA was not significantly different (Table 2.4.2).



Fig. 2.4.5. Gisela 3 (bottom) and Gisela 5 (top) rootballs post-harvest. There were no visible differences between the G.3 and the G.5 rootballs.

There was no significant difference in the recovery of transpiration for Gisela rootstocks after the first irrigation. Transpiration on the day immediately following irrigation was not significantly different at the 0.05 level. However, G.3 transpiration rates were significantly greater on the second and third days after irrigation ($P = 0.01$ and $P = 0.03$, respectively). After five days, transpiration rates between the two rootstocks did not differ (Fig. 2.4.6).

Table 2.4.2 Growth metrics for Gisela 3 and Gisela 5 rootstocks. G.3 rootstocks were larger than G.5 rootstocks at the end of the experiment.

	Leaf Fresh Mass	Leaf Dry Mass	Leaf % Dry Mass	Leaf Area	Specific Leaf Mass	Beginning Trunk Diameter	Ending Trunk Diameter	Leaf Area/ TCSA	Trunk Dry Mass
	(g)	(g)	(%)	(cm ²)	(g/m ²)	(mm)	(mm)	(cm ² /cm ²)	(g)
Gisela 3	48.8	19.0	39.0	1796	106	5.6	11.3	1797	33
Gisela 5	39.0	16.2	41.8	1312	125	5.9	9.3	1957	28
<i>P-Value</i>	<i><0.01</i>	<i>0.01</i>	<i>n.s.</i>	<i><0.01</i>	<i><0.01</i>	<i>n.s.</i>	<i><0.01</i>	<i>n.s.</i>	<i>0.01</i>

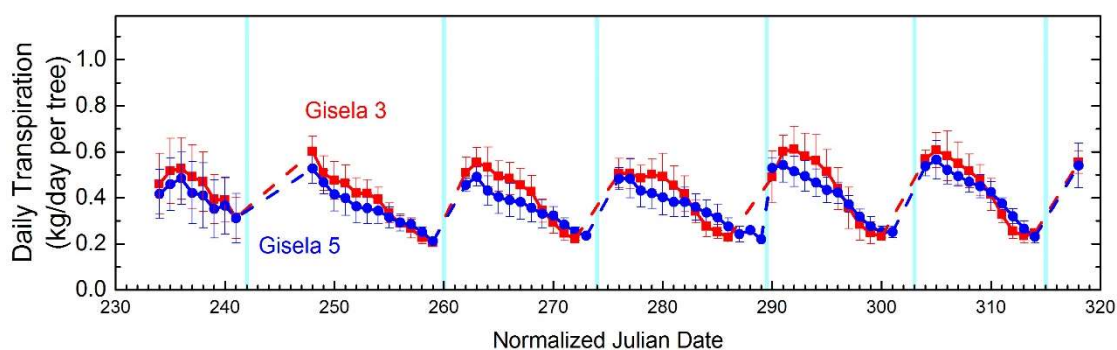


Fig. 2.4.6. Gisela 3 and Gisela 5 rootstock transpiration recovery following irrigations. G.3 rootstocks had higher transpiration rates for several days after irrigation than G.5 rootstocks.

When all dry-down cycles were pooled, transpiration rates were not significantly different between cultivars the day before irrigation or the day after irrigation. G.3 trees had significantly greater transpiration for the second through the seventh day after irrigation (Fig. 2.4.7).

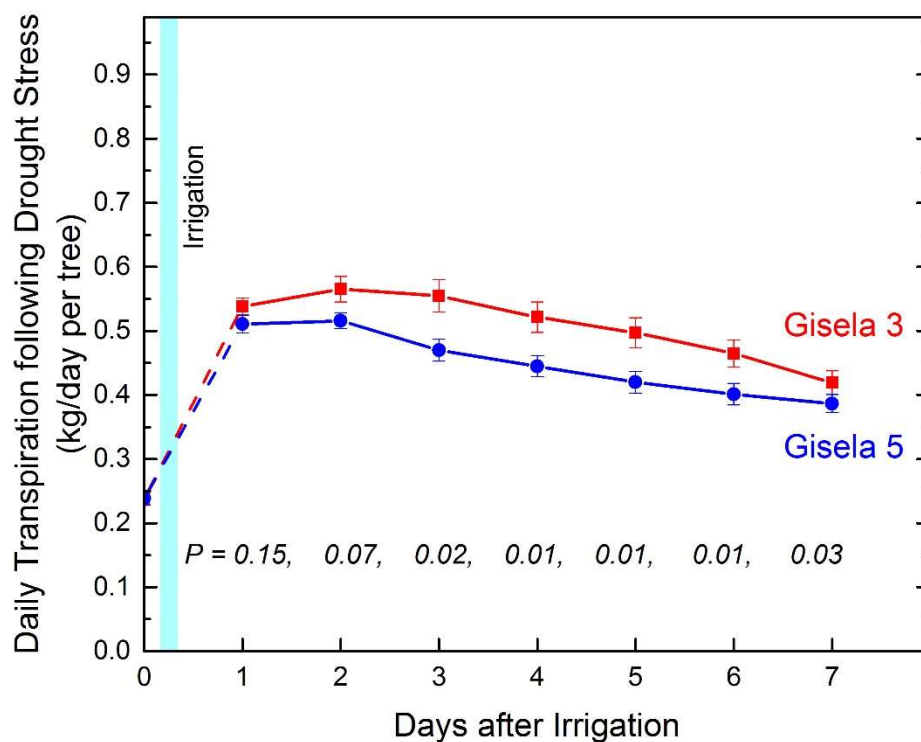


Fig. 2.4.7. Gisela 3 and Gisela 5 rootstock mean transpiration for seven days after 5 irrigations. G.3 transpiration rates weren't different from G.5 rates on the first day after irrigation, but they were higher than G.5 from two to seven days after irrigation.

In the first study, G.5 trees, once stressed, never regained their initial pre-stress daily transpiration rates. Pre-stress daily transpiration rates were nearly 800 g/day, but after the first stress cycle, the rates never exceeded 600 g/day. The same did not occur in the second study. In the second study, G.5 transpiration rates were approximately 500 g/day pre- and post-stress. Perhaps the most likely explanation for this apparent

difference is in the level of stress. In both studies, pre-irrigation transpiration rates were approximately 250 g/day for all cultivars. However, in the first study, the pre-stress transpiration rates were approximately 800 g/day for G.5 and G.12. This is a nearly a 70% decrease in transpiration. In the second study, both cultivars had transpiration rates of approximately 500 g/day before the drought stress. This was a 50% decrease. In the first study, the first stress cycle may have damaged the G.5 trees enough that they were never able to completely recover. In the second study, because the stress was not as extreme, the G.5 trees were able to recover more fully.

The threshold of 250 g/day daily transpiration was selected by observing the trees daily as the media dried. When wilting was observed, the daily transpiration was near 250 g/day. It is apparent, though, that the trees adjusted osmotically because successive dry down cycles did not result in wilting. This also provides evidence that growth of the rootstocks was modified by a mechanism other than changes in turgor pressure.

Another possible explanation for differences in growth would be waterlogging of the media. It is possible that differences in tolerance to hypoxic soils could have led to the differences in growth. Field soils are rarely used in containers because of their propensity to compact and become hypoxic. The maximum volumetric water content over the course of the two studies was 50%, which is likely saturated; but, the duration of the saturation was a few hours immediately following irrigations which occurred every 7 to 10 days. Waterlogged media does not likely explain the difference in growth between Gisela rootstocks.

In both studies, G.5 rootstocks grew more slowly than the other rootstocks. Adjusting transpiration rates for differences in leaf area revealed that, G.5 rootstocks transpired significantly more water per day per unit leaf area than did G.12 rootstocks ($P < 0.01$) or G.3 rootstocks ($P = 0.04$). However, since G.12 and G.3 had significantly greater leaf area than G.5, there was likely some self-shading of leaves. There was most likely little difference in the transpiration rates per unit leaf area between the cultivars. This provides evidence that the differences in growth between the rootstocks were not due to changes in stomatal regulation.

Perhaps the differences are due to root turnover as fine roots die and are regenerated in response to the dry down and irrigation cycles.

At first glance, this seems like a biased comparison due to the differences in leaf area and size between the rootstocks, but it is interesting to note that, since G.12 and G.3 continued to grow in spite of the drought stress, they actually experienced an increasingly greater level of water stress with each cycle and still had significantly greater growth than G.5 trees in both studies.

Grafting the rootstocks with a common scion would provide a way to further test the drought tolerance of these rootstocks. By using a common scion, any interaction between these rootstocks and a common scion could also be evaluated. The contribution of any graft incompatibilities to the drought tolerance of the grafted tree could then also be evaluated.

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CHAPTER 3
SENSING TREE HYDRATION USING
ELECTROMAGNETIC SENSORS

3.1 Abstract

Despite the fact that research has demonstrated that time domain reflectometry (TDR) can be used to determine the water content of tree trunks, the technique has been mostly limited to institutional research. Newer TDR and other electromagnetic sensors have reduced the cost of the instrumentation for this technique. Having an electronic method of determining tree water status would enable tree fruit growers to reduce water consumption while maintaining profitability and improving fruit quality.

Electromagnetic sensors may provide such a method of determining tree water status. Here we tested five different types commercially-available TDR and other electromagnetic soil moisture sensors in tree trunks over two consecutive growing seasons. Sensors varied in their ability to detect changes in trunk hydration, but sensor placement also seemed to play a crucial role. When the sensor's wave guides were exposed to a greater percentage of sapwood, the response from the sensor improved. Before and after irrigation increases of approximately 0.5 MPa in stem water potential produced 0.5 units increases in permittivity over the 2016 growing season.

3.2 Introduction

Many researchers have inserted time domain reflectometry (TDR) sensors into wood to determine water content. Several have used the technique to determine the water

storage capacity of native conifer trunks (Constantz and Murphy, 1990; Irvine and Grace, 1997; Kravka et al., 1999) and to evaluate xylem cavitation (Sparks et al., 2001).

There are several challenges in determining trunk hydration using TDR. Holbrook et al. (1992) cautioned that temperature effects in wood could make TDR measurement of trunk hydration more complicated and that wave guide length could also adversely affect these measurements. They suggested using a wave guide length similar to the radius of the stem. A custom calibration equation relating permittivity to water content may also be necessary (Holbrook et al., 1992; A Nadler et al., 2006).

Nadler et al. (2003) concluded that TDR could determine stem hydration in lemon and mango (A Nadler et al., 2006), but that the signal was too noisy and the system too expensive for managing orchard irrigation. Despite the fact that the system was too expensive for agricultural use (Arie Nadler et al., 2003), it's use in research continued. Kumagai et al. (2009) found that amplitude domain reflectometry (ADR) sensors bolstered predictions of stomatal conductance. Like TDR sensors, ADR sensors can determine the water content of wood, based on the apparent dielectric permittivity.

Over time the technological advances with TDR and other electromagnetic volumetric water content sensors Nadler et al. (2006) predicted have occurred, making the sensors more reliable and cheaper. Garrity (2014) suggested using the Decagon GS3 sensor in the trunks of trees to monitor hydration. Using this technique and sensor, Matheny et al. (2015) were able to measure the trunk water content of red oak and red maple forest trees. Similar work was done on birch trees by Hao et al. (2013), with the exception that the focus was on xylem cavitation. Most recently, Saito et al. (2016)

demonstrated the utility of TDR-like sensors in determining the water content of native and invasive trees in arid environments.

In this study, five different models of TDR and other electromagnetic soil moisture sensors were inserted into the trunks of fruit trees to test their ability to determine changes in trunk hydration associated with irrigation stress.

3.3 Materials and Methods

3.3.1 Sensor Descriptions

The five models of sensors are shown below (Fig. 3.3.1). Some sensors have two wave guides, while others have three (Table 3.3.1). The manufacturer-listed volume of influence ranges from 100 mL to nearly 1.5 L, but volume of influence varies with water content, target medium and installation methods and sensors should be calibrated accordingly (Sutitarnnontr et al., 2014). Frequencies also differ greatly between sensors, ranging from 70 MHz to 3.5 GHz. Probe length for GS1 and GS3 sensors is 5 cm while the CS655 and TDR-315(L) are approximately twice as long. The effective frequency of



Fig. 3.3.1. Electromagnetic soil moisture sensors used in fruit tree trunks. Clockwise from top left: Decagon Devices GS1, Decagon Devices GS3, Campbell Scientific CS655, Acclima TDR-315L, Acclima TDR-315.

Table 3.3.1. Description of electromagnetic soil moisture sensors. Sensors varied in waveguide length, number of waveguides, volume of influence and frequency.

	Decagon GS1	Decagon GS3	CS CS655	Acclima TDR- 315	Acclima TDR-315L
No of Wave Guides	2	3	2	3	3
Wave Guide Length	5 cm	5 cm	12 cm	15 cm	15 cm
Volume of Influence	1430 mL	160 mL	3600 mL	100 mL	100 mL
Frequency	70 MHz	70 MHz	78 MHz	3.5 GHz	4GHz
Output	mV/VWC	Permittivity/ VWC	Permittivity/ VWC	Permittivity/ VWC	Permittivity/ VWC

each sensor will vary with the characteristics and water content of the measured medium (Robinson et al., 2003).

3.3.2 2015

Line-source irrigation systems at the USU Kaysville Research Center delivered ample irrigation and deficits of 68%, 57% and 33% of ample to peach trees (Fig. 3.3.2) and deficits of 81%, 72%, 53% and 43% of ample to tart cherry trees (Fig. 3.3.3). For apples, no line-source irrigation system could be used, so 3 rows of apple trees were deficit irrigated by reducing the total amount of time the sprinklers ran in those three rows (Fig. 3.3.4) while the remainder of the orchard was irrigated for the full cycle. Ample irrigation delivered 2 inches (50.8 mm) of water per week during the heat of the summer. Descriptions of the orchards studied are found below in Table 3.3.2.

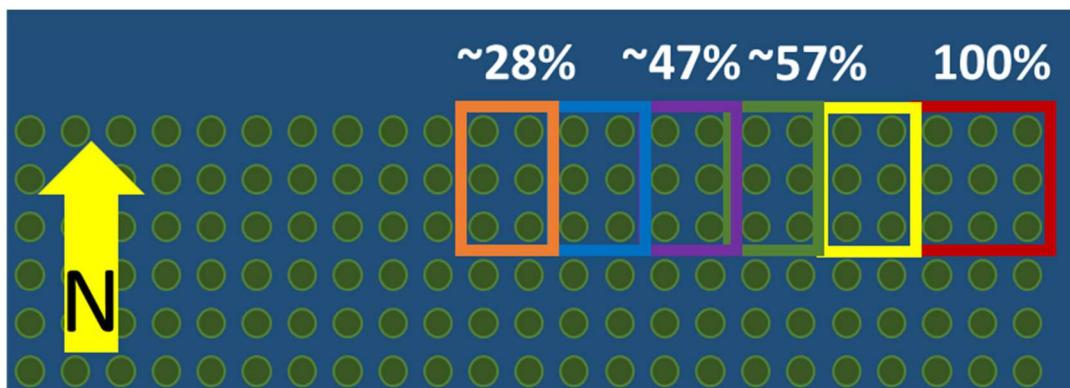


Fig. 3.3.2. 2015 Kaysville peach electromagnetic sensor installation map. One GS1 was installed in a scaffold branch and one CS655 was installed in the trunk of a tree receiving each level of irrigation.

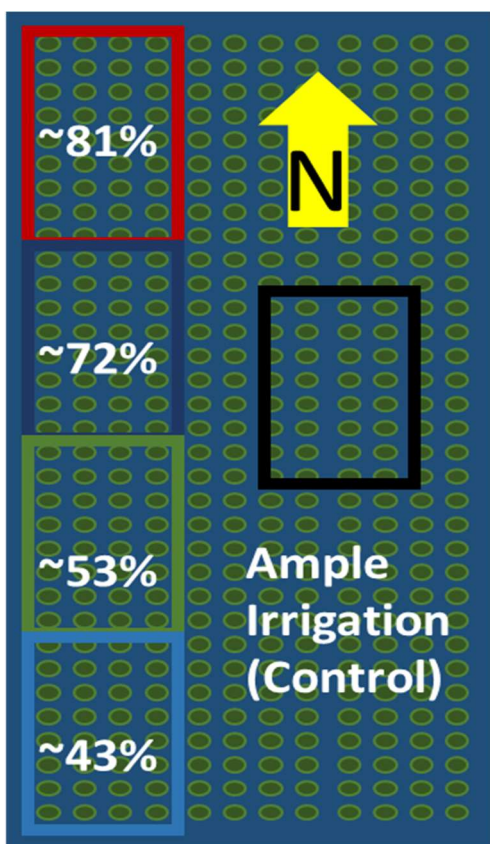


Fig. 3.3.3. 2015 Kaysville tart cherry electromagnetic sensor installation map. One GS1 and one CS655 were installed in the trunk of a tree receiving each level of irrigation.

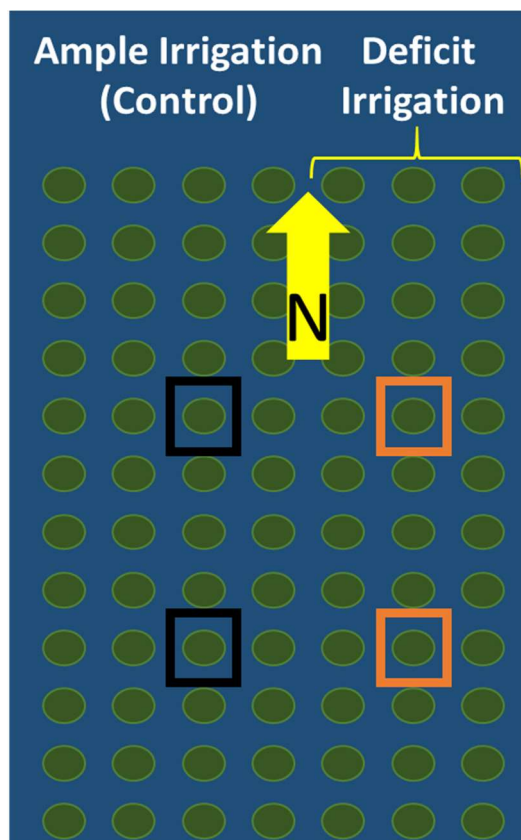


Fig. 3.3.4. 2015 Kaysville apple electromagnetic sensor installation map. GS1 sensors were installed in two replicate trees receiving ample irrigation and in two receiving deficit irrigation.

Table 3.3.2. Crop, scion, rootstock, age and training system of three orchards monitored with electromagnetic sensors.

Site	Crop	Scion	Rootstock	Age (yr)	Training System	Row Spacing (m)	Tree Spacing (m)	Orchard Floor Management
Alpine	Peach							
Santaquin	Peach	'O'Henry'	Lovell'	9	Open Center	4.9	2.4	bare under tree/grass row
Genola	Apple	'Gala'	'Bud 9'	17	V Trellis	4.3	0.9	orchard grass
Payson	Apple	'Fuji BC2'	'M9'	24	Central Leader	4	1.4	bare under tree/grass row

In 2015, one GS1 volumetric water content sensor (Decagon Devices, Pullman, Washington) and one CS655 volumetric water content sensor (Campbell Scientific, Logan, Utah) were inserted into the peach and tart cherry trees (See Fig. 3.3.5). Only GS1 sensors were used in apples. All sensors were installed on the north side of tree trunks and scaffold branches in order to reduce direct exposure to solar radiation.

In peaches and cherries, the probes were inserted into one tree receiving each level of irrigation. In apples, one sensor was installed in the trunk of each of two replicate deficit-irrigated trees and two replicate ample-irrigated control trees. In peaches, the CS655s were inserted into the trunks and the GS1s were inserted into a



Fig. 3.3.5. Electromagnetic soil moisture sensors installed in fruit trees 2015. Sensors were inserted in Peach trunks and scaffold branches (left), Tart Cherry trunks (left) and Apple trunks (right) .

scaffold branch. In tart cherries, both sensors were inserted into the trunks of the trees.

Initially a piece of closed cell foam was installed between the bark and the sensor to act as a gasket. Later,

the foam was removed and the interface was sealed with silicone caulking. The CS655 sensor was installed approximately 20 cm above the GS1 sensor to prevent interference between the sensors.

Pilot holes just larger than the probes of each respective sensor were drilled with a jig to ensure proper alignment. Sensors were then installed using a rubber mallet, if necessary. Sensors were installed in the center of the trunk or the scaffold branch to ensure that all of the wave guide was inside the tree (Fig. 3.3.6).

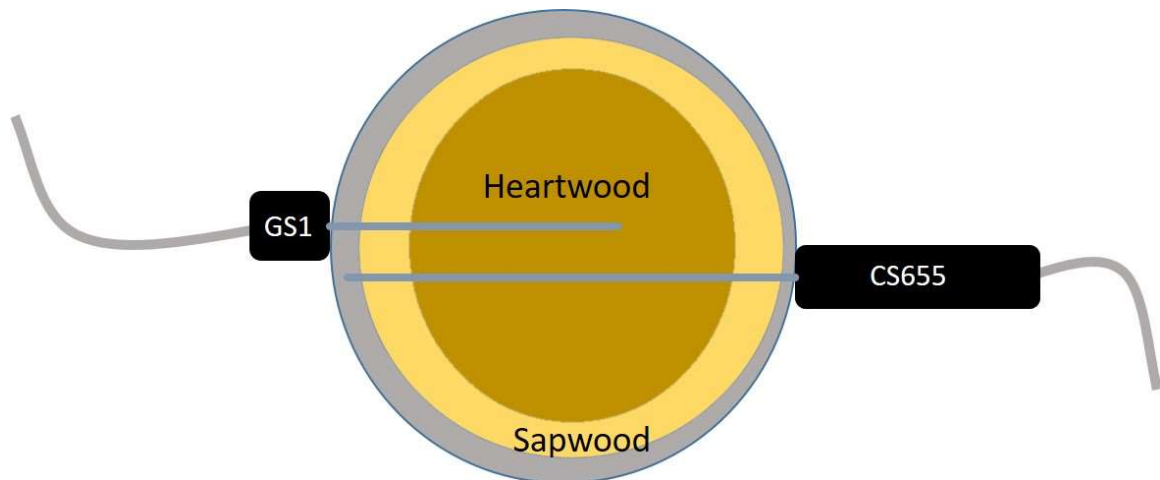


Fig. 3.3.6. 2015 electromagnetic sensor installation focused on having the full wave guide length inside the trunk. Sensors were installed on the same side of the trunk and about 20 cm apart to prevent interference.

Periodically, stem water potential (P. F. Scholander et al., 1965; Per F Scholander et al., 1964) was evaluated using a pressure chamber for each of the three crops to develop a correlation between stem water potential and trunk water content. These correlations provided the basis for determining whether permittivity detected with electromagnetic sensors would be a suitable, automated indicator of plant water status. Wherever possible, at least one reading was taken before each irrigation and at least one after.

3.3.3 2016

Because a water stress gradient was difficult to establish in 2015, rather than attempt to establish different irrigation levels in 2016, the entire orchard was not irrigated for several weeks. Then, the soil moisture was completely replenished. Only a peach orchard was monitored. Seven TDR-315(L), seven CS655 and four GS3 sensors were installed on June 13th. Four additional GS3 sensors were installed on July 20th (Fig. 3.3.7). When possible, sensors were installed on the north side of the peach trees. Some sensors were installed in the west side because of trunk geometry.

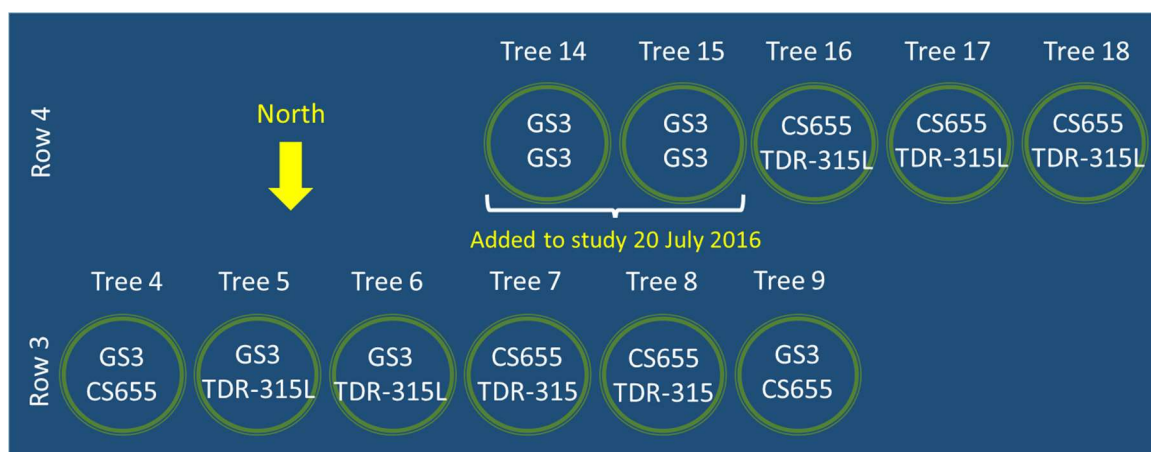


Fig. 3.3.7. 2016 Kaysville peach electromagnetic sensor installation map. Seven TDR-315(L)s, seven CS655s and eight GS3s were installed. Each tree had two sensors.

Pilot holes just larger than the probes of each respective sensor were drilled with a jig to ensure proper alignment. Sensors were then installed using a rubber mallet if necessary. Rather than trying to ensure that the entire length of the sensor probe was inside the tree, installation focused on trying to get as much of the probe in the sapwood of the tree as possible (See Fig. 3.3.8).

Parts of the waveguide near the sensor head were not in the tree (Fig. 3.3.10). In addition, the CS655 and TDR-315(L) probes were long enough to go completely through the tree trunk in some cases (Fig. 3.3.9). This exposed portion of the waveguide would reduce the signal from the sensor because the part of the wave guides exposed to the air would sense the permittivity of air which is 1. This exposure to air would attenuate the signal.

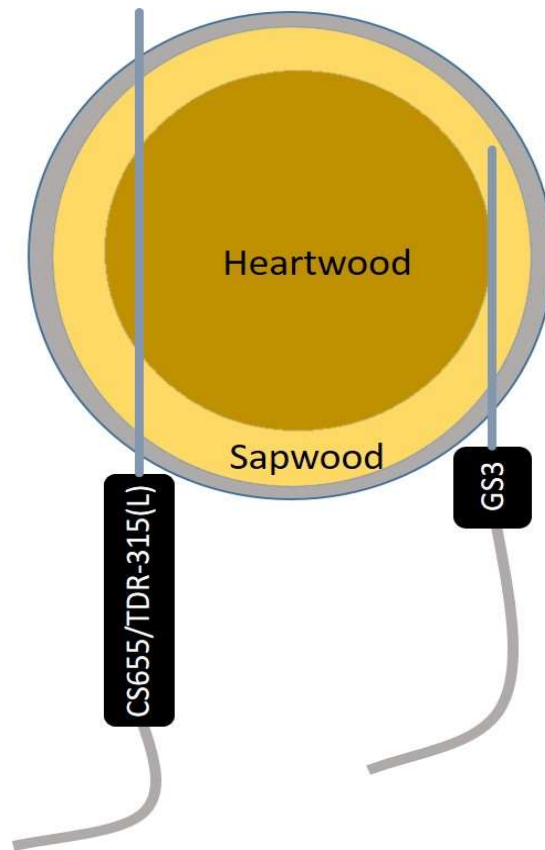


Fig. 3.3.8. 2016 electromagnetic sensor installation diagram focused on placing wave guides in the sapwood.



Fig. 3.3.9. GS3 and CS655 installed in a peach tree trunk revealing some exposed waveguide near the sensor head.



Fig. 3.3.10. CS655 and TDR-315(L) sensors protruding through a peach tree trunk.

Stem water potential using a pressure chamber (P. F. Scholander et al., 1965; Per F Scholander et al., 1964) was evaluated three times per week to develop a correlation between stem water potential and trunk permittivity. These correlations provided the basis for determining whether permittivity detected with electromagnetic sensors would be a suitable, automated indicator of plant water status. Wherever possible, the two readings immediately preceding irrigation were averaged to determine the before irrigation stem water potential. Likewise, the two SWP readings following irrigations were averaged to determine the after irrigation SWP.

At the end of the season, the peach trees were cut down. The section of the trunk in which the sensors were installed was excised and brought to the lab for further analysis (Fig. 3.3.11). Each cut end of each peach trunk section was covered with petroleum jelly to prevent evaporation. All trunk sections were then placed in a dark growth chamber to test for temperature sensitivity. Two thermocouples were installed in each trunk section.

Holes were drilled in the trunk near each sensor to a depth similar to that of the wave guides. The growth chamber ramped steadily from 10 °C to 35 °C over 12 hours and then ramped back down to 10 °C over the next 12 hours. Data from all electromagnetic sensors were collected with a datalogger.

After the temperature sensitivity test, the top end of each trunk section was re-cut and photographed to illustrate the proportions of sapwood and heartwood. A visual assessment of the proportion of each sensor that was in heartwood, sapwood or outside the bark was performed using a ruler to superimpose a line on the top of each trunk section representing the path of the wave guides. The length of the wave guide in each part was measured. Pictures of the trunk sections are shown below (Fig. 3.3.12).



Fig. 3.3.11. Excised peach trunk sections with installed electromagnetic sensors. A total of 22 sensors were installed in 11 Peach trees.



Fig. 3.3.12. Sapwood and heartwood ratios for all excised peach trunk sections. Sapwood was comprised of the outer four or five annular rings and was about 3 cm thick.

3.4 Results and Discussion

3.4.1 2015

The temperature sensitivity of the GS1 sensor made its use in orchards very difficult (See Appendix A). The small response and temperature sensitivity of the GS1 make it an unlikely candidate for detecting changes in trunk hydration in fruit trees. It is also being discontinued by the manufacturer. Data from the GS1 sensors is included in Appendix B.

CS655 permittivity declined throughout August and September 2015 in tart cherries, but declines in trunk permittivity between irrigations and recovery after irrigations was not clearly detectable (See Appendix B)

Season-long averages of sensor output did not reveal any specific trends. When considering only the seven irrigations in tart cherries after which stem water potential recovered, the average changes in CS655 permittivity ranged from -0.01 to 0.16. There are some instances where a recovery in stem water potential corresponded to an increase in permittivity for the 43% irrigation level (e.g. the irrigation on 4 September 2015) (Fig. 3.4.1).

The encouraging trend is that the larger differences in permittivity before and after irrigations in tart cherries corresponded with the larger recoveries in stem water potential, but there is still much noise in the data (Table 3.4.1).

CS655 permittivity followed similar trends in peaches. There was an overall decline in permittivity in August and September 2015, but no clearly detectable recoveries after irrigations (Fig. 3.4.2). (See also Appendix C).

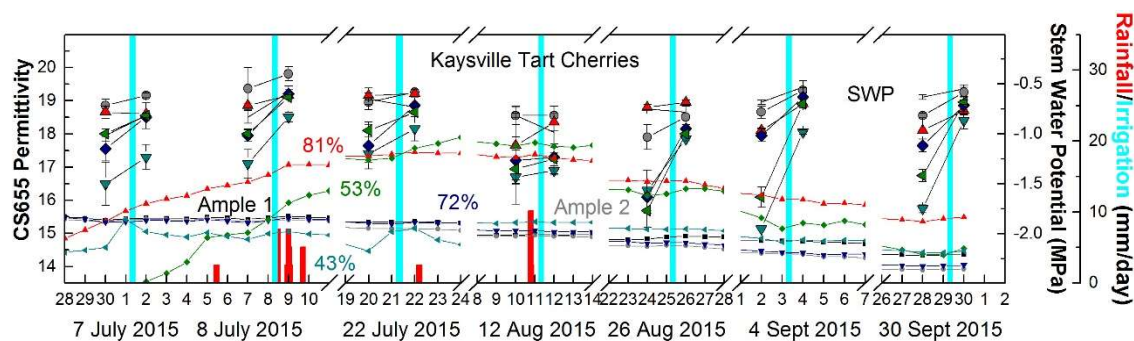


Fig. 3.4.1. 2015 Kaysville tart cherry daily mean CS655 sensor permittivity and stem water potential for seven irrigations. (Irrigations are represented with light blue bars, while rainfall is represented with red bars).

Table 3.4.1. 2015 CS655 before and after irrigation permittivity and stem water potential changes in tart cherries for seven irrigations.

	CS655 Permittivity		Stem Water Potential Difference (Mpa)	
	Mean	SD	Mean	SD
100%	0.02	0.04	0.06	0.16
100%	-0.01	0.04	0.14	0.08
81%	0.11	0.31	0.12	0.11
72%	-0.02	0.04	0.49	0.33
53%	0.16	0.31	0.38	0.19
43%	0.11	0.21	0.47	0.34

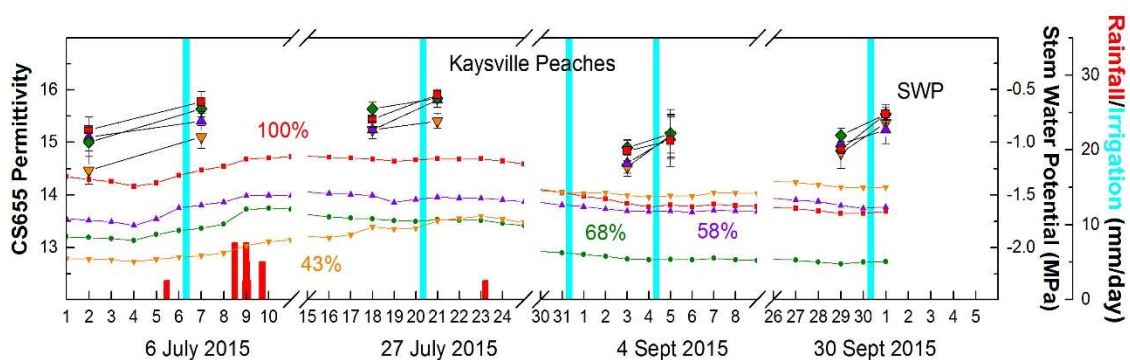


Fig. 3.4.2. 2015 Kaysville peach daily mean CS655 sensor permittivity and stem water potential for seven irrigations. (Irrigations are represented with light blue bars, while rainfall is represented with red bars).

In peaches, small recoveries of permittivity (0.05 to 0.07) could be detected, on average, for the four irrigations where stem water potential recoveries ranging between 0.19 MPa and 0.25 MPa were measured (Table 3.4.2).

Small positive changes in permittivity were associated with positive changes in stem water potential after irrigations (Fig. 3.4.3). In this study, CS655 sensor probes were installed into the center of the tree trunk. Perhaps if the sensor came into contact with a greater percentage of sapwood, the permittivity changes might be larger.

The diurnal cycling of CS655 permittivity could be a real effect, since the electronics of the CS655 are not sensitive to temperature (See Appendix A), but further analysis is required to eliminate other possible contributions to the cycling.

Table 3.4.2. 2015 CS655 summary of before and after irrigation permittivity and stem water potential changes in peaches for four irrigations.

	CS655 Permittivity Change		Stem Water Potential Change (Mpa)	
	Mean	SD	Mean	SD
100%	0.07	0.17	0.25	0.11
68%	0.05	0.11	0.20	0.07
58%	0.07	0.19	0.19	0.10
33%	0.05	0.10	0.23	0.10

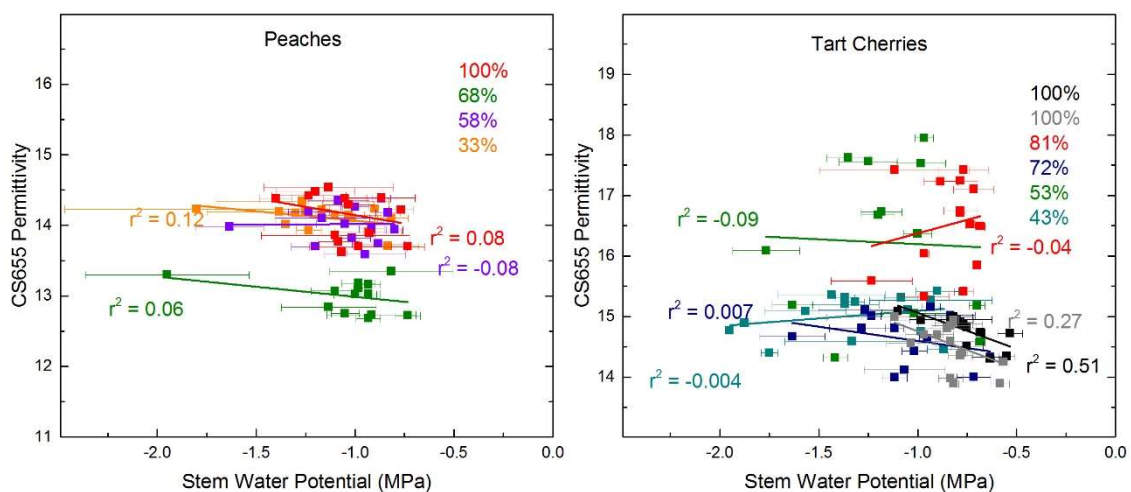


Fig. 3.4.3. 2015 Kaysville stem water potential and CS655 permittivity regressions. Many of the relationships slope in the wrong direction or are not robust.

3.4.2 2016

GS3 permittivity output generally decreased between irrigations and recovered following them. A degree of recovery was immediately detectable, but recovery continued for four or five days following irrigation. Then permittivity values began to decline again (Fig. 3.4.4).

CS655 permittivity values decreased between every irrigation and recovered following the irrigation with the exception of a single sensor which did not respond as expected between the irrigations on July 5 and July 28. Similar to the GS3, permittivity values showed immediate recovery, but increased over the following four to five days before declining again (Fig. 3.4.4).

TDR-315(L) permittivity responded similarly to the other two sensors. After the July 5 irrigation, all sensors detected trunk dehydration between irrigations and recovery of trunk hydration immediately after irrigation with continued recovery for four to five days afterward (Fig. 3.4.4).

Changes in permittivity before and after irrigations were small (< 1 permittivity unit) for each model of sensor. CS655 sensors recorded the largest difference in permittivity, followed by GS3 sensors and TDR-315 sensors (Table 3.4.3).

Ultimately, a strong relationship between trunk permittivity and SWP would indicate that trunk permittivity obtained with soil moisture sensors is a suitable replacement for stem water potential measurements. Stem water potential values varied and r^2 values ranged from $r^2 = 0$ to $r^2 = 0.17$ for GS3 sensors, from $r^2 = 0.01$ to $r^2 = 0.26$ for CS655 sensors and from $r^2 = 0.03$ to $r^2 = 0.29$ for TDR-315(L) sensors (Fig. 3.4.5).

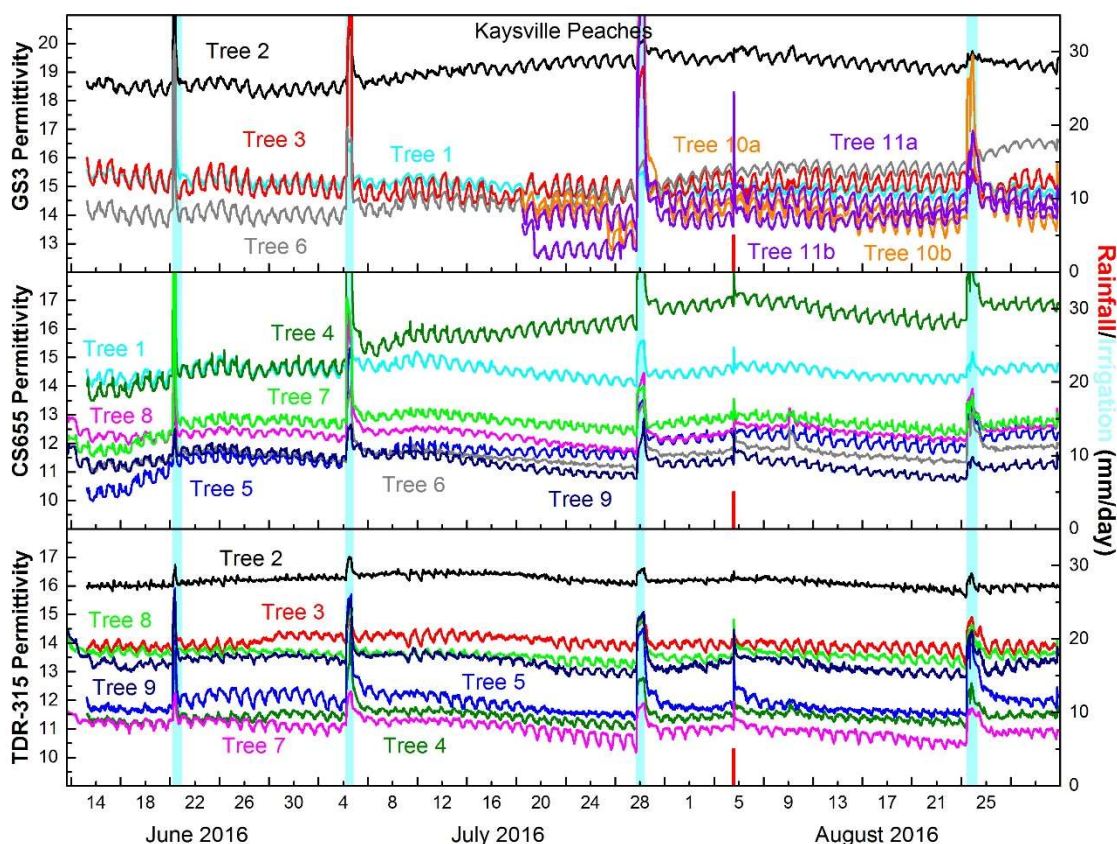


Fig. 3.4.4. 2016 Kaysville peach trunk permittivity from all 22 sensors. Line colors indicate installation in the same tree. The single rainfall event on 5 August 2016 is indicated with a red bar while irrigations are indicated with light blue bars.

Table 3.4.3. 2016 stem water potential and permittivity before and after differences for four irrigations. Stem water potential increases on 0.5 MPa corresponded to permittivity increases ranging from 0.27 to 0.39 units.

	Delta Stem Water Potential (MPa)	Permittivity Increase		
		TDR-315(L)	CS655	GS3
Mean	0.50	0.25	0.39	0.27
SD	0.21	0.19	0.20	0.21
<i>P-Value</i>	$P < 0.01$	$P < 0.01$	$P < 0.01$	$P < 0.01$
Reps	11	7	7	8

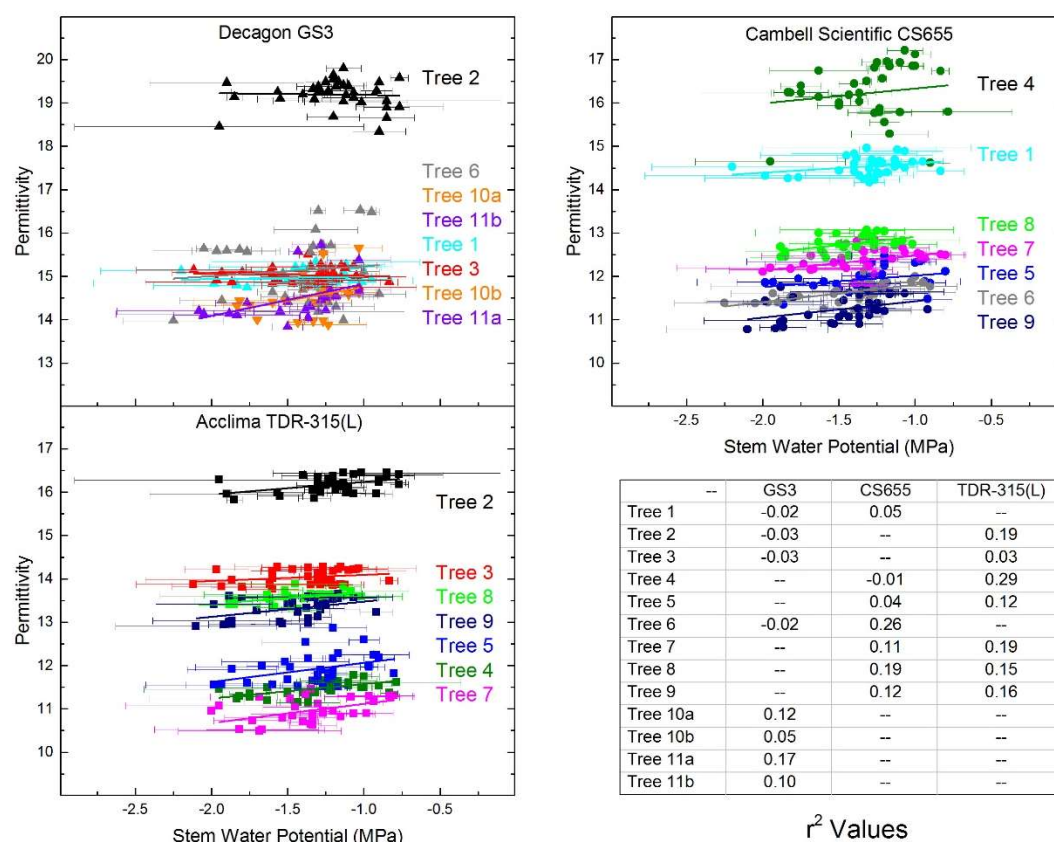


Fig. 3.4.5. 2016 Kaysville daily average peach stem water potential and permittivity regression. Most relationships are positive, as we would expect, but the slopes are small (<0.3 units of permittivity per MPa).

Because the recovery of permittivity from CS655 sensors was greater and more clearly detectable in 2016 than in 2015, it is evident that placing the sensors in a location to maximize contact with sapwood is beneficial. It appears that contact with sapwood may be more important than the actual length of the wave guides. Wave guides of CS655 and TDR-315(L) sensors protruded through the trunks of the peach trees in this study in some cases. Because of this, the part of the sensor in the air would detect a permittivity

of 1, diluting the signal. Maximizing exposure to sapwood is essential and may be accomplished through sensor modification or selection and installation methods.

Changes in temperature could explain the diurnal cycling of the trunk permittivity values. All sensors reported a similar season-long minimum temperature, but the season-long maximum temperature recorded by the TDR-315(L) was approximately ten degrees higher than that recorded by GS3 or CS655 sensors. The sensor body of both the GS3 and the CS655 is white, while the sensor body of the TDR-315(L) is black. This difference in color likely explains why the maximum temperatures vary, while the minimum temperatures do not (Table 3.4.4).

Table 3.4.4. Season-long minimum and maximum temperatures recorded by electromagnetic sensors. The maximum temperatures recorded by TDR-315(L)s averaged ten degrees warmer than those reported by GS3s or CS655s.

	Sensor Body Temperature	
	Minimum (°C)	Maximum (°C)
GS3	6.7	44.6
CS655	6.0	44.0
TDR-315(L)	6.2	54.5

The permittivity of water changes with temperature. The relationship of water and permittivity can be found using $\epsilon = 87.740 - 0.4008t + 9.398 * 10^{-4}t^2 - 1.410 * 10^{-6}t^3$, where ϵ is permittivity and t is temperature in degrees Celsius (Malmberg and Maryott, 1956). The approximate range of temperatures in this study is 5 °C to 55 °C. This part of the curve relating permittivity and water can be approximated with a linear

equation with a slope of -0.36 and an $r^2 = 0.99$. In other words, the permittivity of water decreases by 0.36 for every increase 1 °C increase in temperature from 5 °C to 55 °C.

Assuming sensor electronics are minimally sensitive to temperature (Appendix A) we would expect that, for each 1° C increase in temperature, permittivity values would drop by 0.36 units. However, temperature changes also affect the electrical conductivity of water (EC), which, in the case of the CS655 sensors, affects the period value, and, consequently permittivity (Ritter, personal communication). EC increases by 2% for each degree Celsius increase in temperature in the case of the CS655. These two interacting factors make a temperature correction of sensor output based on the effect of temperature on permittivity difficult. Further, the interacting effects of temperature on water bound to solid surfaces and on bulk soil water create a complex interaction where an empirical temperature correction is impossible (Wraith and Or, 1999). Or and Wraith (1999) suggested that the thickness of the layer of water bound to solid surfaces is affected by temperature and offered corrections based on soil specific surface area and water content. These parameters can be estimated from soil texture, but, in order to employ similar corrections in tree trunks, the wood specific surface area and water content of each tree species would need to be estimated.

For field data, the average slope of temperature and permittivity relations for all GS3 data is -0.037 units of permittivity per degree Celsius. The slopes for the CS655 and the TDR-315(L) are -0.012 and -0.003, respectively. This is much less than the expected value. One possible explanation is that the temperature inside the tree trunk is more stable than the temperature detected in the sensor head. However, the lab temperature

sensitivity test indicated that wood temperature at the depth of the sensor lagged air temperature by only one or two degrees.

However, other factors in the field such as solar radiation, sap flow rates and wind could affect the temperature of both the sensor head and the wood and possibly result in a greater difference in temperature between the two readings. The only way to characterize this difference in the field would be to install a thermocouple or thermistor in the tree near the sensor wave guides to simultaneously monitor differences between wood temperature and sensor body temperature. Even so, temperature effects on permittivity were less than what would be expected if the sensors were only “seeing” bulk water which indicates that bound and unbound water play a role in the response of permittivity to temperature in wood as has been suggested in soils (Or and Wraith, 1999; Wraith and Or, 1999).

Lab tests confirm that the slopes for relationships between temperature and permittivity are small. The average slope for GS3 sensors was -0.0165 units of permittivity per degree Celsius while the slopes for the CS655 and TDR-315(L) were -0.0012 and 0.015, respectively. There is some indication of temperature sensitivity in the GS3 in this test; some sensitivity was also found in the sensor electronics test (See Appendix A). Still, none of the sensors seems to be overly temperature sensitive when installed in peach wood.

Since the effect of temperature on EC can also affect CS655 permittivity, this effect must also be explored in order to provide evidence that the sensors were able to detect a real diurnal fluctuation in permittivity. The average slope of temperature and EC

relations for the CS655 was less than 0.02% per degree Celsius—much less than the expected 2% change. Thus, because the actual slopes of the relationship between temperature and EC are much less than the expected slope, there is no apparent need for temperature correction based on its effect on EC. This may be partly explained by the fact that the EC values detected by the CS655 (approximately 0.05 dS/m) are very low (EC of tap water in the area is approximately 0.34 dS/m). Because the measurements are low, they likely induce a minimal effect on permittivity as temperature increases.

The fact that permittivity readings seem to be temperature-stable for each type of sensor added to the fact that permittivity decreases during the day and increases during the night provides evidence that the sensors are capable of detecting diurnal fluctuations in tree trunk hydration (Fig. 3.4.6).

Still, our work confirms Holbrook's (1992) caution about temperature sensitivity. The difference in temperature between the sensor body and the wood could affect measurements from the electromagnetic sensors, but this is likely not as great as the effect of temperature-sensitive electronics. At the very least, a sensor whose electronics are stable is a must for this type of measurement. Diurnal changes in trunk hydration, while interesting, may be of less value than the daily mean values in terms of scheduling irrigation based on tree water status—particularly if there is uncertainty about temperature effects on measurements.

The large range of temperatures detected by the sensors suggest that insulating the sensors as Saito et al. (2016) did might be of benefit. Despite the insulation, daily temperatures in their study fluctuated approximately 10 °C. The daily fluctuations in our

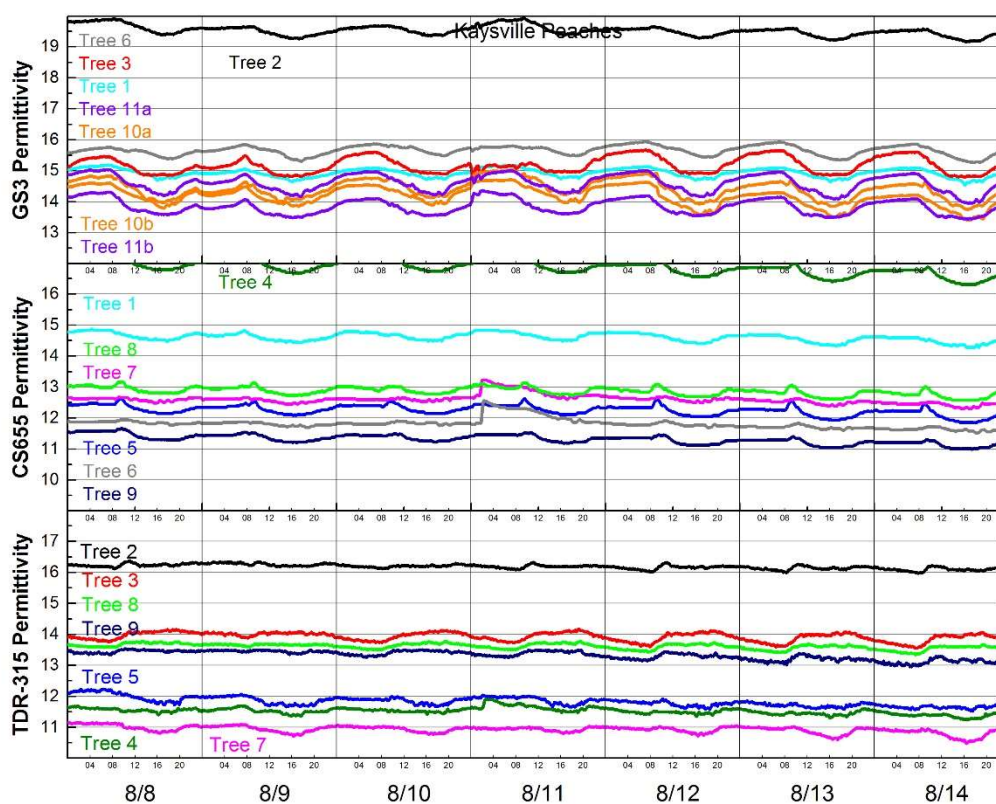


Fig. 3.4.6. Diurnal fluctuations in permittivity for the week of August 8, 2016 occur in the direction we would expect, but could be a result of temperature effects on the permittivity of water.

study were approximately 20 °C for GS3 and CS655 and approximately 30 °C for TDR-315(L). Even with this large diurnal temperature change, the effect of temperature on permittivity readings was small, suggesting that insulation may not be necessary.

Even though temperature sensitivity was small, we would have expected a greater response from the sensors. Perhaps the signal was small because of sensor placement—despite our attempts to maximize waveguide exposure to sapwood. Since sapwood was only about 3 cm thick, many sensors were only exposed to a few centimeters of sapwood.

The proportions of the waveguide exposed to air, heartwood and sapwood for each sensor are listed in Table 3.4.5 or Table 3.4.6 below.

Despite the fact that the relationship between contact with the sapwood and sensor response is not overly robust ($r^2 \leq 0.41$) for any of the sensors, the sensor response increased as the percentage of the sensor wave guide in contact with the sapwood increased (Fig. 3.4.7).

Table 3.4.5. Proportion of waveguide exposed to air, heartwood and sapwood sorted by sensor model for all 22 sensors. 20% of some sensor waveguides were exposed to air. Nearly 70% of some waveguides were exposed to heartwood. The maximum percentage of waveguide exposed to sapwood was 70%

Tree	Sensor	In Air (%)	In Heartwood (%)	In Sapwood (%)
Tree 1	GS3	10	50	40
Tree 2	GS3	10	40	50
Tree 3	GS3	10	40	50
Tree 6	GS3	10	40	50
Tree 10	GS3a	10	20	70
Tree 10	GS3b	20	20	60
Tree 11	GS3a	0	50	50
Tree 11	GS3b	0	60	40
Tree 1	CS655	4	58	38
Tree 4	CS655	0	42	58
Tree 5	CS655	8	50	42
Tree 6	CS655	8	46	46
Tree 7	CS655	4	42	54
Tree 8	CS655	4	42	54
Tree 9	CS655	17	42	42
Tree 2	TDR-315	0	67	33
Tree 3	TDR-315	7	67	27
Tree 4	TDR-315	20	53	27
Tree 5	TDR-315	0	43	57
Tree 7	TDR-315L	20	47	33
Tree 8	TDR-315L	3	50	47
Tree 9	TDR-315L	0	53	47

Table 3.4.6. Proportion of waveguide exposed to air, heartwood and sapwood sorted by tree for all 22 sensors. 20% of some sensor waveguides were exposed to air. Nearly 70% of some waveguides were exposed to heartwood. The maximum percentage of waveguide exposed to sapwood was 70%

Tree	Sensor	In Air (%)	In Heartwood (%)	In Sapwood (%)
Tree 1	GS3	10	50	40
Tree 1	CS655	4	58	38
Tree 2	GS3	10	40	50
Tree 2	TDR-315	0	67	33
Tree 3	GS3	10	40	50
Tree 3	TDR-315	7	67	27
Tree 4	CS655	0	42	58
Tree 4	TDR-315	20	53	27
Tree 5	CS655	8	50	42
Tree 5	TDR-315	0	43	57
Tree 6	GS3	10	40	50
Tree 6	CS655	8	46	46
Tree 7	CS655	4	42	54
Tree 7	TDR-315L	20	47	33
Tree 8	CS655	4	42	54
Tree 8	TDR-315L	3	50	47
Tree 9	CS655	17	42	42
Tree 9	TDR-315L	0	53	47
Tree 10	GS3a	10	20	70
Tree 10	GS3b	20	20	60
Tree 11	GS3a	0	50	50
Tree 11	GS3b	0	60	40

For these peach trees, the sapwood was small in comparison to the heartwood, which made it difficult to insert the sensor wave guides into the sapwood—despite methods designed to do so. It appears that this could be the reason why we were not able to entirely corroborate the results of Saito et al. (2016), Matheny et al. (2015) and Hao et al. (2013). Perhaps doing an evaluation of sapwood thickness using sample cores of the target species as Bovard et al. (2005) and Matheny et al. (2015) did would help to

maximize sapwood contact. It appears that some customization of sensors might also be required to allow them to be installed properly in trees. Still, despite some evidence of temperature influence on the sensors output, it appears that the sensors are indeed capable of detecting small diurnal fluctuations in trunk water status.

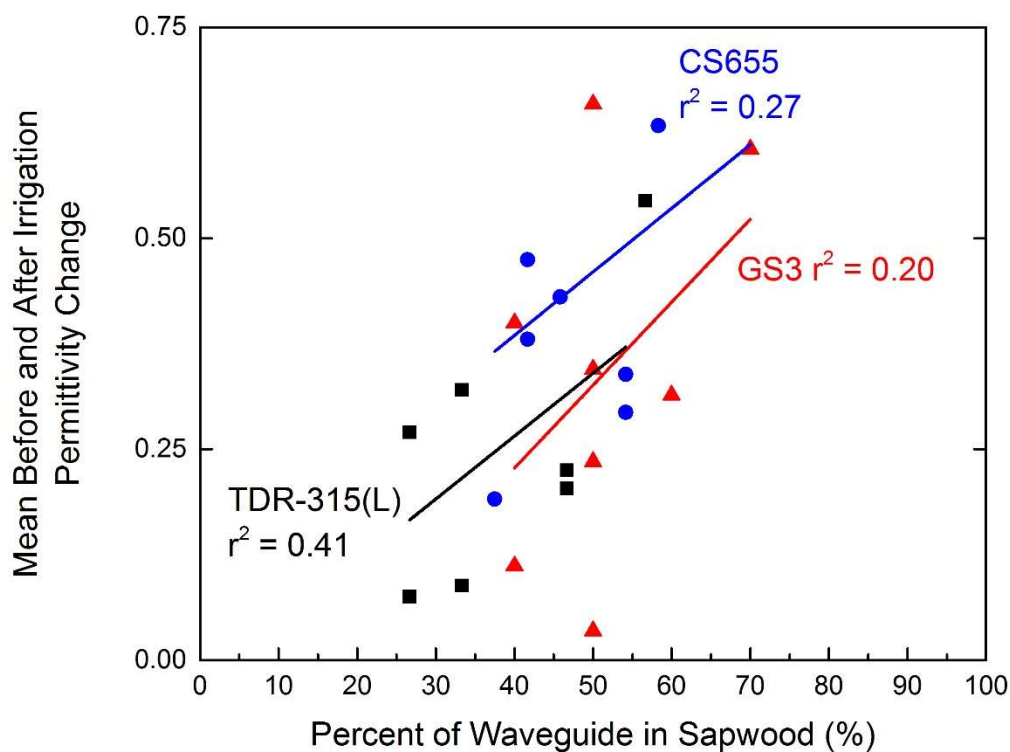


Fig. 3.4.7. Relationship between waveguide contact with sapwood and changes in permittivity before and after irrigations. As contact with sapwood increased, the before and after irrigation permittivity change also increased.

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CHAPTER 4
AUTOMATED MONITORING OF TREE WATER STATUS
USING INFRARED RADIOMETRY

4.1 Abstract

Infrared measurements of changes in crop canopy temperature have been successfully employed to determine plant water status in field crops with uniform canopies. Research continues on the application of infrared techniques in crops with more heterogeneous canopy architecture such as orchards. Here single radiometers were aimed at single tart cherry trees to monitor canopy temperature over two growing seasons to determine if this technique provides a robust measurement of canopy temperature. Two radiometers were also installed above tart cherry, peach and apple orchards in Utah County to determine if sensors aimed at multiple trees could detect changes in canopy temperature. Ideally, the sensor's field of view should contain as many leaves as possible to produce the best signal. Some research has indicated that single radiometers aimed at single trees may provide reliable data. Others have found that approaches that average the signal from several trees are more effective. Here we explored single tree techniques for two consecutive growing seasons and whole orchard techniques for three consecutive growing seasons. Our results indicate that the heterogeneity of orchard canopies make a determination of tree water status using infrared techniques difficult. This technique still requires further refinement before it can be used reliably to determine orchard water status.

4.2 Introduction

In 2015, twenty thousand tons of tart cherries, seven thousand tons of apples and four thousand tons of peaches were utilized in Utah (U.S. Department of Agriculture, 2015). These three tree fruit crops provided the most economic benefit from fruit orchards in Utah. The average annual precipitation in northern Utah is less than the average reference evapotranspiration which forces growers to rely heavily on irrigation (Gillies and Ramsey, 2009) to meet the needs of tree fruit crops.

Previous research suggests that small amounts of properly timed water stress can improve fruit quality (Ben Mechlia et al., 2001), reduce the need for pruning (Mitchell et al., 1986; Mitchell et al., 1989) and save water (Leib et al., 2006). However, because too much water stress can cause crop loss, an accurate indicator of tree water status is paramount. Stem water potential measurements are accurate indicators of tree water status, but are labor intensive and require user expertise (Berni et al., 2009). Since they cannot be automated, the search continues for electronic methods of determining tree water status.

Monitoring the temperatures of tree leaves using infrared radiometers and determining the leaf to air temperature difference (ΔT) is a potential method of determining the water status of orchard trees. Provided climatic conditions remain similar, differences in leaf temperature can indicate differences in crop water status. If soil moisture is sufficient, the temperature of tree leaves can remain below the actual air temperature because of the latent heat of evaporation. When sufficient moisture can no

longer be extracted from the soil, the leaf temperature increases. A good review of these principles can be found here (Blonquist et al., 2009).

Infrared thermometry has been successfully employed to determine the water status of field crops like corn where the surface is more or less homogenous (Clawson and Blad, 1982), though advances are still being made (Parry, 2014). However, heterogeneous surfaces such as those encountered over orchards make these measurements more difficult (Sobrino et al., 1990). The difficulties primarily involve heterogeneity in sensor's field of view (See Guiliani et al. 2000). Field crops like corn eventually have a continuous canopy, which limits the field of view to the target plant material. In orchards, there is frequently bare ground immediately under the tree rows, and sometimes between them. If orchard rows are sodded, the turf's reaction to water status may be different than that of the tree crop. Thus, non-target plant material and soil may confound the measurement when included in the infrared sensor's field of view.

Several have tested infrared radiometric techniques in orchard crops with varying success. Most research incorporates infrared canopy temperature data into a canopy conductance model or a crop water stress index model. Giuliani et al (2000) asserted that a crop water stress index based on infrared thermometry could not be "conveniently applied" to apples or peaches because of variability in canopy architecture. However, Berni et al (2009) found that even single infrared sensors could be used to track canopy conductance when incorporated into a canopy conductance model. Many have aimed single sensors at single trees and related canopy temperature to water status with varying

success (Berni et al., 2009; Giuliani et al., 2000; Gonzalez-Dugo et al., 2014; Huang et al., 2008; Osroosh et al., 2015; Sepulcre-Cantó et al., 2006; Wang and Gartung, 2010).

Raw leaf:air temperature differences were related to mid-day stem water potential in apples when using a single infrared radiometer ($r^2 = 0.63$) (Osroosh et al., 2015); the relationship was even more robust when compared to a crop water stress index ($r^2 = 0.91$). Sepulcre-Cantó et al (2006) found a similar relationship between stem water potential and Delta T in olives ($r^2 = 0.51$) (2006). Others have even gone so far as to say that a crop water stress index based on single tree infrared radiometry could even be used to time irrigation in citrus (Gonzalez-Dugo et al., 2014), apple (Osroosh et al., 2015) and peaches (Wang and Gartung, 2010).

Here single infrared radiometers were installed adjacent to single tart cherry trees at the USU Kaysville Research farm in 2014 and 2015 to determine if single radiometers monitoring single trees could detect changes in tree water status. The Delta Ts obtained from this method were also related to stem water potential measurements to see if this method was reliable enough to recommend this technique to tree fruit growers.

In theory, the greater the number of leaves monitored by the infrared radiometer, the more accurate the measurement will be. Mounting infrared radiometers high above an orchard canopy should average the leaf temperatures of many trees and may provide a more reliable way to determine orchard water status. Accordingly, infrared radiometers were installed high above six different orchards to evaluate their ability to detect changes in orchard waters status. These sensors were monitored in 2014, 2015 and 2016.

4.3 Materials and Methods

4.3.1 Leaf:Air Temperature Difference Calculations

All infrared radiometers were connected to a datalogger (CR1000, Campbell Scientific, Inc., Logan, Utah) to record measurements. Leaf temperature from each radiometer was calculated within the datalogger using the Stefan-Boltzmann Law which relates temperature to the radiation emitted by an object. Each leaf temperature measurement was corrected for emissivity using the equation $T_{Target} =$

$$\sqrt[4]{\frac{T_{Sensor}^4 - (1-\epsilon) * T_{Background}^4}{\epsilon}}$$

as recommended by the manufacturer. Target (leaf) emissivity

was assumed to be 0.98. Air temperatures recorded on the weather station in each orchard were then subtracted from the leaf temperatures of each radiometer in that orchard to determine the leaf:air temperature difference (Delta T) for each sensor in each orchard.

4.3.2 Data Filtering

The assumption of similar solar radiation is not reliable under field conditions, so data from sunny days with high levels of solar radiation must be separated from data on cloudy days with lower levels of solar radiation. Wind speed also affects canopy temperature. Accordingly, data were filtered to only include Delta Ts when solar radiation was above 199 W/m² and wind speed was above 1.5 m/s. A comparison of multiple filter combinations did not result in a greater noise reduction in the data, but some combinations resulted in nearly all of the data being filtered out.

4.3.3 Daily Mean Difference

Once filtered, the daily mean Delta T was calculated from all of the filtered data. If radiation and wind levels did not meet criteria for an entire day, the mean daily Delta T was not calculated for that day.

4.3.4 Precipitation and Irrigation

The weather station in each orchard records the precipitation for each orchard. Daily total precipitation (mm) was calculated and aligned with Delta T data from each orchard. Irrigations were either reported directly from the grower or interpolated from large increases in soil moisture readings from the weather station in each orchard not associated with precipitation. For this study the assumed irrigation rate was 35 mm. The actual irrigation rate was unknown.

4.3.5 Sensor Installation

Single Tree Infrared Radiometry. Four infrared radiometers were installed in a 13 year-old ‘Montmorency’ tart cherry orchard with a ‘Mahaleb’ rootstock at the USU Kaysville Research Center in 2014 and 2015. The orchard was trained with a modified central leader system and had bare soil under the trees with grass between tree rows. Trees were spaced 12 feet (3.7 m) apart in rows that were 20 feet (6.1 m) apart. Adjustable towers were installed on the



Fig. 4.3.1. Infrared radiometer installed adjacent to a single tart cherry tree.

south side of selected tart cherry trees and radiometers were fitted and adjusted to view single trees (Fig. 4.3.1). In 2014, radiometers with a rectangular field of view (SI-1H1, Apogee Instruments, Logan, Utah) were used, while circular narrow angle radiometers (SI-111, Apogee Instruments, Logan, Utah) were used in 2015.

2014. In 2014, a line-source irrigation system was used to establish a water stress gradient within the orchard rows. In 2014, radiometers were installed on 3 July 2014. Two radiometers were installed next to two trees receiving ample irrigation; two were installed adjacent to two trees receiving 30% of ample irrigation (Fig. 4.3.2). Ample irrigation delivered 2 inches (50.8 mm) of water per week during the heat of the summer. Trees were irrigated at weekly intervals.

Examples of the field of view from these infrared radiometers is shown in Fig. 4.3.3.

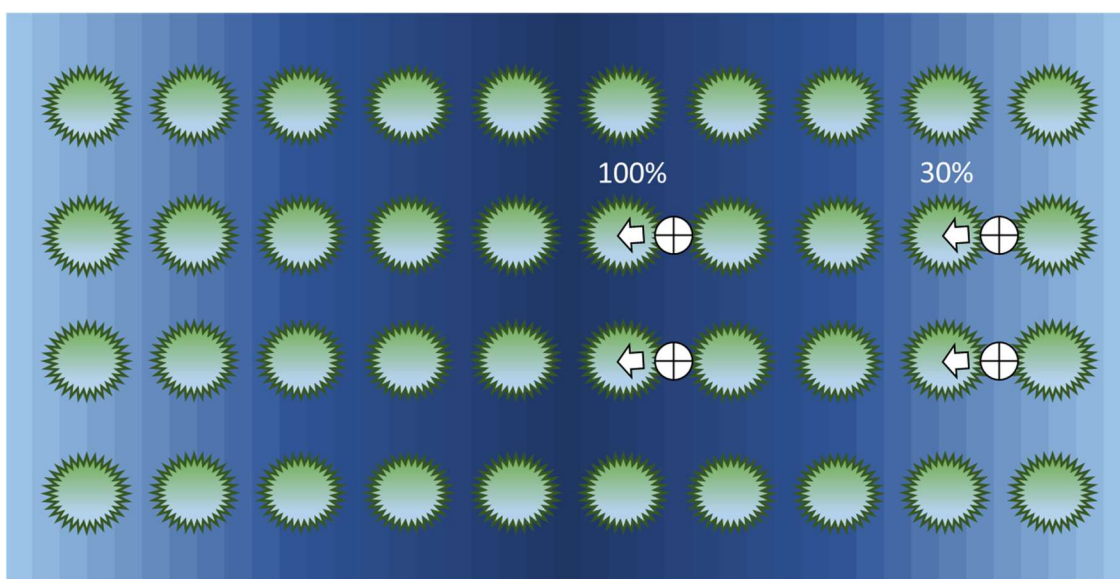


Fig. 4.3.2. 2014 Kaysville tart cherry infrared radiometer installation map. Two radiometers were aimed at the south sides of two replicate trees receiving ample irrigation and two trees receiving 30% of ample irrigation.



Fig. 4.3.3. 2014 Kaysville tart cherry example IRT field of view. Much fruit, some branches and some ground can be seen in the picture.

2015. In 2015, four irrigation levels were established using micro sprinklers with varying orifice sizes. Infrared radiometers were installed on the south side of a single tree within each irrigation level. Trees monitored in 2015 received 81%, 72%, 53% and 43% of ample (Fig. 4.3.4). Ample irrigation delivered 2 inches (50.8 mm) of water per week during the heat of the summer. Trees were watered at weekly intervals during the growing season.

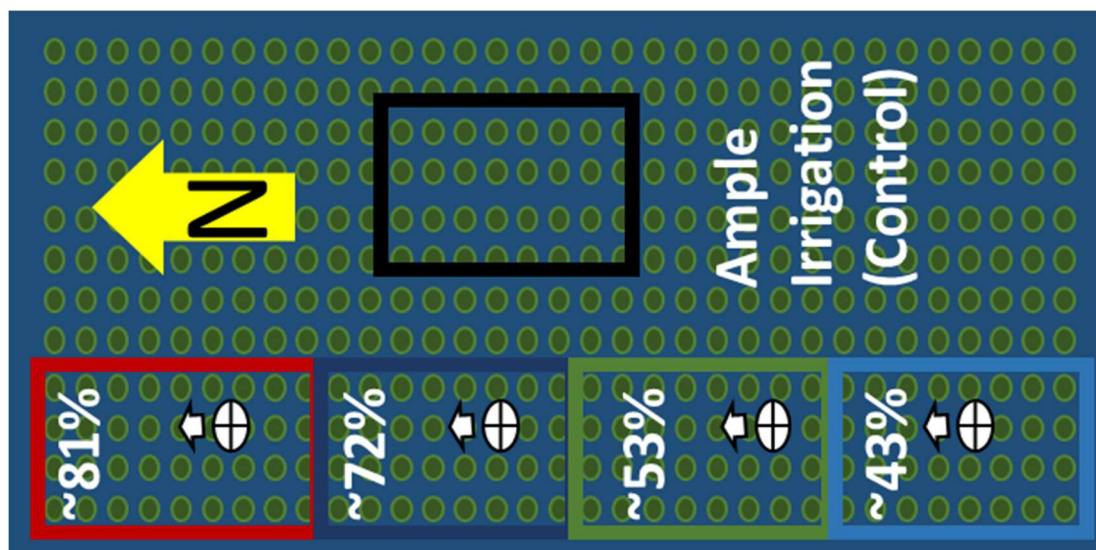


Fig. 4.3.4. 2015 Kaysville tart cherry radiometer installation map. A single radiometer was aimed at the south side of a single tree within each irrigation gradient.

Two examples of the field of view in the Kaysville tart cherry orchard from 2015 are shown below (Fig. 4.3.5).



Fig. 4.3.5. 2015 Kaysville tart cherry IRT example field of view. Several prominent branches and some bare ground can be seen.

Whole Orchard Infrared Radiometry. In June 2014, infrared sensors (SI-1H1, Apogee Instruments, Logan, Utah) were installed in six orchards in Utah county on weather stations maintained by the Utah Climate Center. These sensors were installed near the tops of the 6 m weather station towers in two different tart cherry, peach and apple orchards (Fig. 4.3.6).

Apogee SI-1H1 infrared radiometers have rectangular lenses. Radiometers were mounted with the slit horizontal in all but one case which will be described later. Radiometers were aimed such that they collected input from several trees across the orchards. One sensor was generally east-facing while the other was west-facing. Data from the weather stations where the radiometers were installed were used to calculate leaf to air temperature difference (Delta T) and to report precipitation and irrigation (Utah Climate Center). Installation sites are described in more detail below. The two peach



Fig. 4.3.6. Infrared radiometers mounted near the top of a weather station tower. Generally, one sensor faced east and one faced west.

orchards were near Alpine and Santaquin, Utah. The two apple orchards were near Genola and Payson, Utah and the two tart cherry orchards were both near Santaquin, Utah. In all but one case, the rectangular lens of the radiometer was oriented parallel to the horizon. The weather station at the Alpine orchard is located in the last row of peaches in the orchard. The west-facing radiometer in this orchard was oriented vertically and pointed straight down that row of peach trees. Varieties, rootstocks, orchard ages and training systems for the six orchards are described in more detail below (Table 4.3.1).

The height above the soil surface, azimuth angle and down angle for each radiometer are listed in Table 4.3.2 below, along with the angle that the sensor intersected the tree row. A map of each orchard delineating sensor installation angles is found below in Fig. 4.3.7. A photo representing the field of view from each radiometer is found in Figures 4.3.8 and 4.3.9 below.

Table 4.3.1. Crop, scion, rootstock, age and training system of six orchards monitored with infrared radiometer system

Site	Crop	Scion	Rootstock	Age (yr)	Training System	Row Spacing (m)	Tree Spacing (m)	Orchard Floor Management
Alpine	Peach							
Santaquin	Peach	'O'Henry'	Lovell'	9	Open Center	4.9	2.4	bare under tree/grass row
Genola	Apple	'Gala'	'Bud 9'	17	V Trellis	4.3	0.9	orchard grass
Payson	Apple	'Fuji BC2'	'M9'	24	Central Leader	4	1.4	bare under tree/grass row
EastGapS	Tart Cherry							
SantaWest	Tart Cherry	'Montmorency'	'Mahaleb'	24	Open Center	5.5	4.3	bare under tree/grass row

Table 4.3.2. Height above soil surface, azimuth angle, down angle and tree row intersection angle for each infrared radiometer.

Site	Crop	East-Facing			West-Facing		
		Height (m)	Azimuth (°)	Down Angle (°)	Height (m)	Azimuth (°)	Down Angle (°)
Alpine	Peach	3.59	35	18	3.55	240	14
Santaquin	Peach	4.77	125	13	4.86	240	13
Genola	Apple	4.06	129	15	4.03	289	14
Payson	Apple	5.93	76	18	4.86	240	17
EastGapS	Tart Cherry	6.62	120	14	6.62	249	15
SantaWest	Tart Cherry	5.78	42	11	5.79	215	9

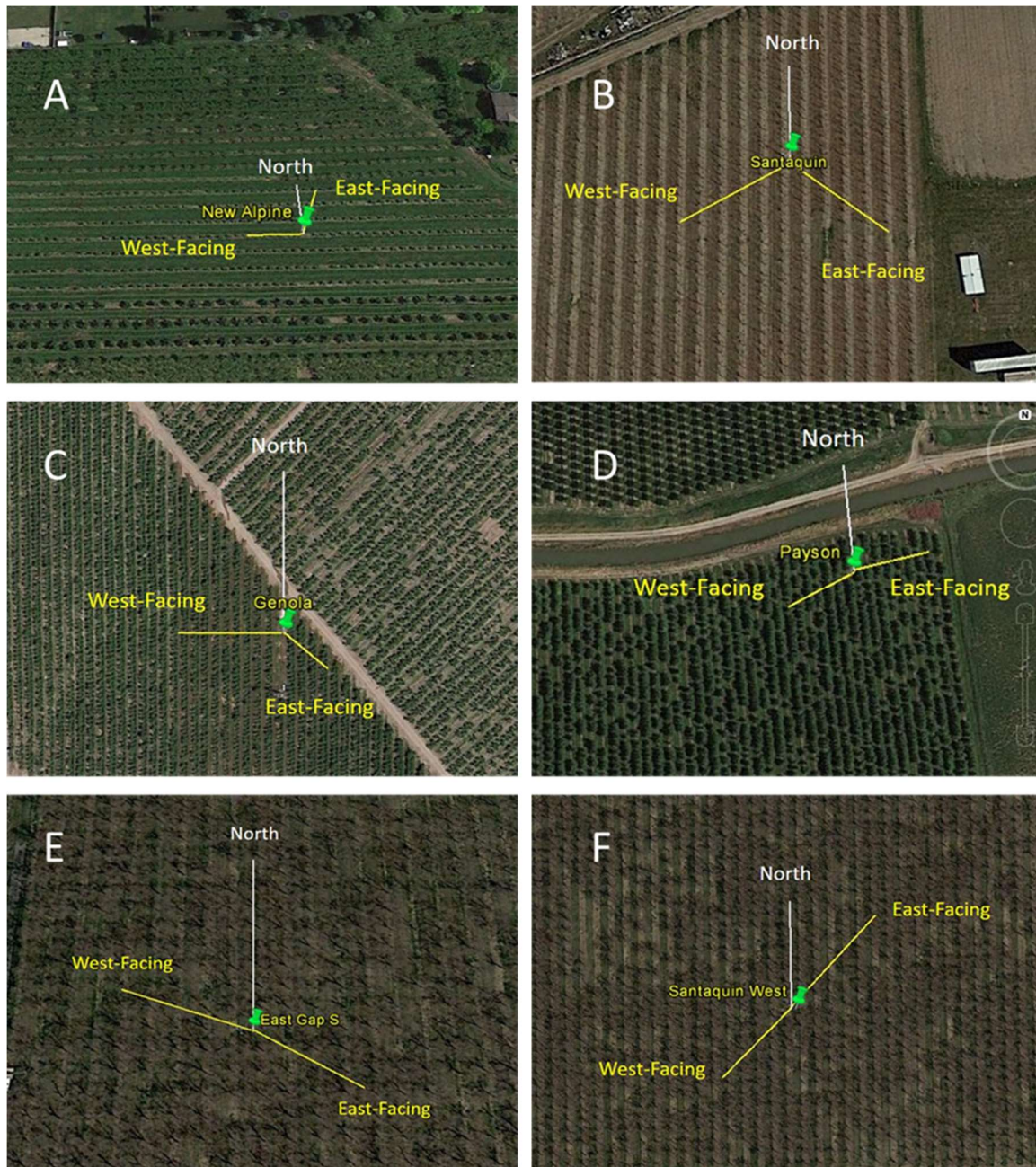


Fig. 4.3.7. Google Earth view of orchard IRT installations in: A) Alpine peach orchard; B) Santaquin peach orchard; C) Genola apple orchard; D) Payson apple orchard; E) EastGapS tart cherry orchard and F) SantaWest tart cherry orchard.

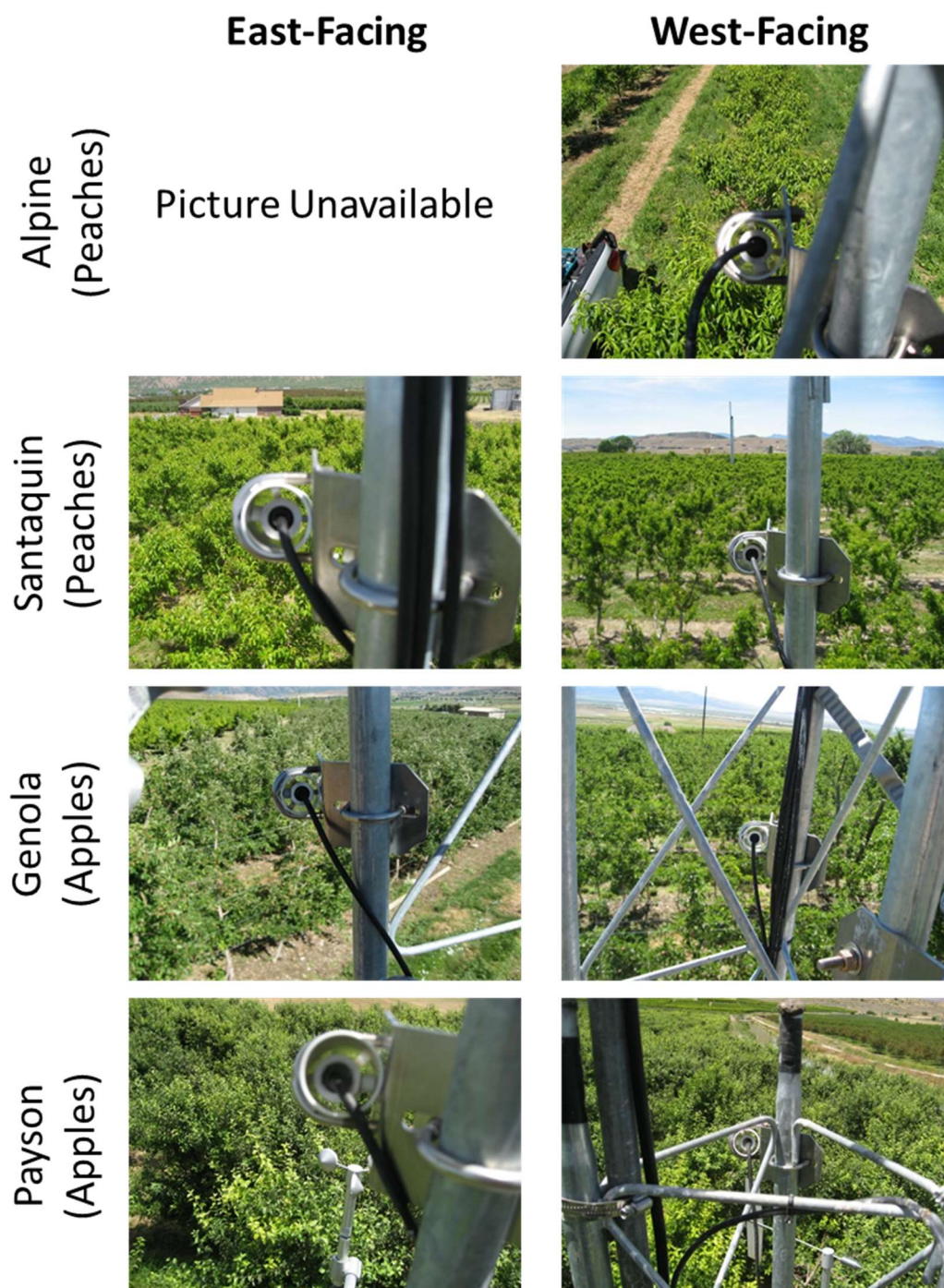


Fig. 4.3.8. Field of view from east-facing (left) and west-facing (right) radiometer for peach and apple orchards.

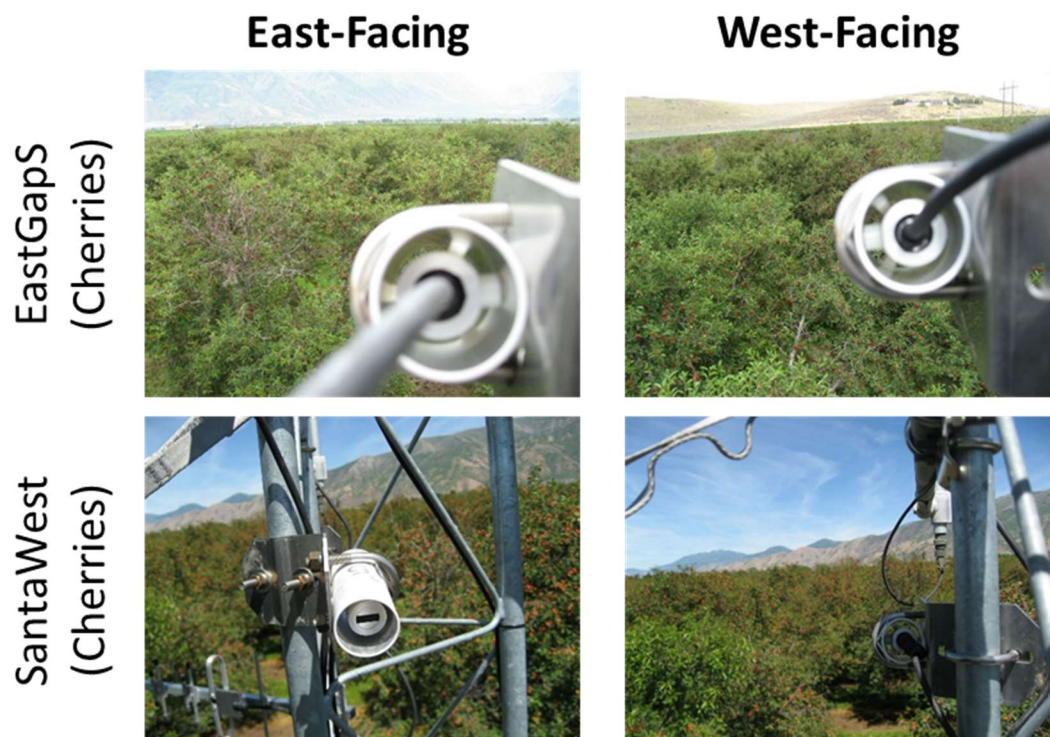


Fig. 4.3.9. Field of view from east-facing (left) and west-facing (right) radiometer for tart cherry orchards.

4.4 Results and Discussion

4.4.1 Single Tree Infrared Radiometry

2014. In some instances, the leaf:air temperature difference responds as we would expect. For example, Delta T becomes less negative between the irrigations on July 16 and July 23rd and then becomes more negative after the irrigation. However, the trend is not consistent and cannot be clearly discerned between all irrigations (Fig. 4.4.1).

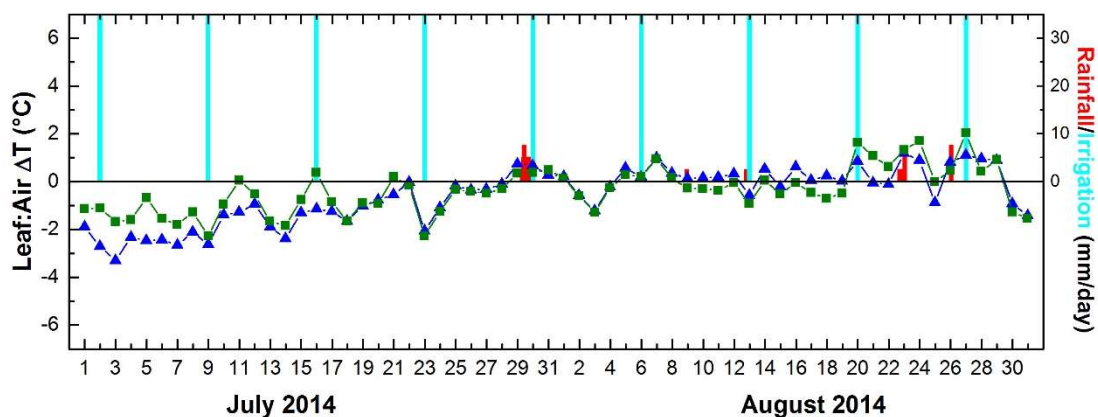


Fig. 4.4.1. 2014 Kaysville tart cherry leaf:air temperature difference. Delta T becomes less negative between some irrigations and more negative after them, but the trend is not consistent.

One possible explanation for this could be non-target objects detected in the sensor's field of view. The infrared radiometer used to collect these data had a rectangular lens (Apogee SI-1H1). These were installed with the slit oriented vertically. The minimum downward angle was 63° from horizontal. With the slit oriented vertically the half-angle in that direction would be 32° , but with down angles greater than 63° , there should have been no sky in the field of view. The narrow 13° half-angle should have limited the field of view primarily to the orchard row. It is possible that some of the grass between the rows of trees was included in the field of view. Photos taken to illustrate the potential field of view reveal that there are many fruits, some large branches and some ground visible in the field of view. Perhaps this could be the reason that the Delta Ts didn't always respond to irrigation and precipitation events as we would have expected.

2015. Though leaf:air temperature difference becomes more negative after some irrigation or precipitation events, there are also times where Delta T does not respond as expected (Fig. 4.4.2).

We would expect that accurate measurements of leaf:air differences would be related to stem water potential readings. However, the relationship between the stem water potential measurements and the temperature differences was not robust ($r^2 < 0.12$) (Fig. 4.4.3).

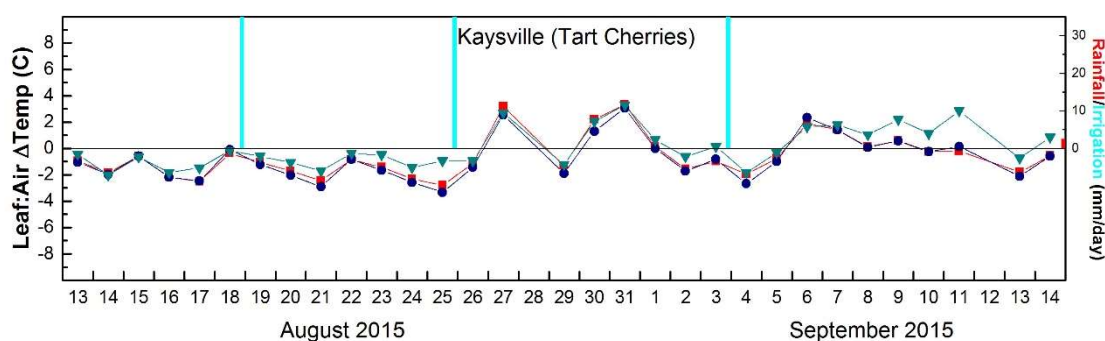


Fig. 4.4.2. 2015 Kaysville tart cherry leaf:air temperature difference. Delta Ts did not become less negative between irrigation and more negative after them as we would expect.

In 2015, we were unable to replicate the robust relationship between leaf:air temperature difference and stem water potential that Osroosh et al. (2015) or Sepulcre-Cantó et al. (2006) found in their respective studies. One potential reason for this would be differences in methodology. The specifications of the radiometers used in these two studies and the SI-111 that we used are very similar. Osroosh et al. used an Exergen radiometer with a 35° view angle (17.5° half-angle) and circular lens, while Sepulcre-

Cantó et al. (2006) used the Apogee IRTS-P with a 17° half-angle. The Apogee IRTS-P was replaced by the Apogee SI-111, which has a 22° half-angle and a circular lens. Perhaps the slightly larger viewing angle of the SI-111 contributed to the discrepancy in our findings.

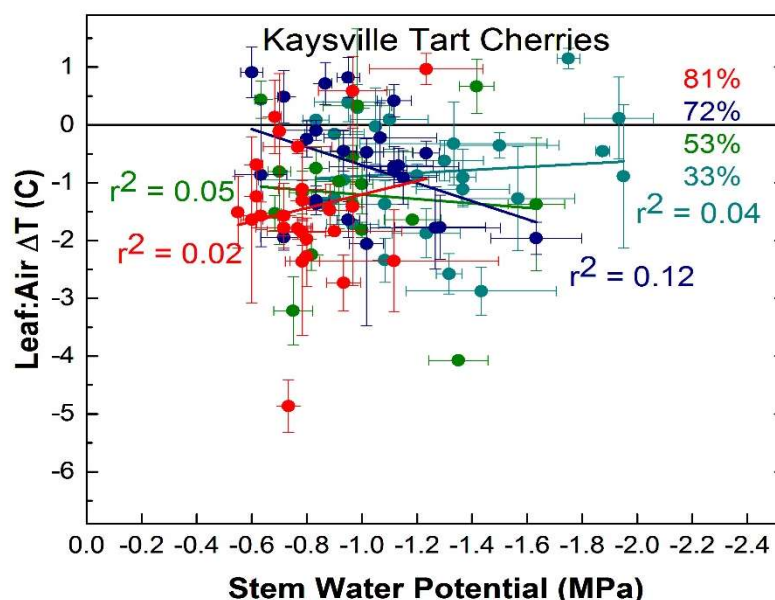


Fig. 4.4.3. 2015 Kaysville tart cherry stem water potential and leaf:air Delta T regression did not reveal a robust relationship between Delta T and stem water potential as we would have expected.

Another possible reason for being unable to reproduce these results could be mounting angles. Sepulcre-Cantó et al. mounted their radiometer 1 meter directly above an individual olive tree and pointed straight down, where such positioning “ensured” that 85% of signal came from the tree (2009). Osroosh et al. (2015) mounted the radiometers at 0° azimuth and 45° zenith angles in 2007 and 2008 and aimed them at both the north and south sides of a tree. In 2013, they mounted the radiometers 1 meter directly above a single apple tree, a similar mounting position to Sepulcre-Cantó. The radiometers in this

study were mounted on the south side of single tart cherry trees at a height of approximately 3 meters and aimed at an angle less than horizontal. Mounting the radiometers directly above individual trees may be a more appropriate technique, but more testing would be required.

Another possibility is the sensing of non-target materials in the field of view. Apples and olives likely have a different canopy architecture than tart cherries, but branches, fruits and the ground can all be seen in the example picture of the potential field of view (Refer to Fig. 4.3.3). These objects will dilute the signal from the leaves. This more likely explains the reason our sensors did not respond to water stress as expected. Computer vision using imaging technology is under development for use in automated fruit harvesting (Bulanon et al., 2009; Zeng et al., 2008). This technology relies on detecting either differences in color or in infrared emissions or both to determine fruit ripeness (Jimenez et al., 2000). Perhaps an adaptation of this type of technology could be used to separate the infrared signal of leaves from that of fruits and other non-target objects.

Whether or not mounting the sensors directly above the tree would help remains to be determined. Osroosh et al. (2015) pooled data from three years to create their regression, so a direct comparison of mounting angles between their data and ours is difficult. The pooling of data from sensors mounted in one orientation with those mounted in a different orientation may not be appropriate—particularly when considering the temporal separation between the first two years (2007-2008) and the last year (2013). However, the data from Sepulcre-Cantó (2006) and Osroosh et al. (2015) suggest that

such a robust relationship between single infrared radiometers and stem water potential is not impossible.

Difference in crop type and sensor installation are two possible reasons why this technique did not work as expected. The most likely reason is problems with the field of view. Perhaps repeating the study with sensors mounted 1 m directly above individual trees would produce similar results, but this would only make a difference if it enabled a greater percentage of leaves to be included in the radiometer field of view. Perhaps repeating the study with apples would produce similar results to those of Osroosh et al. (2015).

4.4.2 Whole Orchard Infrared Thermometry

To illustrate the data filtering process, data from the Alpine peach orchard are shown for 2014 (Fig. 4.4.4). The top graph shows the raw data. The middle graph shows the data filtered by solar radiation levels above 199 W/m^2 and wind speed greater than 1.5 m/s . The bottom graph shows the filtered daily mean Delta T. Raw data from other orchards or other years is not shown. Rather, the summary data from each orchard and each year is displayed below. (See Figs. 4.4.5 through 4.4.7).

Daily total precipitation in mm/day is shown in red on the right axis. Irrigations are also shown on the right axis in light blue and are all assumed to be 35 mm depth equivalent. Irrigation information reported from growers is indicated with solid light blue bars, while irrigation information interpolated from soil moisture data is indicated with white-striped light blue bars.

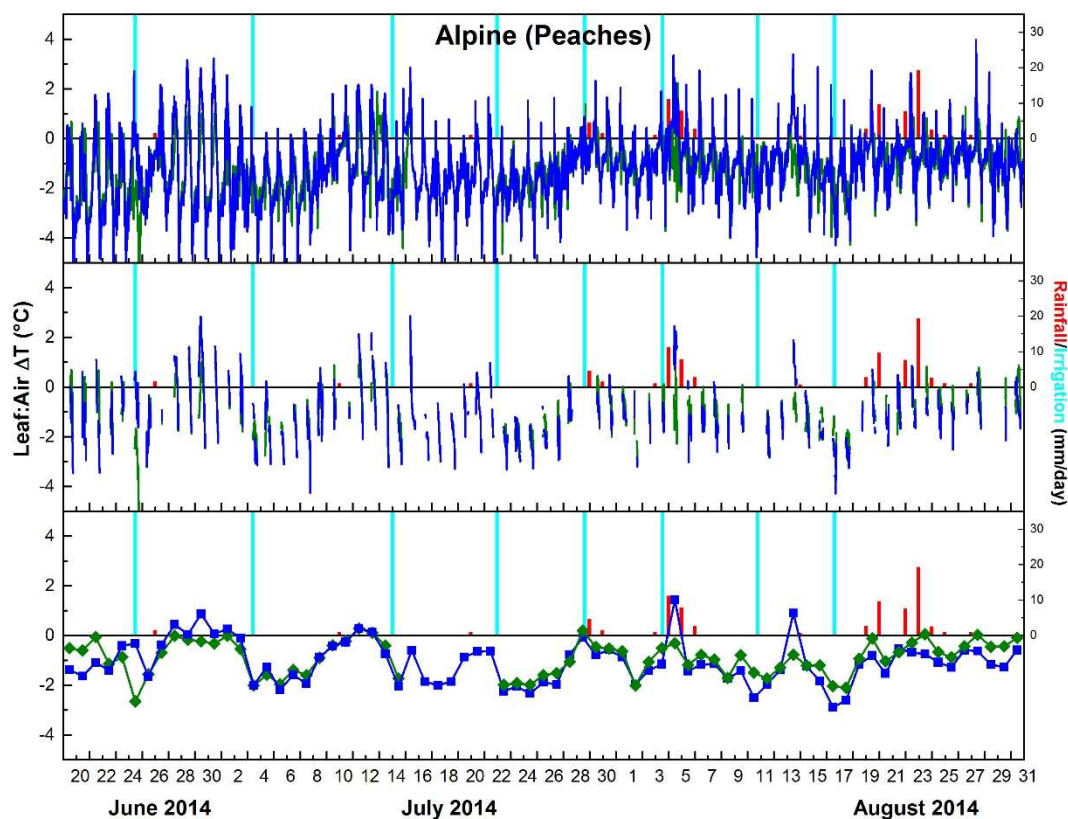


Fig. 4.4.4. Leaf:air temperature difference in peaches. The raw (top), filtered (middle) and filtered daily mean (bottom) leaf: air temperature difference in Peaches grown near Alpine, Utah in 2014.

In 2014, there were some instances where leaf:air Delta T increased between irrigations and declined following them (black dashed lines). However, the trend is not as consistent as would be expected (Fig. 4.4.5).

For 2015, most rainfall events or irrigations are not associated with reductions in Delta T. A few of the expected trends are marked with black dashed lines (Fig. 4.4.6).

For 2016, some precipitation events or irrigations coincide with a reduction in leaf:air Delta T, but not many. Dashed black lines mark a few positive examples (Fig. 4.4.7).

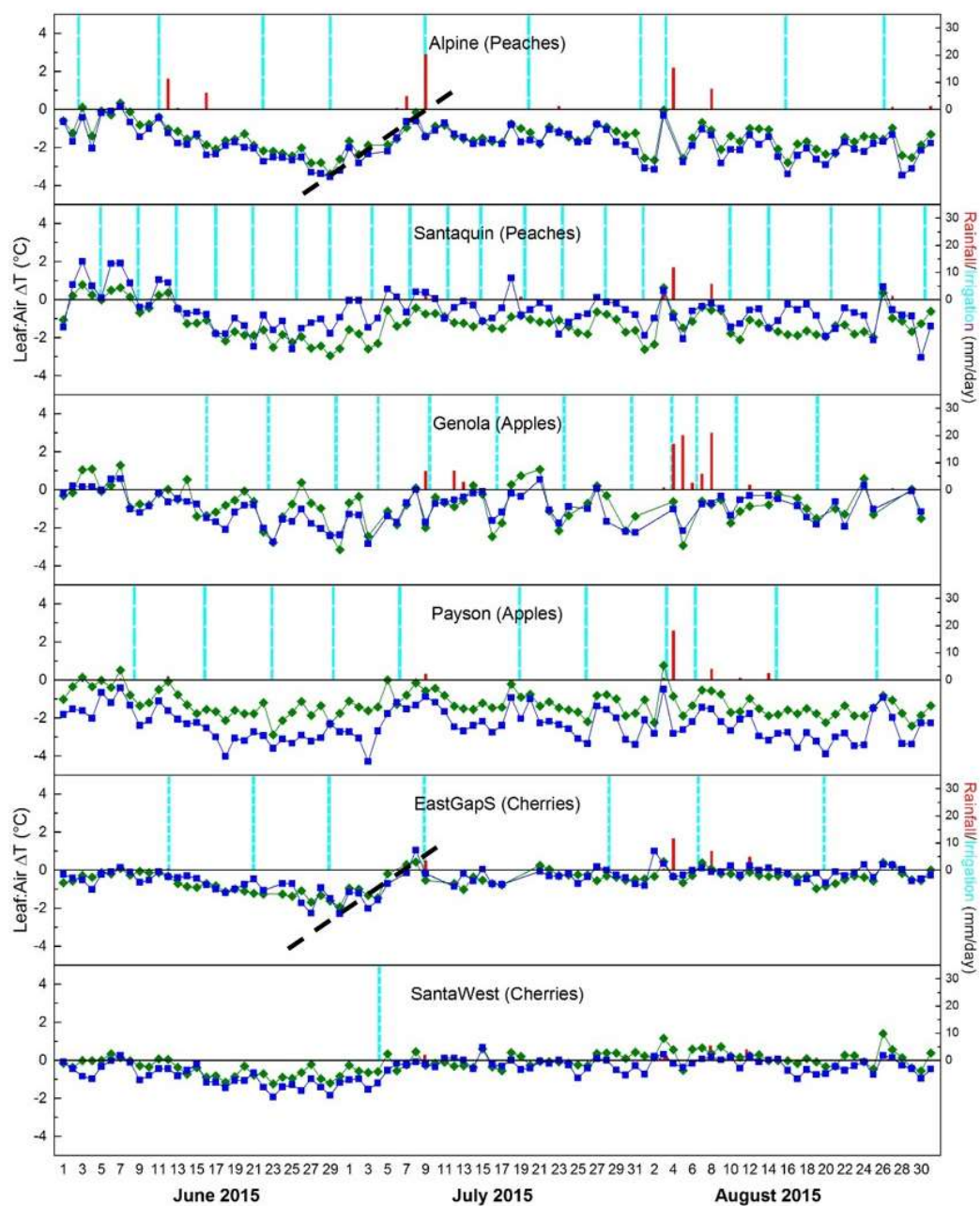


Fig. 4.4.5. 2014 whole orchard daily mean Delta Ts followed expected trends in a few cases indicated by dashed black lines, but trends weren't consistent.

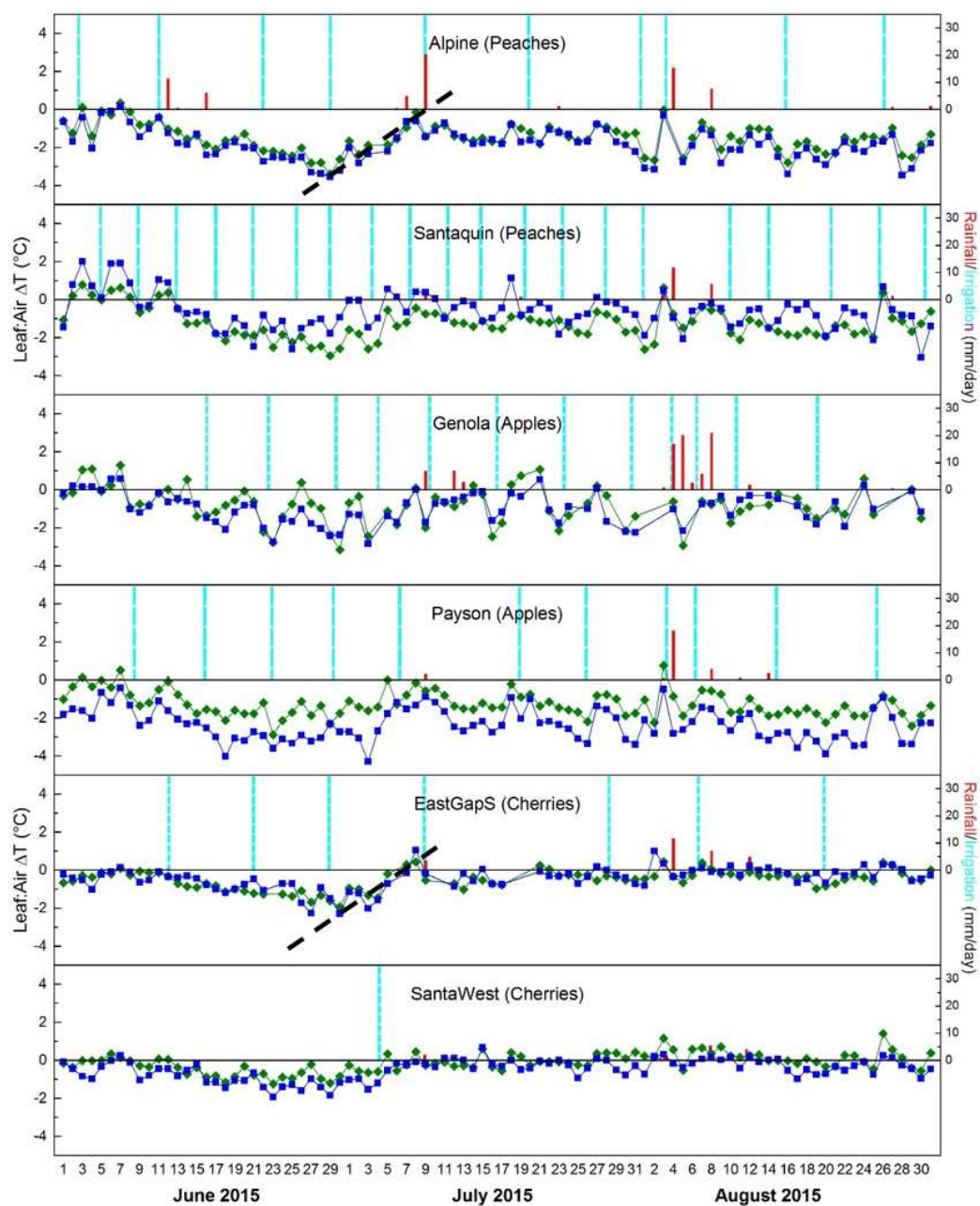


Fig. 4.4.6. 2015 whole orchard daily mean Delta Ts did not follow expected patterns except in a few case indicated with black dashed lines.

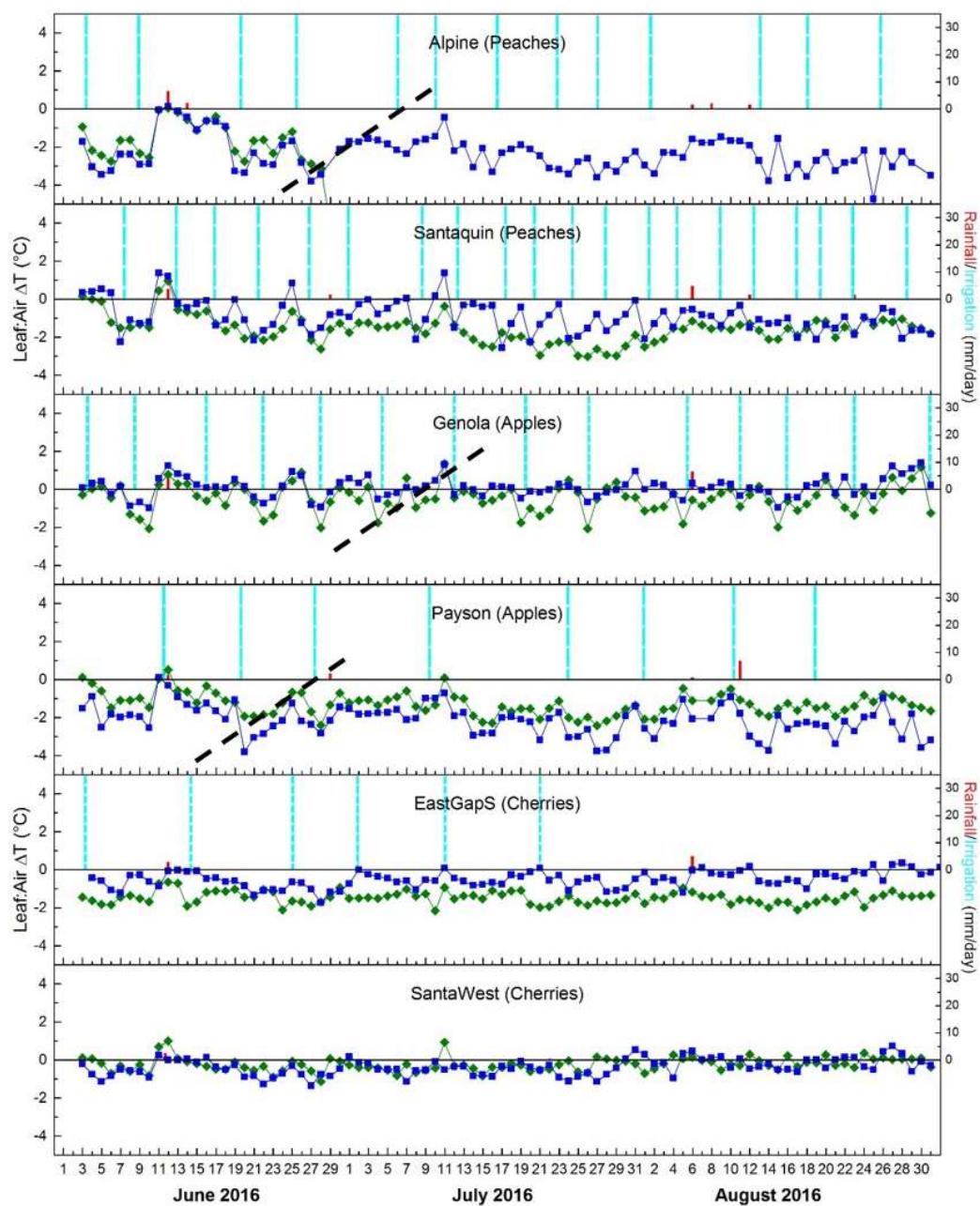


Fig. 4.4.7. 2016 whole orchard daily mean Delta Ts followed expected trends in a few cases, but not consistently.

There were some instances where the leaf:air temperature differences behaved as we would have expected. However, in many cases Delta T changed little throughout the growing season. Since this study was primarily observational, it is possible that some orchards were always so well-watered that change in canopy temperature occurred before and after irrigations was not readily detectable. However, should that have been the case, we would have expected that Delta T would be more negative than the values we observed for the SantaWest cherries. Perhaps it is more likely that, even with efforts to maximize the number of trees in the field of view, there was still bare ground, scaffold branches or row cover plant material in the field of view.

In these studies, neither single tree nor whole orchard infrared thermometry produced a clean enough signal to recommend their use in controlling irrigation in orchards.

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CHAPTER 5

SUMMARY AND CONCLUSIONS

The timing, level and method of precision irrigation can all affect the efficacy of such a system. However, the physiological characteristics of the trees themselves cannot be ignored. A weighing lysimeter system provides an effective method of determining the drought tolerance of different rootstocks. Incorporating this method into the rootstock selection process could aid in the selection of rootstocks that are well-suited to precision irrigation.

Much research has been devoted to the proper timing and method of applying precision irrigation in orchards. This research focused on finding an automated indicator of tree water status. Electromagnetic sensors inserted into the trunks of trees still have potential for this application, but installation methods and sensor design may need to be altered for this technique to be reliable enough for widespread application. Exposure to sapwood appears to be a key in the installation of these sensors. This may be accomplished by altering insertion angles or by modifying the wave guides to maximize the percent of the wave guide that is located in the sapwood. The electromagnetic sensors tested here were designed to be buried in the soil. When adapting these sensors to above-ground use, it is essential that the electronics are not sensitive to the inevitable diurnal changes in temperature—especially considering the complexity of factors involved in a potential de-facto temperature correction.

Infrared measurements of canopy temperature, though successful in some crops, are difficult in orchards. The variability in canopy architecture of an orchard makes it

difficult to monitor only leaves with the radiometers. Non-target items such as the orchard floor, branches and fruits in the field of view all create noise in the signal from the radiometers. Neither radiometers aimed at single trees nor radiometers aimed at whole orchards produced clean enough data to recommend this technique as an indicator of water status to be used in controlling precision irrigation systems.

APPENDICES

APPENDIX A
TEMPERATURE SENSITIVITY OF ELECTROMAGNETIC
SOIL MOISTURE SENSORS

A.1 Introduction

Electromagnetic soil moisture sensors may be able to detect hydration changes in the sapwood of tree trunks. If these sensors are buried in soil where temperature changes are small and gradual, sensor electronics that don't respond to temperature changes are not crucial. However, in order to use these sensors above-ground, the sensor electronics must be temperature-stable.

A.2 Materials and Methods

Five types of electromagnetic soil moisture sensors were suspended in the air and placed in a dark growth chamber to test for temperature sensitivity (Fig. A.2.1). Each sensor was monitored with either a Decagon Em50 or a Campbell Scientific CR1000 datalogger (Table A.2.1).



Fig. A.2.1. Temperature sensitivity of five types of electromagnetic soil moisture sensors. All sensors were suspended the air in a dark controlled environment chamber with large diurnal temperature gradients to determine electronics temperature sensitivity.

Table A.2.1. Sensors and dataloggers used in sensor electronics temperature sensitivity test. GS1 and GS3s were tested with a Decagon Em50 datalogger. GS3s and all other sensors were tested using a Campbell Scientific CR1000.

Sensor Type	CR1000	Em50
Decagon Devices GS1	--	4 reps
Decagon Devices GS3	2 reps	2 reps
Campbell Scientific CS655	3 reps	--
Acclima TDR-315	2 reps	--
Acclima TDR-315L	3 reps	--

Controlled environment chamber temperatures increased incrementally from 10 °C to 35 °C over a 12-hour period and then back to 10 °C over the next 12 hours. The permittivity or voltage response of each sensor was then compared to the temperature. The water content reading of each sensor was also compared to temperature.

A.3 Results

The Decagon GS1 sensor electronics were temperature-sensitive for both raw voltage output and for volumetric water content (Fig. A.3.1).

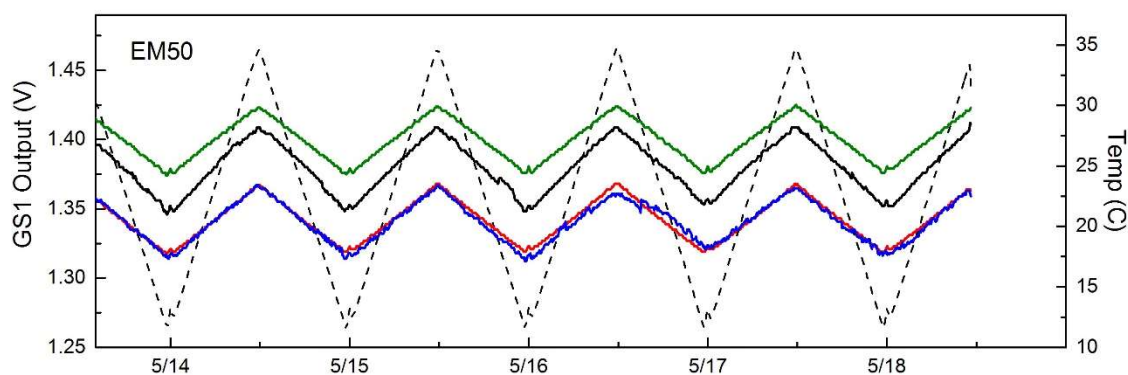


Fig. A.3.1. GS1 electronics temperature sensitivity. Sensitivity ranged from 7 to 10 mV per degree C.

Decagon GS3 sensor electronics were less sensitive to temperature than GS1 sensors. Whether monitored with a Decagon Em50 or with a Campbell Scientific CR1000, temperature sensitivity varied among GS3 sensors (Fig. A.3.2).

Campbell Scientific CS655 sensors were not sensitive to temperature for permittivity or water content and had very little sensitivity for period (A.3.4).

Acclima TDR-315 sensors also showed minimal temperature-sensitivity for permittivity and water content (Fig. A.3.3). Some digital noise can be observed for one of the two TDR-315 sensors, but the source of this noise is unknown.

Acclima TDR-315L sensors also showed minimal temperature-sensitivity for permittivity and water content (Fig. A.3.5).

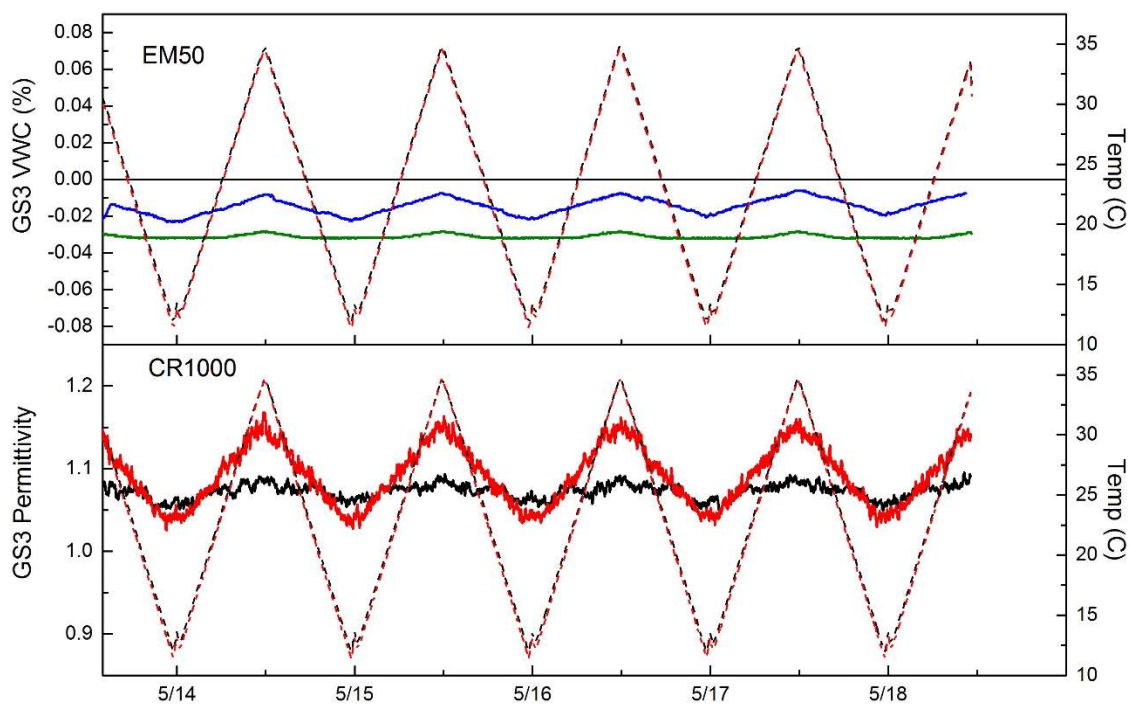


Fig. A.3.2. GS3 electronics temperature sensitivity. Sensitivity ranged from 1.4 to 5.8 mV per degree C.

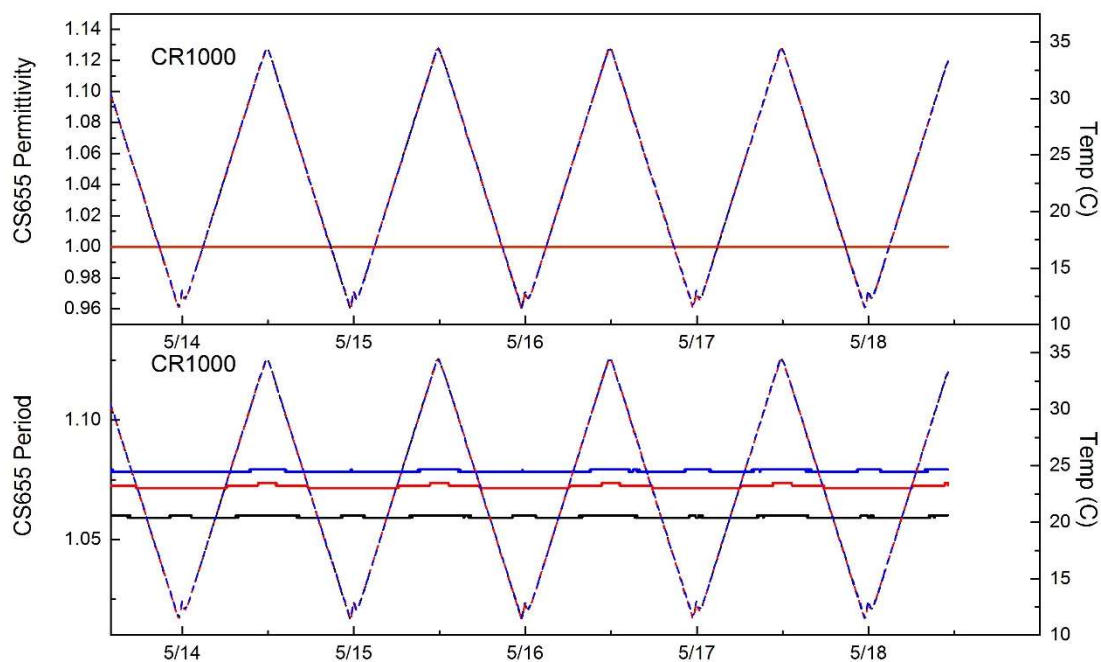


Fig. A.3.4. CS655 electronics temperature sensitivity. Sensitivity was zero for permittivity and volumetric water content. There was also very little sensitivity in period values.

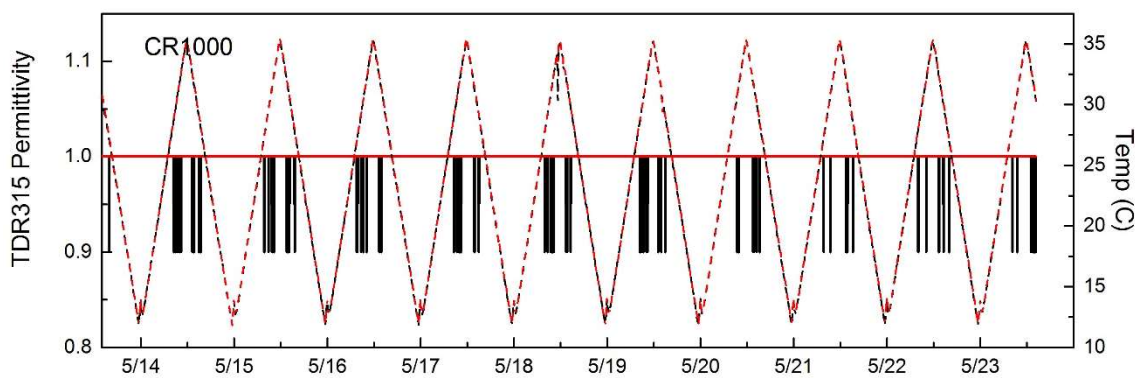


Fig. A.3.3. TDR-315 electronics temperature sensitivity was negligible but one sensor did produce some digital noise.

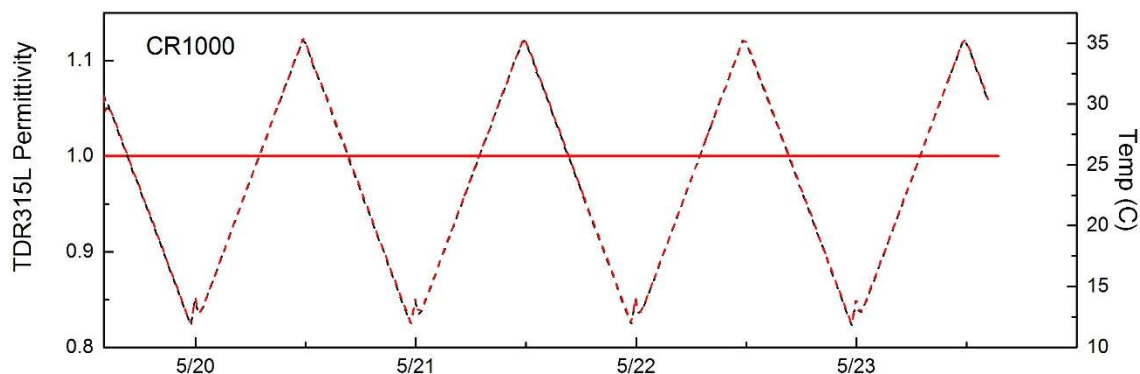


Fig. A.3.5. TDR-315L electronics temperature sensitivity was negligible.

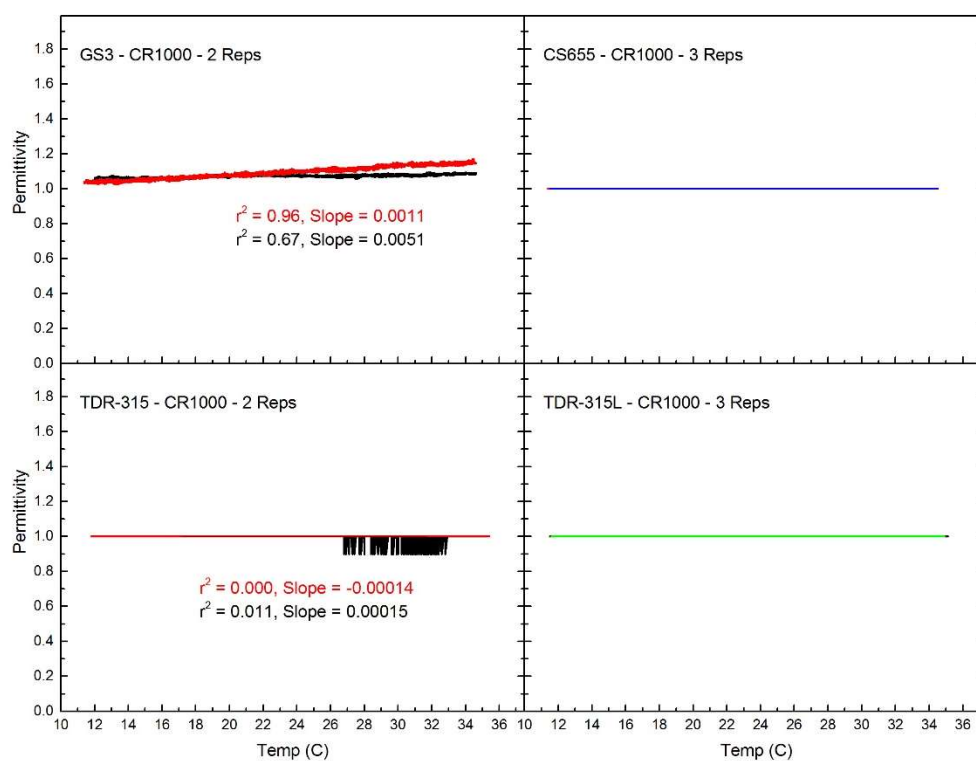


Fig. A.3.6. Slope of temperature:permittivity relationship for GS3, CS655, TDR-315 and TDR-315L sensors in air.

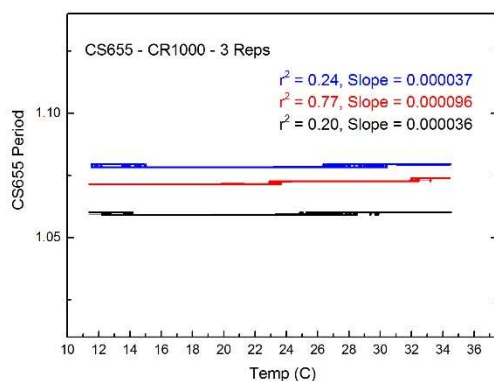


Fig. A.3.7. Slope of temperature:period relationship for CS655 shows negligible temperature sensitivity.

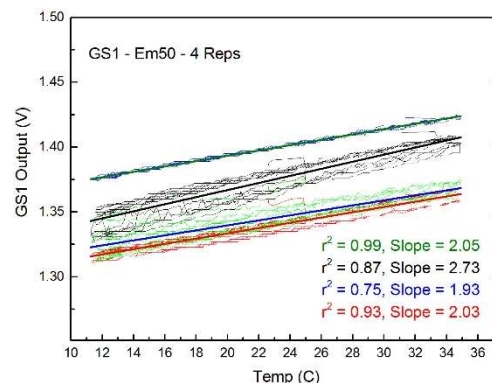


Fig. A.3.8. Slope of temperature:voltage output of GS1 ranges between 7 and 10 mV per degree C.

The permittivity output of GS3 sensors increased less than six thousandths for every degree increase in temperature. Permittivity remained unchanged as temperature increased for Campbell Scientific CS655 sensors. Acclima TDR-315 sensor permittivity increased less than two ten thousandths with each degree increase in temperature. Responses were similar for the Acclima TDR-315L (Fig. A.3.6). For each degree increase in temperature, output voltage from GS1 sensors increased 2 to 3 mV (Fig. A.3.8). Period measurements from the CS655 increased by less than one thousandth of a unit for each degree increase in temperature (Fig. A.3.7).

A.4 Discussion

Based on these data, both the Campbell Scientific CS655 and the Acclima TDR-315(L) would be suitable for above-ground use since temperature sensitivity is minimal. It would be more difficult to use the Decagon GS1 or the Decagon GS3 because of their sensitivity to temperature.

APPENDIX B

GS1 SENSOR TRUNK HYDRATION DATA

B.1 Results and Discussion

In August and September of 2015, GS1 trunk hydration (sensor V output) declined between and recovered following irrigations when 43% of ample or 53% of ample irrigation was applied to tart cherries. These differences were not detected at 72% or 81% of ample with the GS1 sensor or when ample irrigation was applied (Fig. B.1.1).

GS1 voltage output declined between irrigations in August and September of 2015 and recovered after them for the 43% and 53% of ample irrigation treatment in tart cherries. The season-long average before and after irrigation change in stem water potential in tart cherries ranged from 0 MPa at the ample irrigation level to 0.20 MPa at the 43% irrigation level (Table B.1.1).

Recovery in tart cherry stem water potential was detected before and after seven different irrigations (Fig. B.1.2).

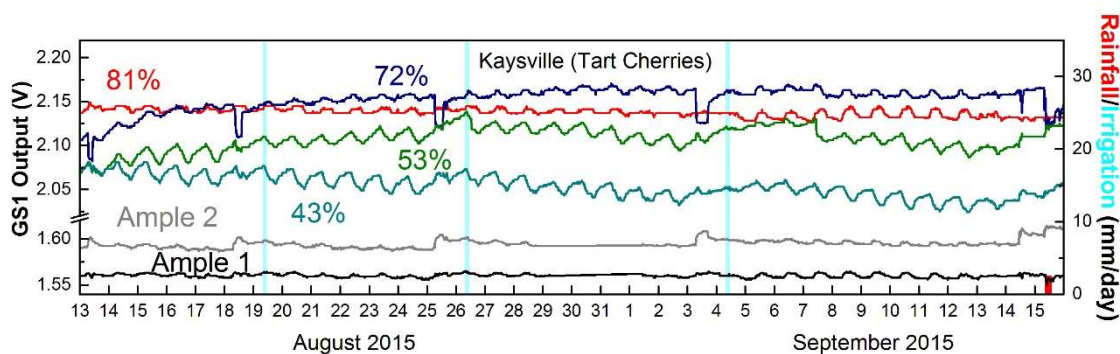


Fig. B.1.1. 2015 Kaysville tart cherry GS1 soil moisture sensor output. Voltage declined between irrigations (light blue bars) and recovered after them for the 43% and 53% of ample irrigation treatment, but the changes were small and inconsistent.

Table B.1.1. 2015 GS1 season-long average before and after irrigation voltage output and stem water potential changes in tart cherries did not reveal a treatment effect.

	GS1 Output Change (V)		Stem Water Potential Difference (Mpa)	
	Mean	SD	Mean	SD
100%	-0.003	0.005	-0.02	0.20
100%	0.006	0.005	0.05	0.18
81%	0.003	0.005	0.02	0.19
72%	0.002	0.009	0.19	0.54
53%	-0.005	0.020	0.20	0.33
43%	0.000	0.008	0.20	0.61

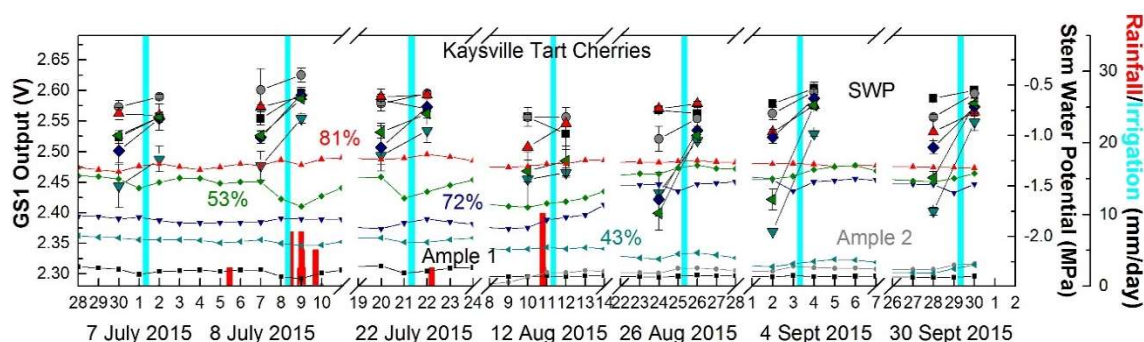


Fig. B.1.2. 2015 Kaysville tart cherry daily mean GS1 sensor output and stem water potential for seven irrigations. (Irrigations are represented with light blue bars, while rainfall is represented with red bars). Stem water potential increased 0.5 to 1.0 MPa, but corresponding increases in sensor voltage output were not consistent.

Considering these seven irrigations revealed that, when tart cherries experienced water stress, stem water potential rebounded between 0.06 MPa and 0.49 MPa on average. But, the average GS1 voltage change for the seven irrigations ranged between -2.0 mV and 8.0 mV (Table B.1.2). The response is small and does not indicate a water stress treatment effect. There is little evidence that GS1 sensors detected changes in tart cherry trunk hydration.

The GS1 voltage output in peaches declined between irrigations for deficit-irrigated trees. The most pronounced response was for the trees receiving 33% of ample irrigation, where voltage declined between irrigations and recovered immediately following them (Fig. B.1.3).

Based on the fact that GS1 voltage output declined between irrigations in August and September of 2015 and recovered after them (most specifically for the 33% of ample irrigation treatment), we could infer that the GS1 sensor is capable of detecting changes in peach trunk hydration. Averaging before and after irrigation changes in stem water potential over the whole season makes it appear that the peach trees experienced no water stress. Stem water potential differences are all small negative numbers (Table B.1.3).

Still, recovery in peach stem water potential was detected before and after four different irrigations (Fig. B.1.3). Since recovery in stem water potential was not detected before and after all irrigations, a closer look at these four individual recoveries in stem water potential is warranted.

Table B.1.2. 2015 GS1 before and after irrigation voltage output and stem water potential changes in tart cherries for seven irrigations did not reveal a treatment effect.

	GS1 Output Change (V)		Stem Water Potential Difference (Mpa)	
	Mean	SD	Mean	SD
100%	0.001	0.002	0.06	0.16
100%	0.002	0.003	0.14	0.08
81%	0.000	0.007	0.12	0.11
72%	0.001	0.003	0.49	0.33
53%	0.004	0.002	0.38	0.19
43%	0.003	0.003	0.47	0.34

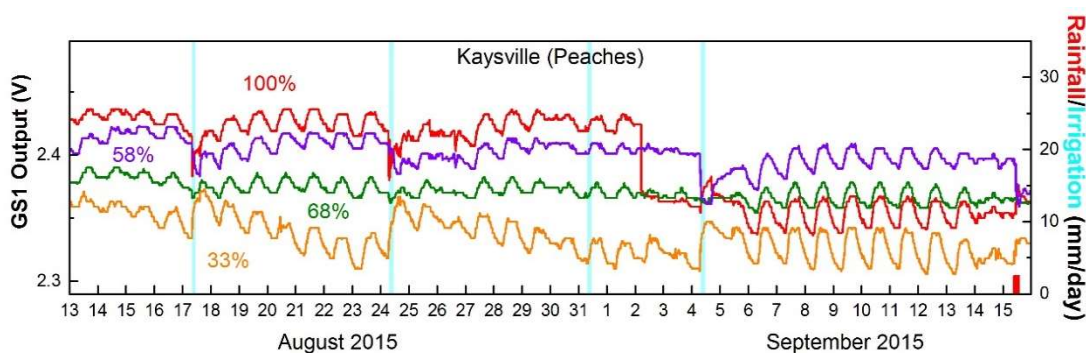


Fig. B.1.4. 2015 Kaysville peach GS1 soil moisture sensor output. Voltage declined between irrigations (light blue bars) and recovered after them for the 33% of ample irrigation treatment, but trends were inconsistent.

Table B.1.3. 2015 GS1 season-long average before and after irrigation voltage output and stem water potential changes in peaches did not reveal any treatment effect.

	GS1 Output Change (V)		Stem Water Potential Change (Mpa)	
	Mean	SD	Mean	SD
100%	-0.010	0.014	-0.07	0.33
68%	-0.003	0.004	-0.12	0.32
58%	-0.013	0.010	-0.02	0.31
33%	0.007	0.015	-0.06	0.43

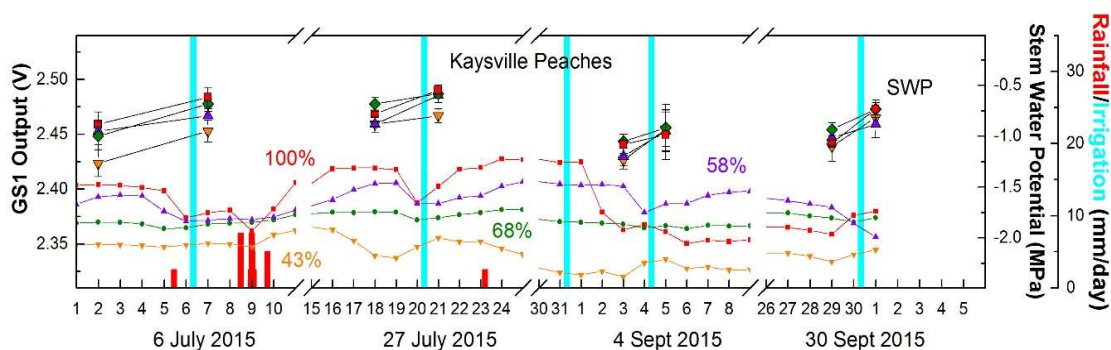


Fig. B.1.3. 2015 Kaysville peach daily mean GS1 sensor output and stem water potential for four irrigations. (Irrigations are represented with light blue bars, while rainfall is represented with red bars).

Considering these four irrigations revealed that, when peaches experienced water stress, stem water potential rebounded between 0.19 MPa and 0.25 MPa on average. But, corresponding average changes in GS1 voltage output could not be detected. In fact, the average GS1 voltage change for the four irrigations was negative for three of the four irrigation levels, which would indicate that the trees had actually become slightly drier after irrigation. The remaining GS1 sensor reported a very small increase in voltage (9 mV) (See Table B.1.4). In short, the GS1 sensor was unable to detect changes in trunk hydration in peaches.

Table B.1.4. 2015 GS1 before and after irrigation voltage output and stem water potential changes in peaches for four irrigations did not reveal a treatment effect.

	GS1 Output Change (V)		Stem Water Potential Change (Mpa)	
	Mean	SD	Mean	SD
100%	-0.006	0.018	0.25	0.11
68%	-0.001	0.003	0.20	0.07
58%	-0.019	0.006	0.19	0.10
33%	0.009	0.005	0.23	0.10

In apples, GS1 voltage output was steady and did not change between irrigations or recover thereafter (Fig. B.1.5). A decline in GS1 voltage output between irrigations and recovery afterward was not evident for apples in August and September 2015. The season-long average stem water potential difference before and after irrigations ranged between -0.04 MPa and 0.08 MPa in apples (Table B.1.5). A closer look reveals that stem water potential only recovered after three irrigations (Fig. B.1.6). GS1 output increased between 3 and 5 mV for these three irrigations and the stem water potential recovery was between 0.09 MPa and 0.37 MPa (Table B.1.6).

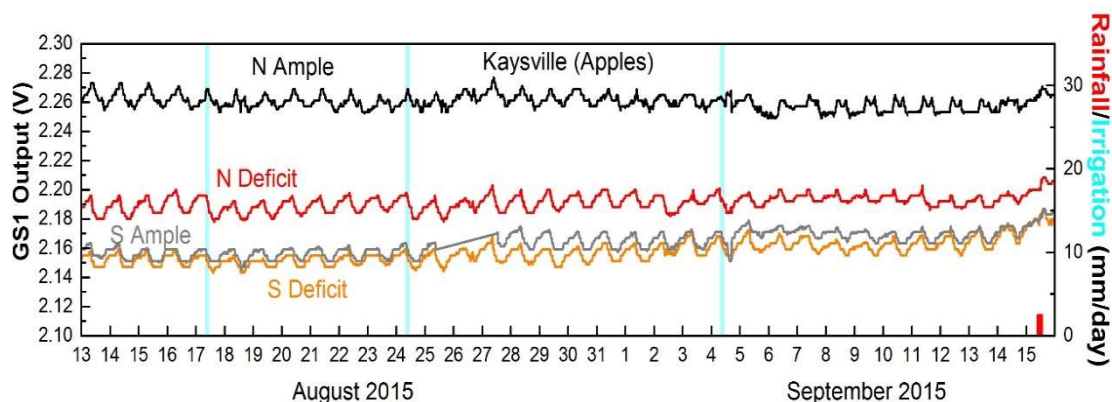


Fig. B.1.5. 2015 Kaysville apple GS1 soil moisture sensor output changed very little between irrigations.

Table B.1.5. 2015 GS1 season-long average before and after irrigation voltage output and stem water potential changes in apples did not reveal any treatment effect.

	GS1 Output Change (V)		Stem Water Potential Difference (Mpa)	
	Mean	SD	Mean	SD
Ample1	-0.002	0.006	0.01	0.30
Ample2	0.001	0.005	0.08	0.32
Deficit1	-0.001	0.008	-0.13	0.41
Deficit2	-0.123	0.410	-0.04	0.47

Looking at each irrigation level and irrigation individually reveals that for some irrigations, stem water potential changes very little after irrigation, while GS1 voltage output responds. In other cases, the opposite is true. These interactions may help explain why GS1 voltage output decreases between some irrigations and increases immediately following them, while the overall relationship between peach stem water potential and GS1 output voltage is weak (Fig. B.1.7).

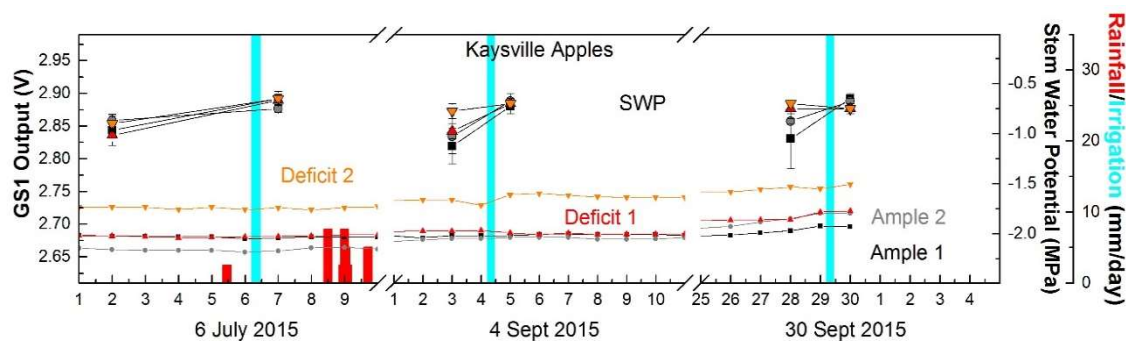


Fig. B.1.6. 2015 Kaysville apple daily mean GS1 sensor output and stem water potential for three irrigations. (Irrigations are represented with light blue bars, while rainfall is represented with red bars). Recovery of nearly 1.0 MPa stem water potential did not correspond with an increase in GS1 voltage output.

Table B.1.6. 2015 GS1 before and after irrigation voltage output and stem water potential changes in apples for three irrigations did not reveal a treatment effect.

	GS1 Output Change (V)		Stem Water Potential Difference (Mpa)	
	Mean	SD	Mean	SD
Ample1	0.003	0.004	0.37	0.05
Ample2	0.005	0.005	0.22	0.12
Deficit1	0.004	0.009	0.21	0.18
Deficit2	0.005	0.005	0.09	0.15

Measurement errors in both metrics may make a correlation between stem water potential and GS1 voltage output difficult to achieve. Still, there is some evidence that the GS1 sensor can detect changes in trunk hydration in fruit trees.

The temperature sensitivity of the GS1 sensor made its use in orchards very difficult (See Appendix A). We would expect that stem water potential would decline during the day and recover at night. However, the diurnal changes in GS1 voltage output

occur in the opposite direction of what we would expect, indicating that this is an effect of temperature on the GS1 sensor electronics. The small response and temperature sensitivity of the GS1 make it an unlikely candidate for detecting changes in trunk hydration in fruit trees.

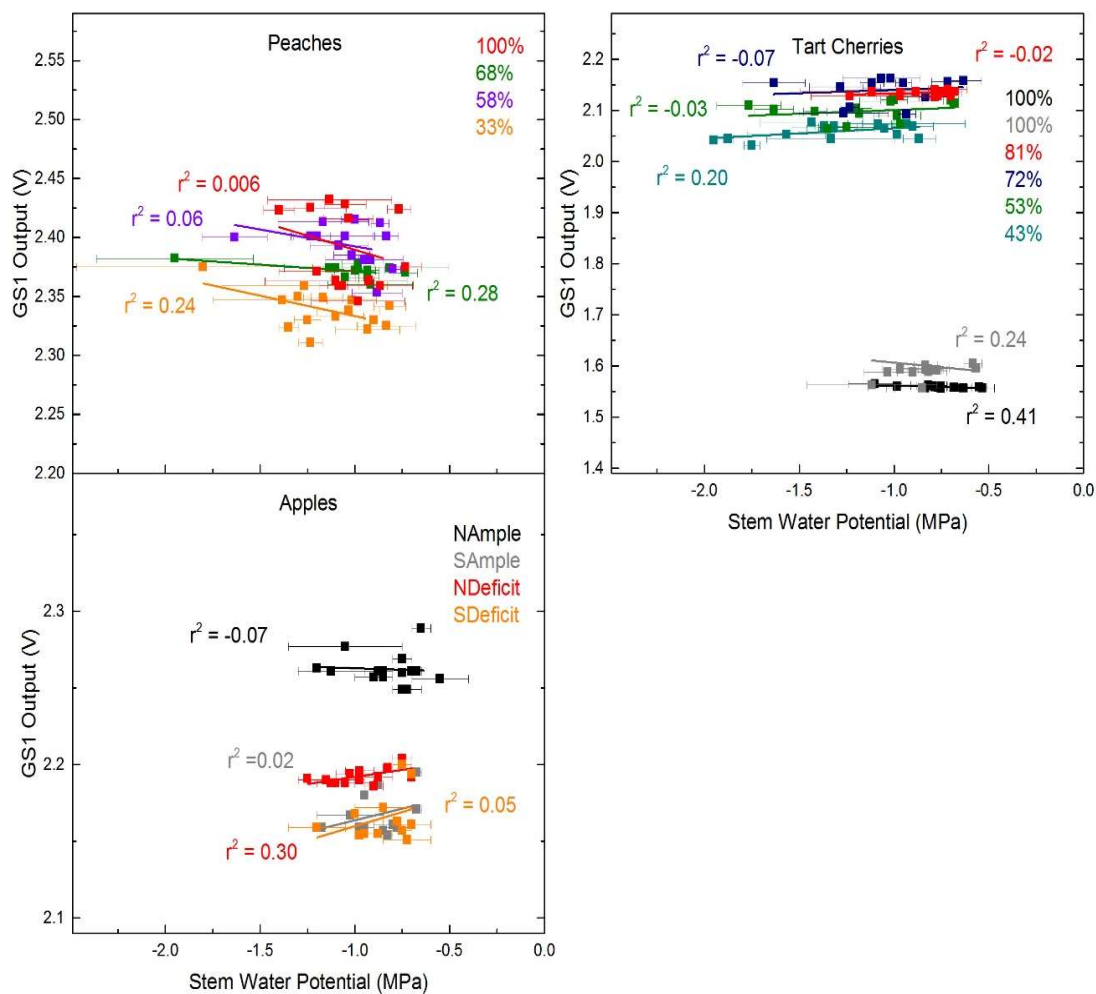


Fig. B.1.7. 2015 Kaysville stem water potential and GS1 sensor output (V) regression revealed that relationships were inconsistent.

APPENDIX C

SUPPLEMENTAL ELECTROMAGNETIC SENSOR DATA

C.1 Results and Discussion

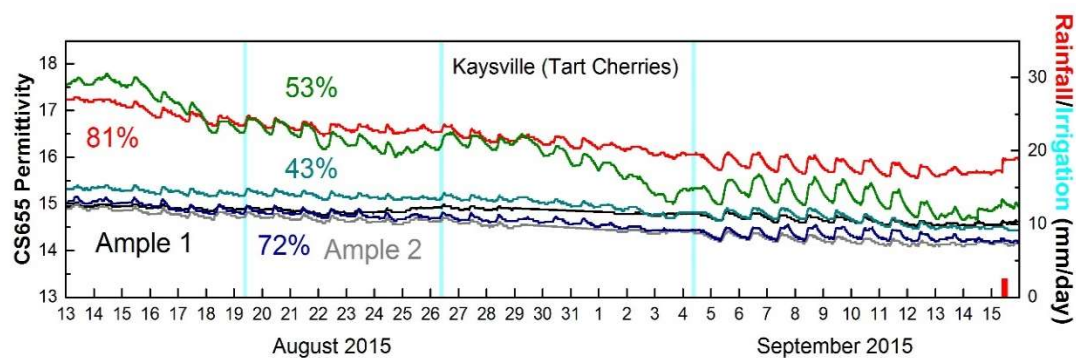


Fig. C.1.1. 2015 Kaysville tart cherry CS655 soil moisture sensor permittivity did not seem to respond to irrigation patterns.

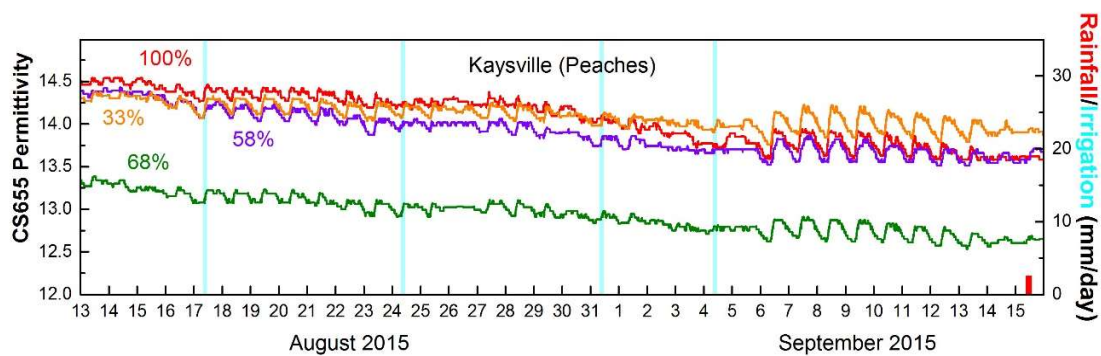


Fig. C.1.2. 2015 Kaysville peach CS655 soil moisture sensor permittivity did not seem to respond to irrigation patterns.

APPENDIX D
THERMOCOUPLE PSYCHROMETRY AND
HEAT DISSIPATION SENSORS

D.1 Materials and Methods

Six thermocouple psychrometers (75-3V, JRD Merrell Specialty Equipment, Logan, Utah) and three heat dissipation matrix potential sensors (CS229, Campbell Scientific, Logan, Utah) were inserted into a block of dimensional lumber 3.8 cm by 9 cm by 12 cm long to determine water content. For each type of sensor, a hole slightly larger than the sensor body was drilled into the top of the wood block to a depth of approximately $\frac{3}{4}$ the thickness of the wood block. Sensors were then installed in the holes and silicone caulk was spread around the sensor body to seal the interface between the wood and the sensor (Fig. D.1.1). All sensors were then connected to a datalogger (CR6, Campbell Scientific, Logan, Utah) and measurements were taken every two hours.

Since sensor wiring makes it difficult to obtain accurate mass measurements, two other identically sized pieces of similar mass were cut from the same piece of dimensional number wood to characterize weight changes in the wood. The mass of each block of wood was recorded at intervals and compared with changes in the readings of the two types of sensors over a ten-week period. All three wood blocks were placed in a plastic container with a closed lid (Fig. D.1.2).

All three wood blocks were then weighed down and all but submerged in tap water (See example of water line in Fig. 1 above.) from 4/18/2016 to 4/20/2016, allowed to dry for several days and then rewet from 4/27/2016 to 5/2016 before being allowed to dry again. After several days, the wood blocks were placed on 5 mm shims to allow air to reach all sides of the wood blocks to promote even drying.

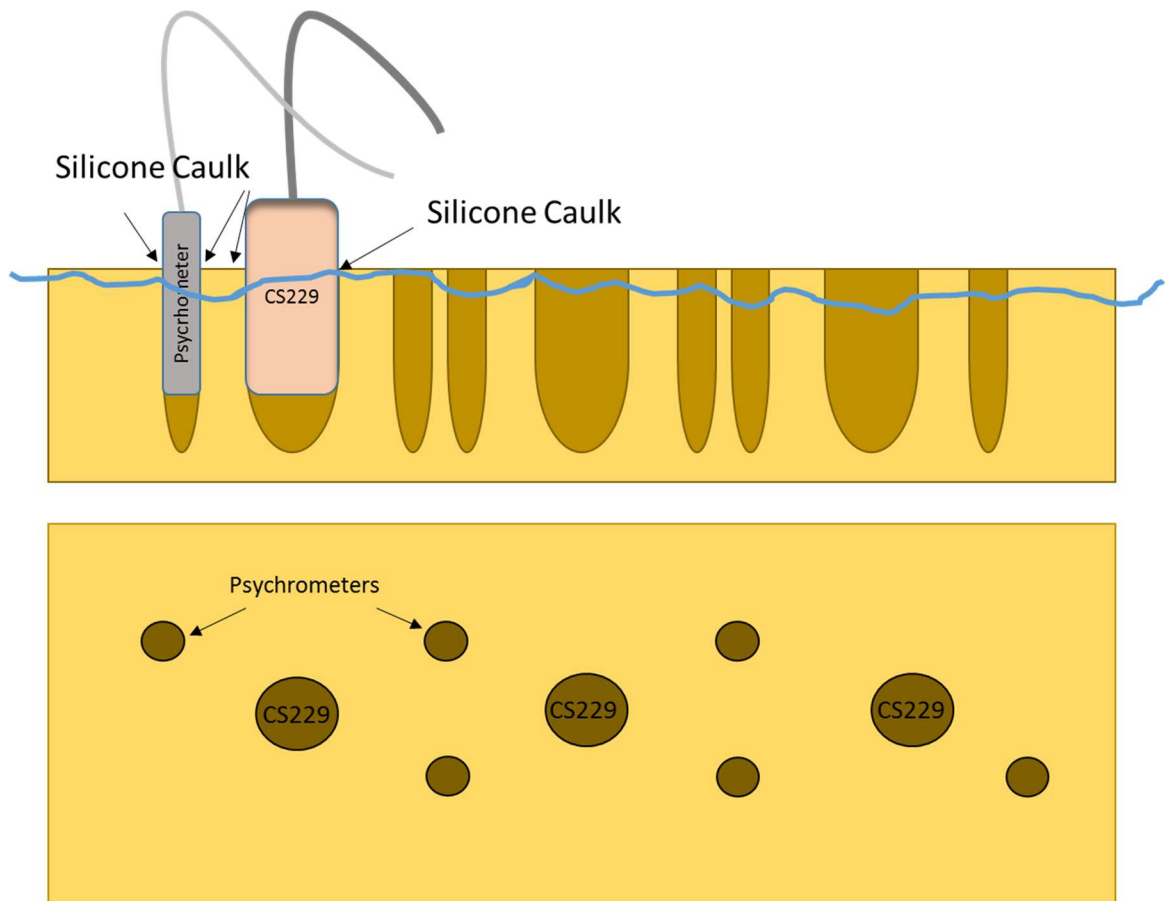


Fig. D.1.1. Thermocouple psychrometer and heat dissipation water potential sensor installation diagram. Sensors were evenly spaced and installed to a depth of approximately $\frac{3}{4}$ of the thickness of the block.

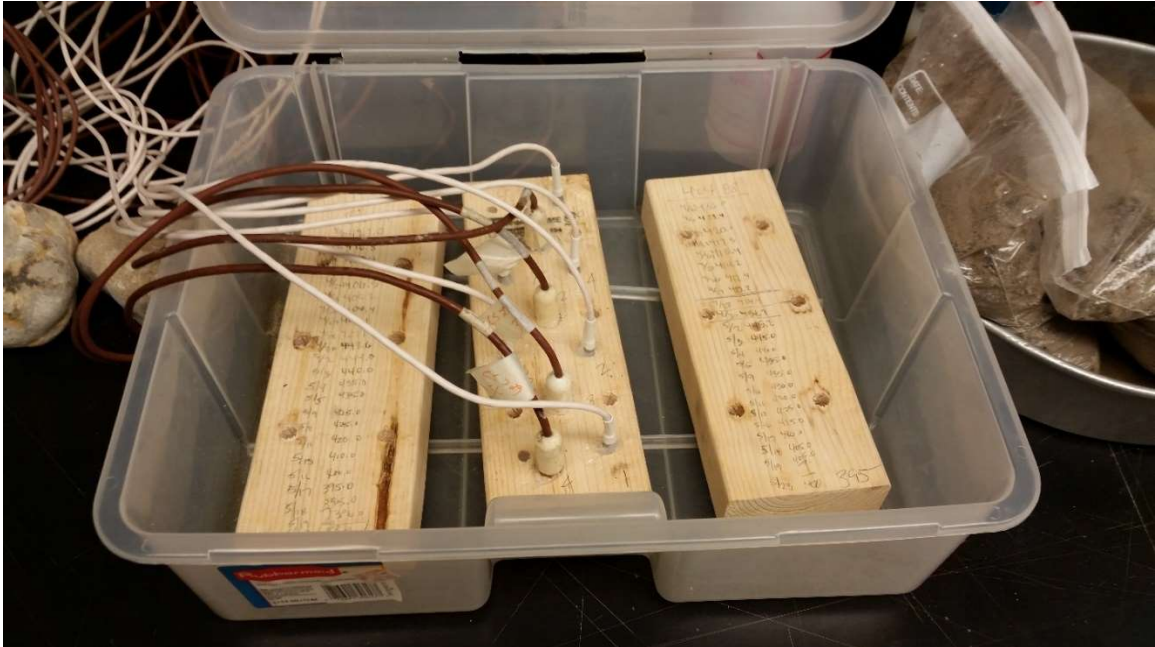


Fig. D.1.2. CS229 heat dissipation matric potential sensors and thermocouples installed in a block of wood were placed in a plastic container with a closed lid. Wood blocks without sensors were weighed frequently.

D.2 Results and Discussion

All heat dissipation matric potential sensors responded to wetting and drying of wood (Fig. D.2.1). Since these heat dissipation sensors heat continuously during a measurement, we would expect to have a larger change in temperature during a measurement in dry wood than we would in wet wood. One (blue line) of the three sensors evidently had better contact with the wood as it responded more dramatically than the other two (red and black lines).

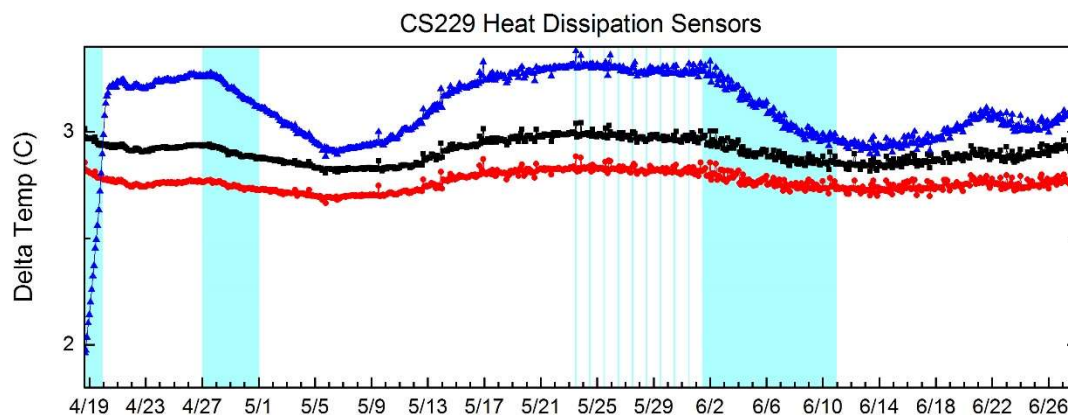


Fig. D.2.1. CS229 heat dissipation matric potential sensor output from dimensional lumber. Delta temp was greatest when wood was dry and decreased as wood hydrated.

Thermocouple psychrometers did not respond as we might have expected. When the wood was dry on the first day, we should expect that the water potential would be more negative than in wet wood. Instead, we see that water potential is near zero in the dry wood blocks and, after wetting, the potential readings range from -2 to over -7 MPa (Fig. D.2.2).

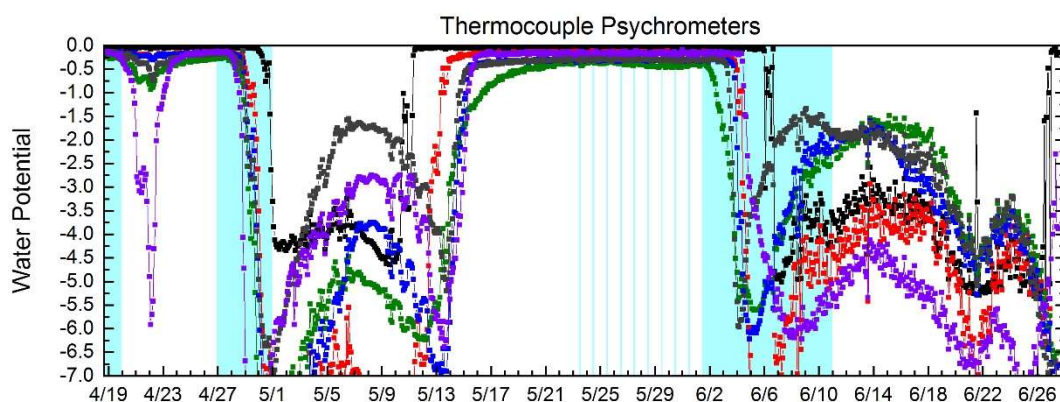


Fig. D.2.2. Thermocouple psychrometer output from dimensional lumber did not respond as expected. Near zero values occurred when the wood blocks were dry and more negative potentials when the wood was wet.

When related to changes in mass, neither type of sensor was able to predict changes in water content with great accuracy. Correlation values from thermocouple psychrometers ranged between $r^2 = 0.44$ and $r^2 = 0.65$. Correlation values from the heat dissipation matrix potential sensors ranged between $r^2 = 0.51$ and $r^2 = 0.60$ (Fig. D.2.3).

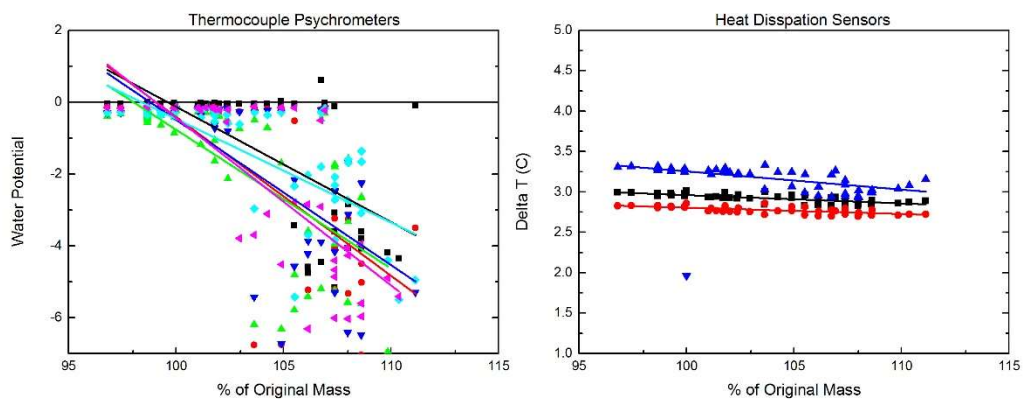


Fig. D.2.3. Relationship of water potential to changes in mass of the wood block. Delta T of the wood decreased as the wood gained mass (got wetter) as we would expect, but the changes were small. The relationship between water potential and wood mass did not follow any meaningful trend.

APPENDIX E
AN UPDATE ON THE EFFICACY OF USING INVINSA
TO MITIGATE TEMPERATURE STRESS IN RICE

E.1 Introduction

Rice growth and development are temperature-dependent. During each stage of rice growth and development, there is an optimum temperature range. The ideal temperature range varies slightly for each stage of growth, but is generally between 20 °C and 30 °C (Yoshida, 1981). Above and below this range, negative impacts on growth are more likely to occur. For example, Yoshida (1981) asserted that ripening takes place in 30 days in the tropics and takes up to 65 days in cooler regions. Aimi et al. (1959) found that ripening was not complete even after 75 days when rice was grown at 17 °C. Conversely, they found that high temperatures also reduced ripening. Yoshida (1981) also mentioned that lengthy periods above 35 °C resulted in spikelet sterility. Similar temperature values (25 °C to 35 °C) for the ideal temperature range of rice were suggested by Arrau deau and Vergara (1988).

1-methylcyclopropene (1-MCP) is a molecule similar in structure to ethylene. It can attach to ethylene receptors in plants (Ottoman and Kimball, 2011), blocking the perception of ethylene. Because of this, 1-MCP has previously been used to preserve post-harvest quality in bananas (Golding et al., 1998), avocados (Jeong et al., 1999) and cut flowers (Han, 2007; Sankhla et al., 2001). However, little research has been done on in-situ applications of 1-MCP. The following are two examples of pre-harvest use. 1-MCP applied to apples prior to harvest can prevent pre-harvest fruit drop and prolong postharvest quality (Watkins et al., 2010). Initial studies by Ottoman and Kimball (2011) provide some indication that 1-MCP may help mitigate the effects of drought stress on corn, but the effects were not always significant.

The objectives for this series of experiments was to determine if 1-MCP (Invinsa, Agrofresh Inc., Spring House, Pennsylvania) would block ethylene perception and: 1) increase yield of rice plants under temperature stress; 2) reduce transplant shock stress in rice plants. Accordingly, four yield experiments and a series of transplant shock stress studies were carried out.

E.2 Yield Experiments

E.2.1 Materials and Methods

General Growing Conditions. In all four yield experiments, seeds of Ai Nan Tsao rice were germinated on blotter paper and subsequently transplanted into peat:vermiculite soilless media until of sufficient size to be used. Rice was grown at 30 °C day/25 °C night with a twelve-hour photoperiod. After reaching sufficient size, either 4 or 6 rice plants were transplanted into plastic containers (36 cm x 47 cm x 18 cm deep) in soilless media for the experiments. All plants received a 12-hour photoperiod under high intensity lighting. In each experiment, half of the plants received the 1-MCP treatment while half were untreated controls. Rice was continuously fertilized with a 50 ppm nitrogen solution and watered daily. With the exception of plants in Experiment IV which were treated four times over four consecutive days, rice plants received only a single 1-MCP treatment.

1-MCP Treatments. Treated plants were removed from growth chambers and treated with 356 grams of active ingredient per hectare (nearly six times greater than the recommended rate) using a spray chamber. Treated plants remained in the closed spray

chamber for twenty minutes after spraying. After being removed from the chamber, treated plants were allowed to dry to prevent contamination of the untreated controls before being placed back into the growth chambers.

Harvests and Data Collection. In each experiment, the number of emerged panicles was recorded periodically for each container until the total number in each container exceeded fifty. With the exception of Experiment II., at harvest panicles were snipped and visually separated into groups of immature, sterile and mature panicles and thrashed separately. Culms were clipped at the media surface and bagged. Fresh mass was recorded for immature panicles, sterile panicles, mature panicles and culms for each container. Panicles and culms were dried at 80 °C for at least 48 hours and then dry mass was taken for each sample.

After taking dry mass measurements, immature, sterile and mature panicles were thrashed separately and yield measurements were recorded. To obtain seed mass, seeds were either counted directly or five small samples were taken, weighed and then counted. The average mass per seed of the five samples was used as the seed mass for the lot. To calculate seeds per panicle, the total number of seeds was divided by the number of immature or mature panicles, respectively.

Specifics by Experiment. *Experiment I.* Four seedlings were placed in a two plant by two plant grid in each of two containers for each temperature treatment (12 containers, 48 total plants). After 58 (days after planting (DAP) one of the two containers from each temperature treatment was treated with 1-MCP. Temperature remained constant for the duration of the experiment. The number of emerged panicles

was recorded for each container beginning at 68 DAP and ending at 83 DAP. Harvests began at 106 DAP.

Experiment II. At 65 DAP, seedlings were transplanted into containers in soilless media. Six seedlings were placed in a three plant by two plant grid in each of four containers for each temperature treatment (24 containers, 96 total plants). From 65 to 87 DAP, rice received temperature stress, after which all rice was grown at 30 °C day/25 °C night temperature until harvests began at 101 DAP. Two of the four containers were treated with 1-MCP at 63 DAP.

Experiment III. At 55 DAP, six seedlings were transplanted in a three plant by two plant grid into four containers per temperature treatment (24 containers, 96 total plants). Temperatures remained constant for the duration of the experiment. Harvests began at 110 DAP.

Experiment IV. At 55 DAP, six seedlings were transplanted in a three plant by two plant grid into four containers per temperature treatment (24 containers, 96 total plants). Beginning at 66 DAP, plants were subjected to a 14-day heat stress and then grown at 30 °C day/25 °C night for the remainder of the experiment. Rice received 1-MCP treatments for four consecutive days (67, 68, 69, and 70 DAP). Harvests began at 116 DAP.

E.2.2 Results

Mean Temperatures. During the experiment rice was grown at the following temperature in each experiment. Arrows indicate a change in the temperature setting. The actual mean temperatures are shown (Table E.2.1).

Table E.2.1. Summary of set and actual mean temperatures for all rice temperature stress experiments.

	Day Setting	Night Setting	Actual Mean Temperature	
	(°C)	(°C)	(°C)	(°C)
Experiment I.	35	30	32.6	
	30	30	N/A	
	35	25	30.3	
	30	25	25	
	30	20	25.5	
	25	20	22.8	
Experiment II.	35→30	30→25	30	32.5
	30→30	30→25	28.1	30
	35→30	25→25	28.9	30
	30→30	25→25	27.3	27.5
	30→30	20→25	N/A	25
	25→30	20→25	25.4	22.5
Experiment III.	35	30	32.2	32.5
	30	30	29	30
	35	25	29.8	30
	30	25	26.9	27.5
	30	20	N/A	25
	25	20	22.8	22.5
Experiment IV.	40→30	35→30	30.3	37.5
	35→30	35→30	29.1	35
	35→30	30→30	29	32.5
	30→30	30→30	28.7	30
	30→30	25→30	28.1	27.5
	25→30	20→30	26.6	22.5

Total Dry Biomass. *Experiment I.* Total dry biomass was greater at the two extremes than at the intermediate temperatures. Total dry biomass for the treated plants at 25.0 °C and 30.3 °C mean temperature was greater, while that for untreated plants at 25.5 °C and 32.6 °C was less. No clear trends emerged due to MCP treatment (Fig. E.2.1A).

Experiment II. Total dry biomass was similar for all temperatures and treatments. Untreated plants produced significantly more dry biomass at 30.0 °C than did the treated plants (Fig. E.2.1B). Biomass decreased slightly as temperature increased.

Experiment III. Though not statistically significant, 1-MCP treated plants had less total dry biomass at 22.8 °C mean temperature and more total dry biomass at 29.0 °C mean temperature than untreated plants (Fig. E.2.1C). Only one significant difference in dry biomass occurred in relation to temperature, where untreated plants at 26.9 °C mean temperature had more total dry biomass than untreated plants at 29.8 °C mean temperature.

Experiment IV. Total dry biomass was slightly less for plants grown at 30.3 °C than for plants grown at any other temperature, though differences were not always significant. Total dry biomass was near 600 g for all temperatures and treatments (Fig. E.2.1D). No significant differences in biomass were found between treated and untreated plants.

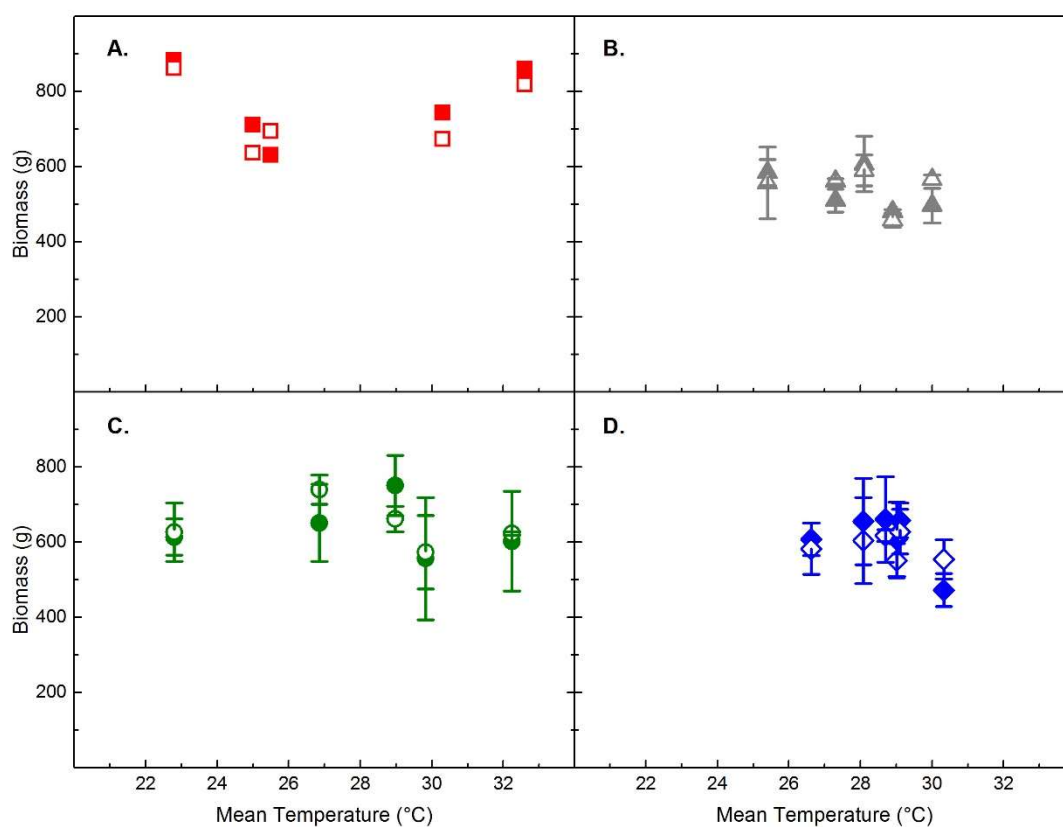


Fig. E.2.1. Rice Total Dry Biomass. **A.** Plants grown at the coolest and warmest temperatures produced more biomass than the remaining temperatures. **B.** Biomass decreased slightly as temperature increased. The only significant difference in biomass between treated and untreated plants occurred at 30.0 °C. **C.** No significant 1-MCP treatment effects were observed for total dry biomass, though some differences were nearly so. Dry biomass was similar for all temperatures with only one statistically significant difference occurring between untreated plants at 26.9 °C and 29.8 °C mean temperatures. **D.** No significant 1-MCP treatment or temperature effects were observed for total dry biomass.

Biomass Distribution. *Experiment I.* No clear treatment effect emerged in the distribution of biomass into stems, immature panicles and mature panicles. Rice grown at the coolest and warmest temperatures generally contained more stem and immature panicle and less mature panicle biomass. Most of the dry biomass was found in mature panicles and culms, with less than 10% found in immature panicles (Fig. E.2.2A).

Experiment II. The upper half of the plants including the panicles accounted for at least 65% of the total dry biomass, while culms accounted for 35% or less. No significant treatment effect emerged. Cooler temperatures produced less biomass in the upper half of the plant and more culm biomass, but differences were not significant (Fig. E.2.2B).

Experiment III. While no treatment effect is visible, plants grown at 22.8 °C and 32.2 °C mean temperatures produced significantly less mature panicle biomass coupled with significantly more stem biomass. Plants grown at 22.8 °C also produced significantly more immature panicle biomass. Immature panicles accounted for less than 20% of the total biomass in all cases (Fig. E.2.2C).

Experiment IV. No significant 1-MCP treatment effects emerged. Mature panicles accounted for at least 19% of the total dry biomass. Immature panicles accounted for less than 15% of the total dry biomass. However, at 27.9 °C, the portion of biomass allocated in immature panicles was greater than that for any other temperature except 27.3 °C. The portion of biomass allocated to mature panicles at 27.9 °C was significantly less than any other temperature (Fig. E.2.2D).

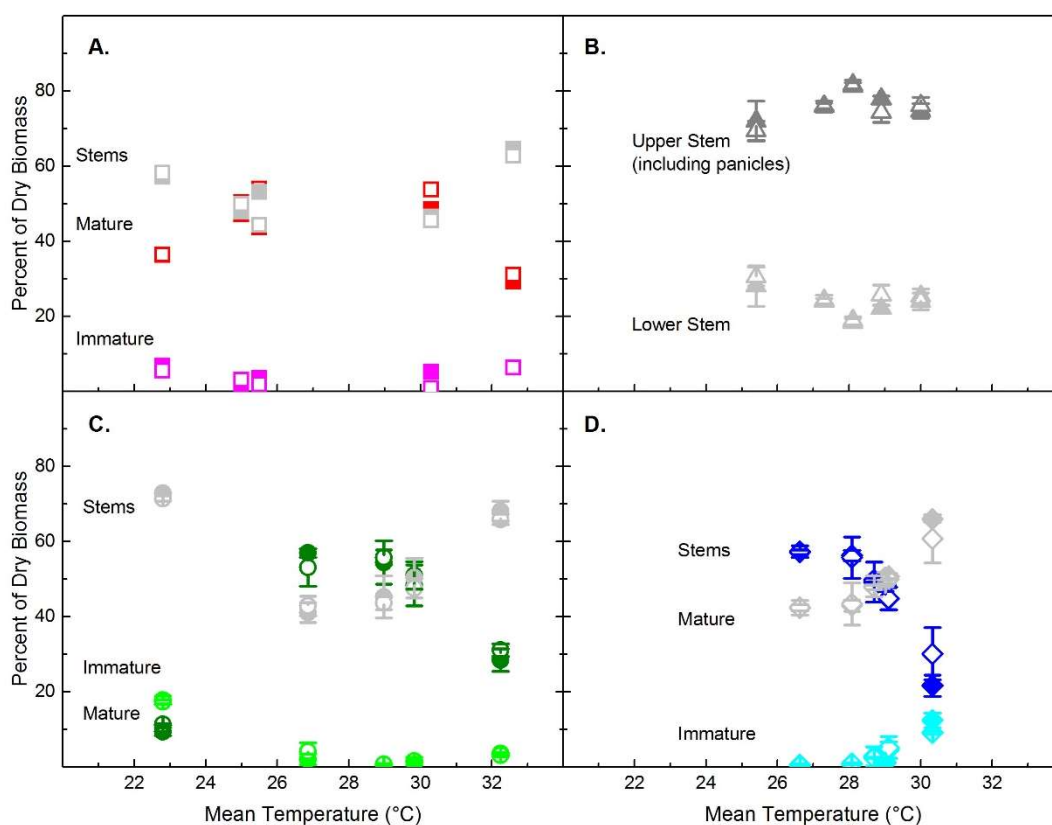


Fig. E.2.2. Rice Biomass Distribution. **A.** No clear treatment effect can be observed. Plants grown at the warmest and coolest temperatures contained more immature panicle and stem biomass and less mature panicle biomass. The biomass of immature panicles accounted for less than 10% of the total biomass. **B.** No clear treatment effect can be observed. Plants grown at the coolest temperature contained more lower-stem biomass and less upper-stem and panicle biomass. The upper stem and panicles accounted for at least 65% of biomass in all cases. **C.** Plants grown at 22.8 °C and 32.2 °C produced significantly less mature panicle biomass and significantly more stem biomass than those grown at intermediate temperatures. No 1-MCP treatment emerged. Immature panicles accounted for less than 20% of the total biomass. **D.** No significant differences occurred between treated and untreated plants in biomass distribution. Plants grown at 30.3 °C had significantly more biomass in immature panicles than plants grown at any other temperature.

Panicle Initiation. *Experiment I.* Rice grown at 25.0 °C and 30.3 °C mean temperature contained at least 50 panicles per container by 77 DAP. Rice grown at 32.6 °C did not reach 50 panicles per container until 83 DAP. Untreated rice grown at 22.8 °C mean temperature had 50 panicles per container at 77 DAP, while 1-MCP treated rice did not have 50 panicles per container until 83 DAP. All containers had at least 50 panicles by 83 DAP (Fig. E.2.3A). Final panicle counts will be discussed later in this report.

Experiment II. Rice grown at cooler temperatures (25.4 °C, 27.3 °C) initiated panicles more slowly than the remainder of the rice; rice grown at each of these temperatures had less than fourteen panicles per container by 70 DAP. Rice grown at warmer temperatures contained at least twenty panicles by 70 DAP (Fig. E.2.3B).

Experiment III. The first panicles emerged at 72 DAP for containers with mean temperatures at or above 27.3 °C. For the cooler treatments, panicles began to emerge at 75 DAP. By 99 DAP, all containers had at least 50 emerged panicles (Fig. E.2.3C). Plants treated with 1-MCP initiated panicles more quickly than the untreated controls at 27.3 °C mean temperature, with significant differences occurring between 10 and 89 days after planting (Fig. E.2.4). There were no significant differences in panicle emergence between plants treated with 1-MCP and the untreated controls for any other mean temperature. Significant differences in final panicle count will be discussed later on.

Experiment IV. Panicle initiation in rice grown at 32.3 °C mean temperature was delayed; the last container at this temperature did not have more than 50 emerged panicles until 98 DAP. Rice grown at 26.6 °C was also delayed, but all containers had 50

emerged panicles by 95 DAP. All other containers contained at least 50 emerged panicles by 91 days after planting (Fig. E.2.3D).

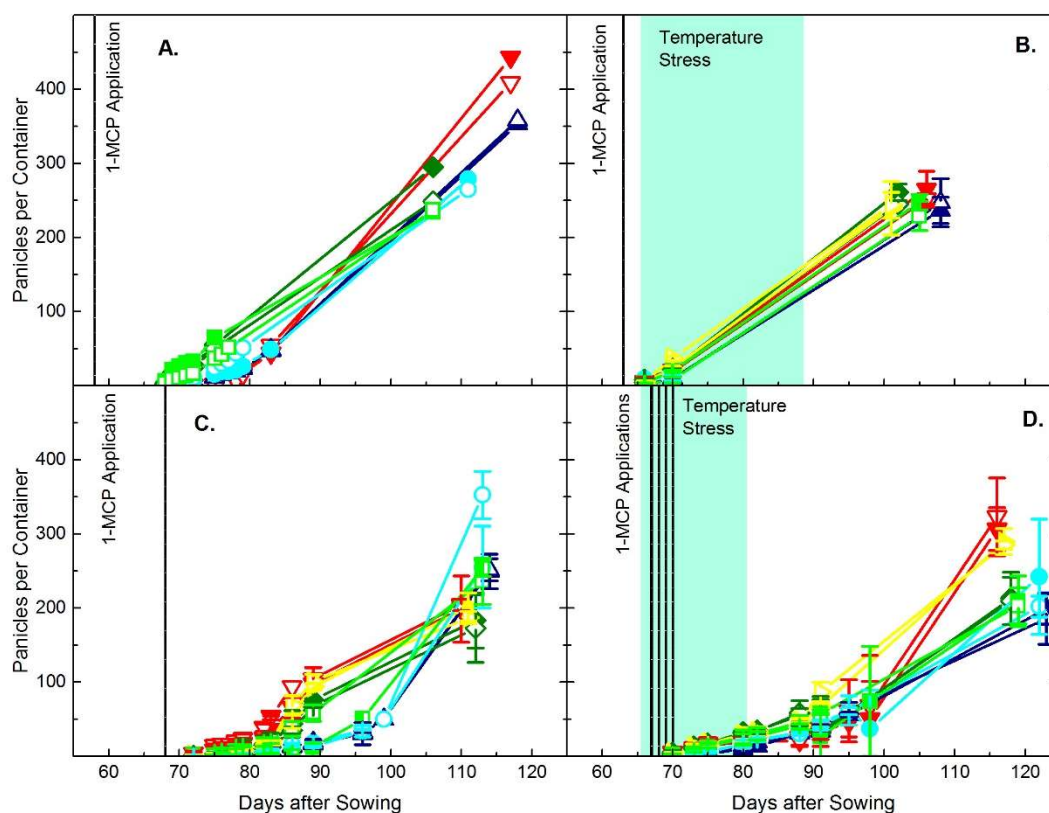


Fig. E.2.3. Rice Panicle Initiation. **A.** Rice grown at 25.0 °C and 30.3 °C initiated panicles more quickly than that grown at cooler or warmer temperatures. All containers had 50 emerged panicles by 83 DAP. **B.** Rice stressed with cooler temperatures initiated panicles more slowly than that grown at warmer temperatures. **C.** Panicles began to emerge at 72 DAP for temperatures at or above 27.3 °C mean temperature. For cooler temperatures panicles began to emerge at 75 DAP. All containers had 50 emerged panicles by 99 DAP. **D.** Rice grown at 30.3 °C and at 26.6 °C mean temperatures did not contain 50 emerged panicles until 98 DAP and 95 DAP, respectively. All other containers contained at least 50 emerged panicles by 91 DAP.

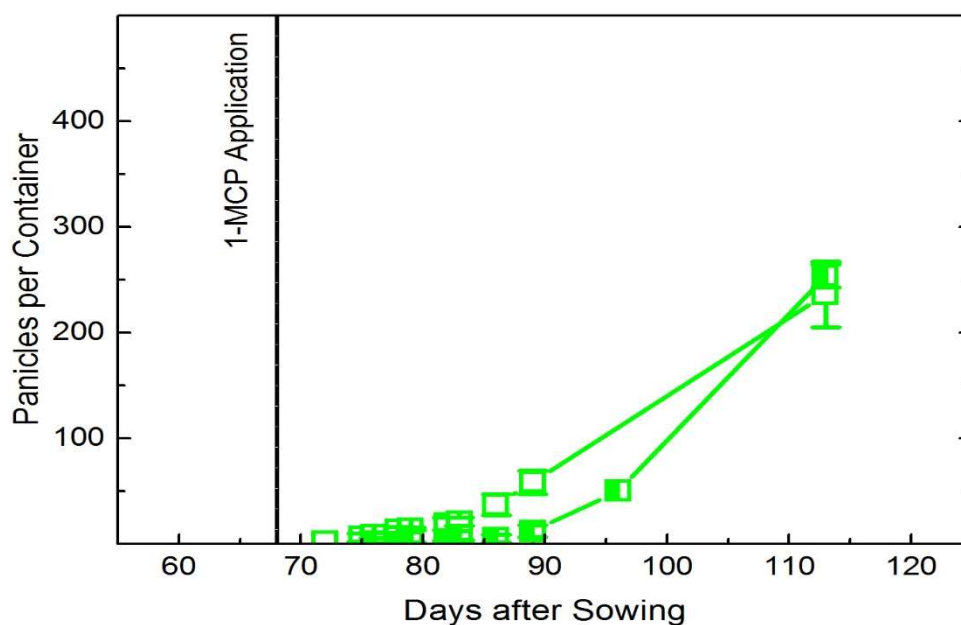


Fig. E.2.4. Rice Panicle Initiation 27.3 °C. At 27.3 °C mean temperature, containers treated with 1-MCP contained significantly more panicles than the untreated controls between 10 and 89 days after planting.

Final Panicle Count. *Experiment I.* At harvest, rice from the coolest and hottest treatments produced more panicles than rice at temperatures in between those two extremes. Treated rice grown at 32.6 °C and rice grown at 30.3 °C mean temperature produced more panicles than their untreated counterparts (Fig. E.2.5A).

Experiment II. Rice plants in this experiment all produced similar quantities of panicles per container—between 200 and 250. There were no differences between temperatures or treatments (Fig. E.2.5B).

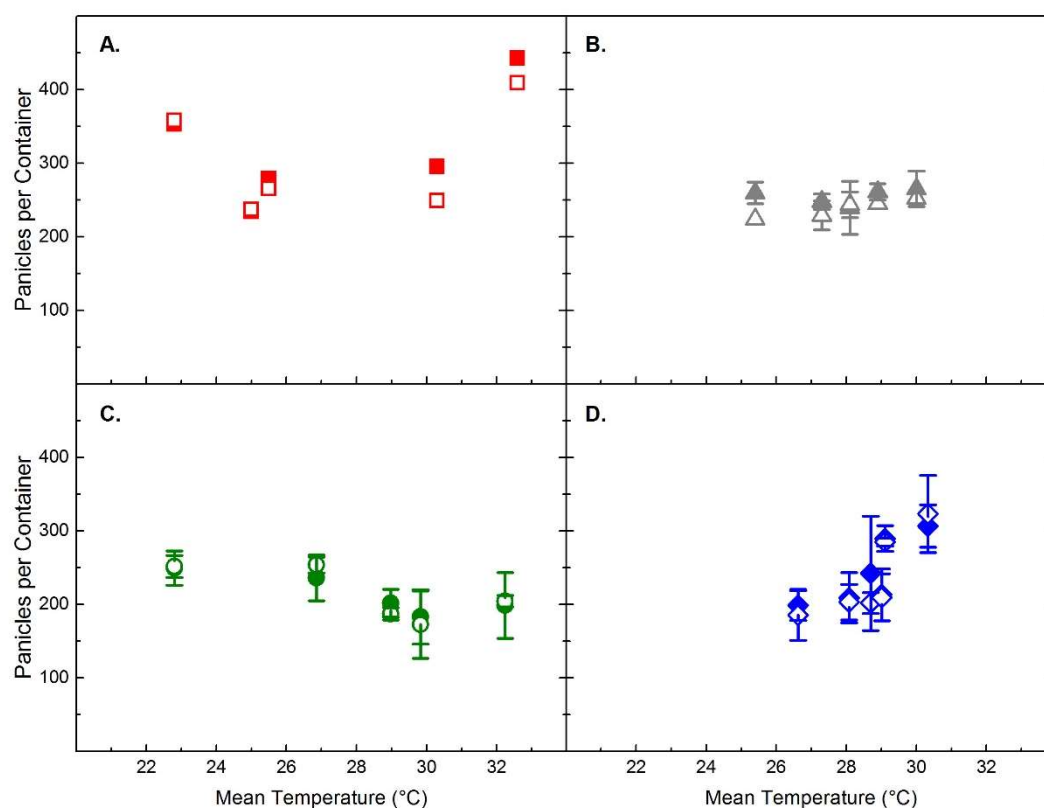


Fig. E.2.5. Rice Final Panicle Count. **A.** The coolest and warmest temperatures produced more panicles than the intermediate temperatures. Treated rice grown at the two warmest temperatures produced more panicles per container than the UTCs. **B.** No significant panicle count differences occurred between 1-MCP treated and untreated plants occurred. Panicle counts tended to increase with temperature, but no significant differences were associated with temperature. **C.** No significant treatment 1-MCP treatment effects in panicles per container occurred. Cooler temperatures tended to be associated with more panicles, though the differences were not always significant. **D.** Untreated rice produced significantly more panicles than the UTCs at 28.1 °C, but treated rice produced significantly more at 28.7 °C mean temperature. The three warmest temperatures resulted in significantly fewer panicles than the two intermediate temperatures.

Experiment III. No significant differences in final panicle count between treated and untreated containers occurred (Fig. E.2.5C). Plants tended to produce fewer panicles as temperature increased, though differences were not always significant.

Experiment IV. Untreated rice at 28.1 °C mean temperature produced significantly more panicles than treated rice, while at and 28.7 °C the opposite was true. There were no significant differences in panicle count per container at any other temperature. There was a general trend for the rice to produce fewer panicles per container as mean temperature increased or decreased from the intermediate temperatures (Fig. E.2.5D).

Panicle Maturity. *Experiment I.* The percentage of mature panicles was slightly less for plants grown at 22.8 °C than for the other temperatures. No clear 1-MCP treatment effect is evident. At least 50% of all panicles were mature (Fig. E.2.6A).

Experiment II. N/A

Experiment III. There were no significant differences in the percentage of mature panicles at harvest between 1-MCP treated plants and the untreated controls (Fig. E.2.6C). Plants grown at 22.8 °C had a significantly lower percentage of mature panicles at harvest than any other temperature. Plants grown at 32.2 °C had a significantly lower percentage of mature panicles than did plants grown at 29.0 °C and 29.8, but were not significantly different from those grown at 26.9 °C mean temperature.

Experiment IV. Rice grown at the hottest temperature produced significantly fewer mature panicles than rice grown at any other treatment. Treated plants at this temperature contained significantly fewer mature panicles than untreated plants. No other treatment differences occurred (Fig. E.2.6D).

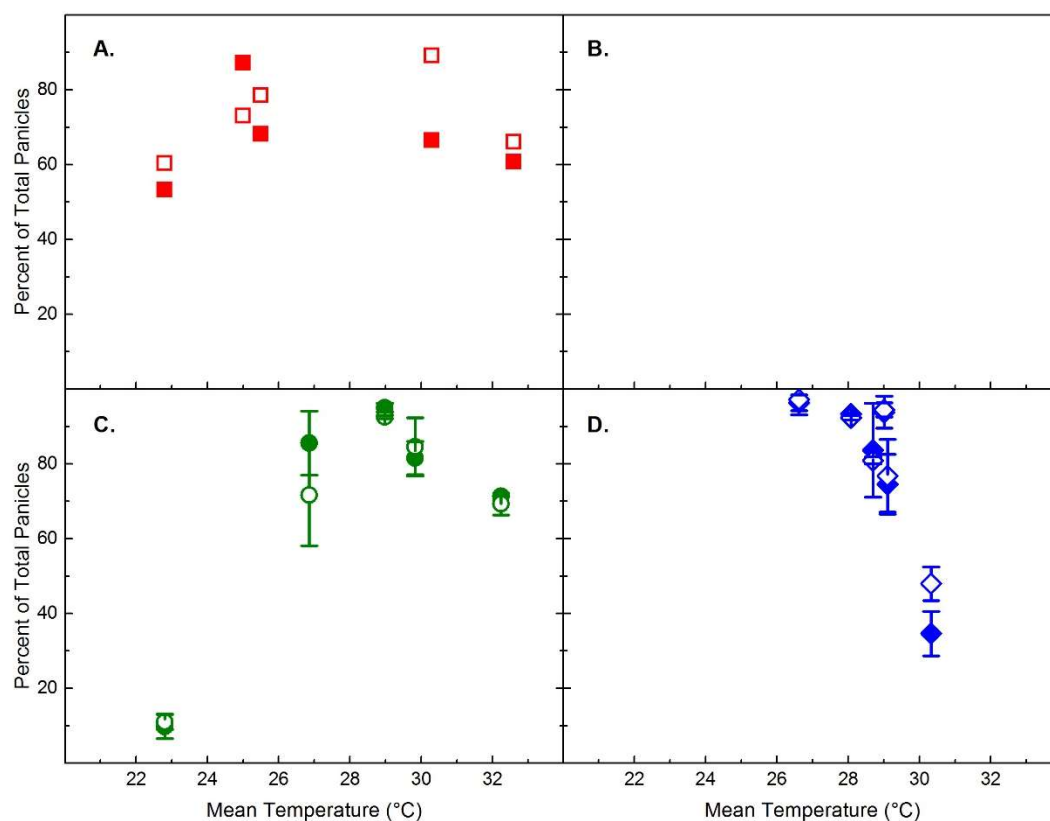


Fig. E.2.6. Rice Panicle Maturity. **A.** No significant 1-MCP treatment effects were observed for percent mature panicles at harvest. The coolest mean temperature plants had a lower percentage of mature panicles than any other temperature. **B.** N/A. **C.** No significant 1-MCP treatment effects were observed for percent mature panicles at harvest. The coolest mean temperature plants had a significantly lower percentage of mature panicles than any other temperature. **D.** The only significant 1-MCP treatment effect occurred at 30.3 °C, where untreated plants contained more mature panicles than treated plants. The coolest mean temperature plants had a significantly lower percentage of mature panicles than any other temperature.

Seeds Per Panicle. *Experiment I.* For mature panicles, the two extreme temperatures produced fewer seeds per panicle than the intermediate temperatures. Mature panicles from untreated rice grown at 30.3 °C contained more seeds per panicle than the 1-MCP treated rice (Fig. E.2.7A). Immature panicles contained fewer than 10 seeds while mature panicles contained 30 or more.

Experiment II. Untreated plants produced significantly more seeds per panicle than treated plants at 27.3 °C and 30.0 °C mean temperatures. No significant differences between treated and untreated plants occurred at other temperatures (Fig. E.2.7B). Though differences were not always significant, plants grown at cooler and warmer temperatures produced fewer seeds per panicle than those grown at intermediate temperatures.

Experiment III. Mature panicles from untreated plants grown at 26.9 °C mean temperature contained more seeds than the UTCs. Mature panicles grown at 32.2 °C contained fewer seeds than all other temperatures and treatments with the exception of panicles from treated plants grown at 22.8 °C and 26.9 °C mean temperatures. Immature panicles contained fewer than twenty seeds, while mature panicles contained at least 35. No significant treatment effect was observed for immature panicles. (Fig. E.2.7C).

Experiment IV. No significant differences were found in the number of seeds per panicle between treated and untreated plants at any temperature. Panicles from plants grown at 30.3 °C contained significantly fewer seeds than all other temperatures except those grown at 29.1 °C. Immature panicles contained fewer than 30 seeds while mature panicles contained 40 or more (Fig. E.2.7D).

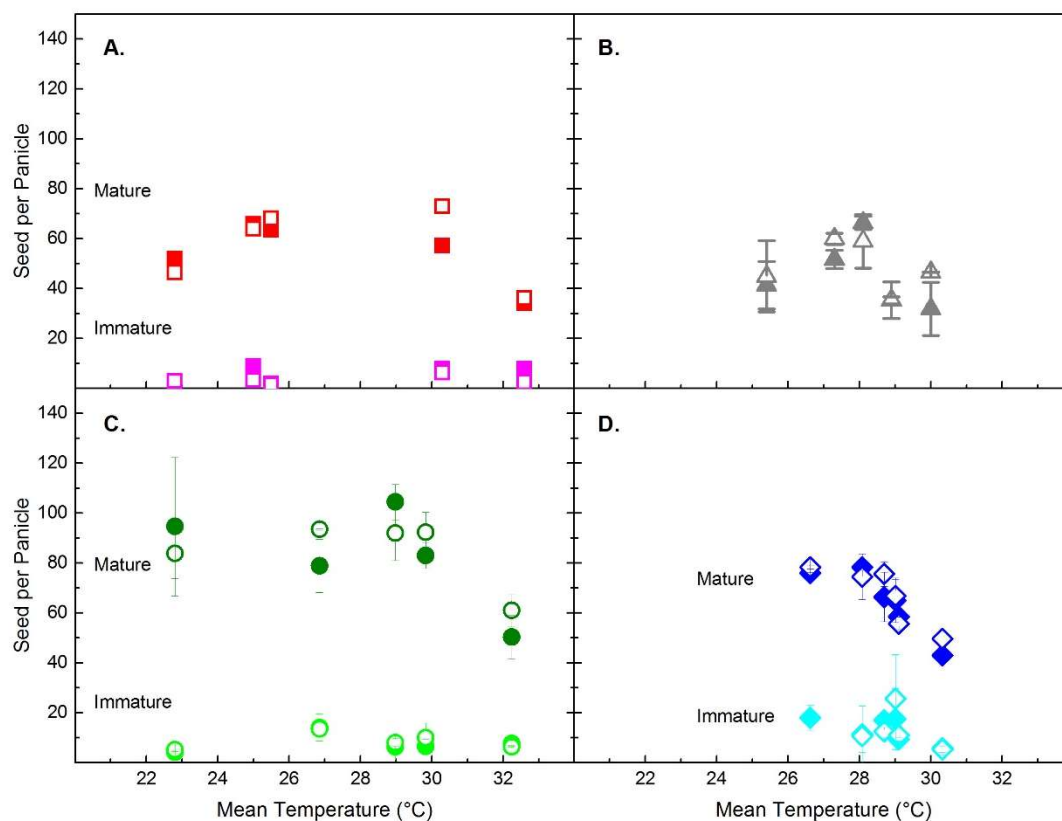


Fig. E.2.7. Rice Seeds per Panicle. **A.** Mature panicles grown at the coolest and the warmest temperature contained fewer seeds than those grown at the intermediate temperatures. Immature panicles contained fewer than 10 seeds while mature panicles contained at least 30. **B.** Untreated plants produced more seeds per panicle than treated plants grown at 27.3 °C and at 30.0 °C mean temperature. The number of seeds per panicle tended to decrease with cooler and warmer temperatures, though not all differences were significant. **C.** Mature panicles from untreated plants produced significantly more seeds per panicle than untreated plants grown at 26.9 °C. The number of seeds per panicle at 32.5 °C mean temperature was significantly less than at any other temperature, except untreated plants at 22.8 °C and 26.9 °C. No significant treatment effects were observed in the number of seeds per immature panicle. **D.** No significant treatment effects were observed in seeds per panicle. However, the number of seeds per panicle at 30.3 °C mean temperature was significantly less than at any other temperature except 29.1 °C.

Mass Per Seed. *Experiment I.* As mean temperature increased, the mass of a seed tended to decrease. Seeds from mature panicles grown at the coolest temperature (22.8 °C mean) had a mass near 23.5 mg while those from the hottest temperature (32.6 C mean) weighed around 18 mg (Fig. E.2.8A). Immature seeds weighed about 5 mg less than mature seeds, but followed the same general trend. No clear 1-MCP treatment effect is clear.

Experiment II. No significant differences in mass per seed occurred between the treated and untreated plants. Similar to Experiment I, the mass of a seed tended to decrease slightly with an increase in mean temperature, but differences were not significant (Fig. E.2.8B). Immature panicles and mature panicles were not separated for this experiment.

Experiment III. No significant differences in seed mass were observed between seeds from treated plants and untreated plants whether harvested from mature or from immature panicles. Seed size decreased as temperature increased. Seeds from mature panicles grown at the lowest mean temperature were significantly larger than those grown at the highest mean temperature (Fig. E.2.8C). Seeds from immature panicles had significantly less mass than those from mature panicles regardless of the treatment or temperature.

Experiment IV. Once again, mass per seed decreased slightly as temperature increased. No significant difference in mass per seed occurred between treated and untreated plants for seed from mature panicles. Treated seeds from immature panicles were significantly larger than untreated seed for plants grown at 26.6 °C. Seeds from

immature panicles were significantly smaller (about 5 mg less) than seeds from mature panicles (Fig. E.2.8D).

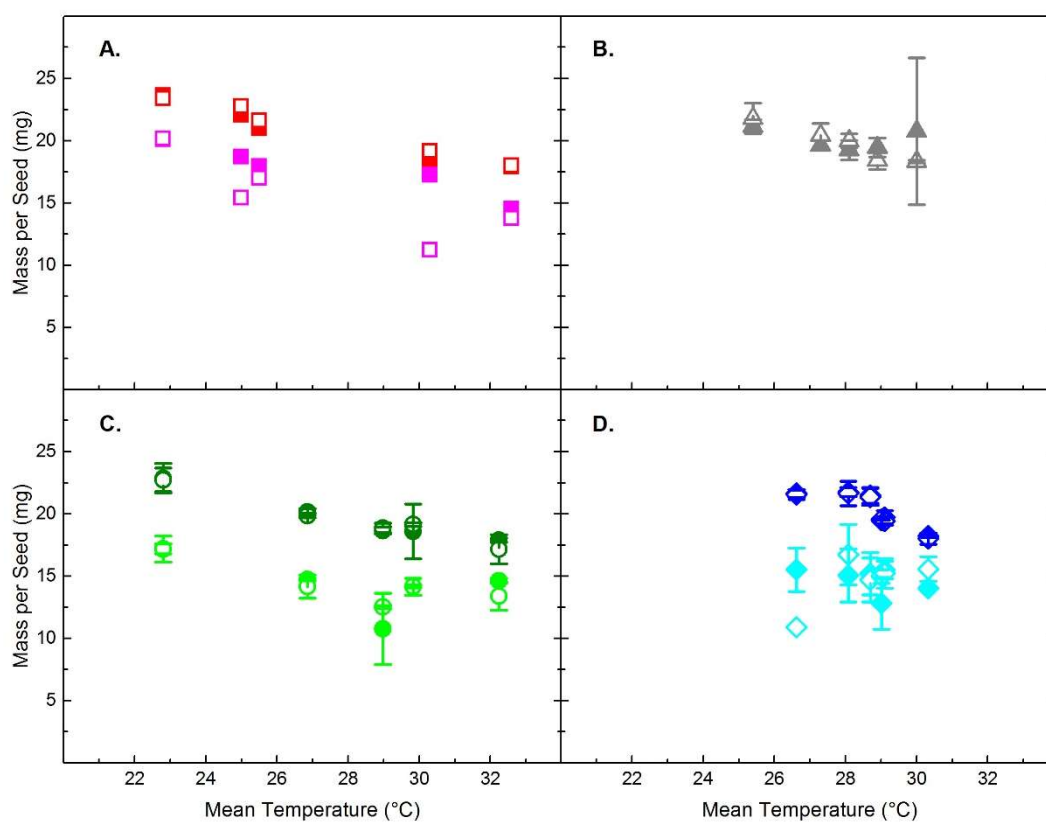


Fig. E.2.8. Rice Mass Per Seed. **A.** Seed mass for both immature and mature panicles decreased as temperature increased. Seeds from immature panicles weighed around 5 mg less than seeds from mature panicles. No clear treatment effect is evident. **B.** Seed size decreased as temperature increased, but no significant differences in seed size were associated with 1-MCP treatment or temperature. **C.** Seed size decreased as temperature increased, but no significant differences in seed size were associated with 1-MCP treatment. Seeds from immature panicles were smaller than those from mature panicles, in some cases significantly so. **D.** Seed size decreased as temperature increased, but no significant differences in seed size were associated with 1-MCP treatment except at 26.6 °C, where seed from immature panicles of treated plants were significantly larger than the UTCs. Seeds from immature panicles were smaller than those from mature panicles.

Yield. *Experiment I.* Yield from plants grown at the coolest and warmest temperatures was slightly less than that for the remaining temperatures. Some treated rice yields were greater than the UTC, while others were less (Fig. E.2.9A).

Experiment II. Treated rice plants at 27.3 °C and 30.0 °C mean temperature had greater yield than their untreated counterparts. No significant differences occurred between treated and untreated plants at other temperatures. Plants at 25.4 °C yielded slightly less than those at 27.3 °C (near optimum temperature), while those grown at 28.9 °C and 30.3 °C had significantly less yield than those grown at 27.3 °C temperature (Fig. E.2.9B).

Experiment III. No significant differences in yield were observed between treated plants and untreated controls, though there was a yield increase for treated plants at 29.0 °C mean temperature. Yield was reduced for the two hottest and the coolest temperature, though differences were not always statistically significant (Fig. E.2.9C).

Experiment IV. No significant difference in yield occurred between treated and untreated plants. Yield decreased as temperature increased. The yield for plants grown at 30.3 °C was significantly less than all but the untreated plants grown at 29.0 °C (Fig. E.2.9D).

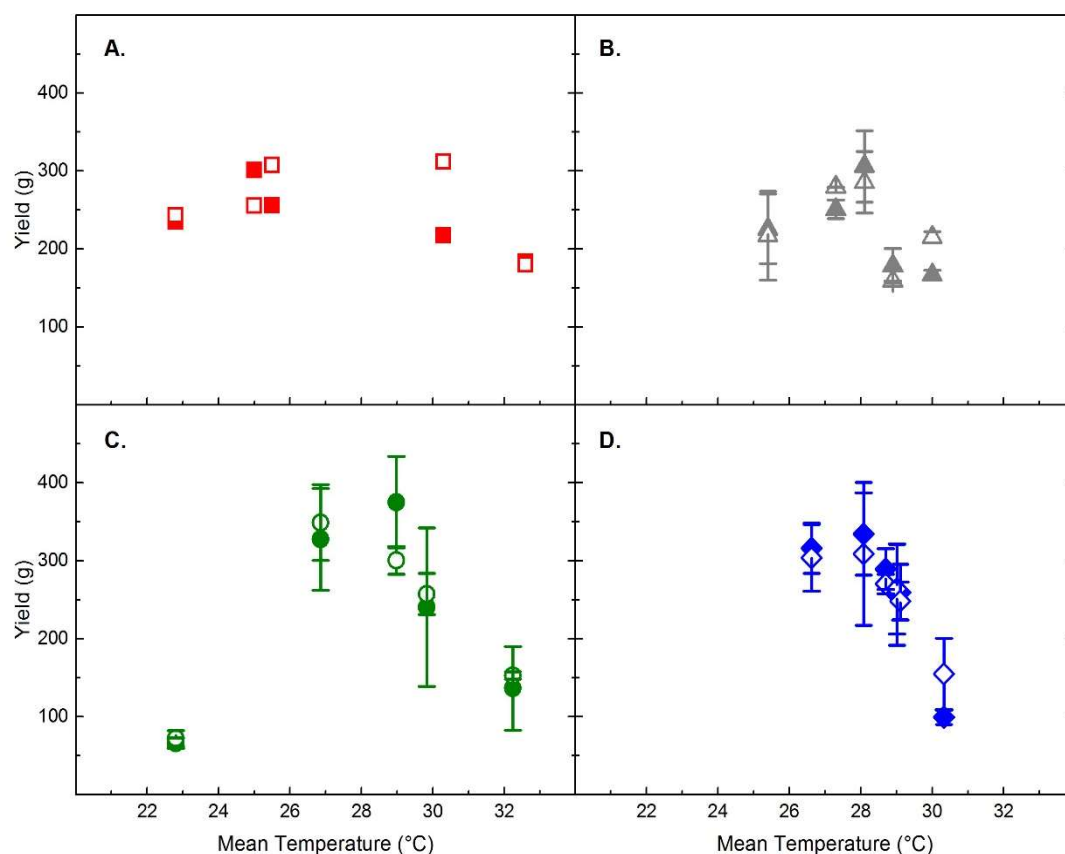


Fig. E.2.9. Rice Yield. **A.** Though some yield differences occurred between treated and untreated plants, the differences did not follow any clear trends. Plants grown at the coolest and the warmest temperatures yielded slightly less. **B.** Yield for plants grown at the two warmest mean temperatures was significantly less than that of those grown at near optimum temperature (27.3 °C). Though some significant yield differences occurred between treated and untreated plants, the differences did not follow any clear trends. **C.** No significant differences in yield occurred between treated and untreated plants. However, the warmest and the coolest temperatures resulted in significantly lower yields than the optimum temperature. **D.** No significant differences in yield occurred between treated and untreated plants. Plants grown at 30.3 °C yielded significantly less than all but the treated plant at 29.0 °C.

Harvest Index. *Experiment I.* The harvest index of rice plants grown at the extreme temperatures was slightly less than that of the intermediate temperature treatments. The harvest index of treated and untreated plants was similar with the exception of those grown at 30.3 °C, where the untreated plants had a higher harvest index than the 1-MCP treated plants (Fig. E.2.10A).

Experiment II. The only significant difference in harvest index between treated and untreated plants occurred at 25.4 °C mean temperature where the untreated plants had a significantly greater harvest index. Harvest indices were significantly greater for the 27.3 °C and 28.1 °C than for the 28.9 °C and 30.0 °C plants. While the untreated plants at 25.4 °C were not significantly different from treated and untreated plants at 27.3 °C and 28.1 °C, the treated plants at this temperature were not significantly different from the 28.9 °C and 30.0 °C temperatures (Fig. E.2.10B).

Experiment III. There were no significant differences in the harvest index between treated and untreated plants. Plants grown at 22.8 °C mean temperature had significantly lower harvest indices than any other temperature. Plants grown at 32.2 °C mean temperature had significantly lower harvest indices than the remaining temperatures, among which there were no significant differences (Fig. E.2.10C).

Experiment IV. Harvest index tended to decline as mean temperature increased (Fig. E.2.10D). No significant differences in harvest index were found between treated and untreated plants at any temperature. Plants grown at 30.3 °C had a significantly lower harvest index than the plants grown at any other temperature.

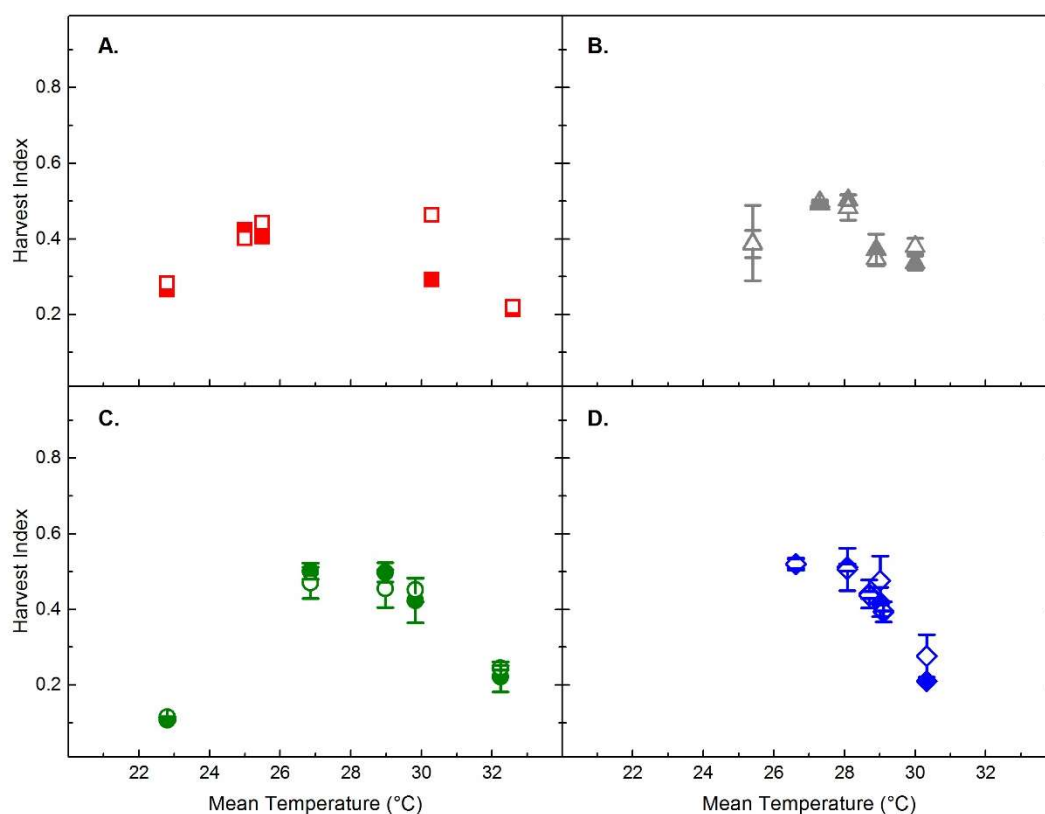


Fig. E.2.10. Rice Harvest Index. **A.** Harvest indices were similar between treated and untreated plants with the exception of the 30.3 °C mean temperature, where there was a much larger difference. Plants grown at cooler and warmer temperatures had lower harvest indices. **B.** Treated plants grown at 25.4 °C had a significantly higher harvest index than the UTCs. The two hottest treatments had significantly lower harvest indices than the two intermediate treatments. **C.** Plants grown at 22.8 °C mean temperature had the lowest harvest index. Plants grown at 32.2 °C mean temperature had lower harvest indices than the remaining temperatures. No significant 1-MCP treatment effects were observed for harvest index. **D.** Plants grown at 30.3 °C mean temperature had the lowest harvest index. No significant 1-MCP treatment effects were observed for harvest index.

E.2.3 Discussion

Experiment I. Rice plants grown at intermediate temperatures produced less total dry biomass than plants grown at temperature extremes. If these plants were truly stressed by temperature extremes, we would expect the opposite to occur. However, these two temperatures were harvested over ten days later than the other treatments because they did not look mature enough for harvest. This likely explains the increase in dry biomass when a decrease would have been the expectation. Treatment with 1-MCP produced no clear positive treatment effects.

No clear treatment 1-MCP treatment effect was evident for the distribution of biomass between stems, mature panicles and immature panicles. Rice grown at cooler and warmer temperatures, in general, contained a higher percentage of stem and immature biomass with less biomass found in mature panicles. This is indicative of a delay in maturity correlated with less- or more-than-optimal temperatures. Less than 10% of the biomass was contained in immature panicles with the remainder split fairly evenly between stems and mature panicles.

It took four days longer for the first panicles to emerge on plants grown at the hottest temperature (32.6 °C). In addition, it took as much as eight days longer for these plants, as well as those grown at the coolest temperature (22.8 °C), to reach 50 panicles per container. Eventually plants grown under all temperatures reached at least 150 panicles per container.

The number of panicles per container ranged from 239 to 577—more than a two-fold difference. This discrepancy seems to be explained by the combination of the fact

that the rice grown at the coolest and the warmest temperatures was harvested 11 days (117 DAP) and 12 days (118 DAP) later than the first harvests (106 DAP) occurred and the fact that extreme temperatures in either direction delay the maturity of rice. In other words, since the rice grown under these two temperatures appeared immature visually, harvest was delayed in order to allow time for maturation.

This conclusion is supported by the fact that, despite producing more panicles under cooler- or warmer-than-normal temperatures, a smaller percentage of these panicles were mature. Apparently, the plants continued to produce more panicles in addition to whatever maturation of existing panicles may have occurred. Temperatures either too warm or too cool seem to delay panicle maturity.

Temperature stress was again evident in the number of seeds per panicle. Mature panicles grown under cool or hot temperatures contained fewer seeds than those at intermediate temperatures. Mature panicles contained more seeds than immature panicles, which contained fewer than 10 seeds. This corroborates an accurate visual assessment of panicle maturity. No clear positive response due to 1-MCP can be seen.

The mass of a single seed decreased as temperature increased for seeds from both mature and immature panicles. Generally, seeds from immature panicles were 5 mg lighter than those from mature panicles. Though there were some differences in treated and untreated seeds, 1-MCP did not produce a consistent change in seed mass.

Yield also responded to temperature stress, with yield for plants grown under the coolest and the warmest temperature less than that of the remaining temperatures. No clear effects of 1-MCP on yield surfaced.

Harvest Index for this experiment ranged from about 0.2 to about 0.5. Harvest index was less for rice grown under temperature extremes than it was for rice grown at moderate temperatures. There were no important positive 1-MCP effects.

With the exceptions of total dry biomass and mass of a seed, temperature stress resulted in either a delay or a reduction (or, perhaps, a combination of the two) in the growth parameter measured. It is evident that the temperatures applied both cold stressed and heat stressed the rice plants. Total dry biomass actually increased with temperature stress in either direction, but, as discussed previously, this was likely due to a later harvest date than an actual biological response to temperature. The mass of a seed either was not affected as much by cold temperatures as it was by hot or seeds grew larger under cooler conditions while not growing as large under warmer conditions. Overall, there was no difference between rice treated with 1-MCP and the untreated controls.

Experiment II. Total dry biomass for this experiment decreased slightly as temperature increased. The response of biomass to temperature was more linear in this experiment than in Experiment I. There were no positive 1-MCP treatment effects on total dry biomass. Total biomass was slightly less overall for this experiment, but that is most likely because they were harvested nearly a week sooner than those in Experiment I (101 to 108 DAP versus 106 to 118 DAP).

A direct comparison of biomass distribution to the other experiments is impossible because panicles were not harvested separately and classified as mature or immature. However, the upper stem including the panicles accounted for at least 65% of the total biomass while the lower stem accounted for the remaining approximately 35%.

It is conceivable that subtracting immature panicle biomass and more stem biomass from the values for the upper stem could yield similar values to those observed in Experiment I.

Despite the fact that there was no a detectable difference in the appearance of the first panicles in Experiment II, plants grown at the two coolest temperatures initiated panicles more slowly during the period of temperature stress (fewer than 14 at 70 DAP), compared to more than twenty for those grown at 28.1 °C and 28.9 °C. During this period, plants grown at 30.0 °C mean temperature also had fewer panicles at 70 DAP (19 panicles) than those grown at 28.1 °C and 28.9 °C. Still, in the end, all of these containers produced at least 150 panicles.

The range of final panicle count for this experiment was 214 to 282. The smaller divergence in panicle count in this experiment is likely explained by two things. First, the harvests all occurred within one week (101 to 108 DAP). Second, after the initial stress period, the temperatures of all chambers was set to 30 °C day/25 °C night for the remainder of the experiment, resulting in a narrower range of mean temperatures than those in Experiment I (4.6 °C versus 9.8 °C).

Panicles were not classified at harvest in this experiment, but inferences may be possible based on other parameters as to the maturity of the rice at harvest in this experiment.

Though there were some positive 1-MCP treatment effects observed in the number of seeds per panicle, the trend was not consistent over the range of temperatures. Still, plants grown at extreme temperatures produced fewer seeds per panicle than those

at intermediate temperatures. There were at least 30 seeds in all panicles, with nearly 60 seeds in the panicles of rice grown at the intermediate temperatures. This indicates that a visual classification of mature and immature panicles would likely have been informative because it suggests that plants grown at extreme temperatures may have produced fewer mature panicles.

The mass of a seed from treated and untreated plants did not differ significantly with 1-MCP treatment. The mass of a seed was around 20 mg for rice grown under all temperatures, but an increase in temperature was correlated with a decrease in mass. Immature and mature panicles were not classified separately, but the mass of a seed in this experiment is similar to that from Experiment I. This similarity indicates that a majority of the panicles were mature because, had a large percentage of them been immature, it would likely have been reflected in a reduction of the average mass of a single seed.

The yield curve in response to temperature for this experiment was similar to that in Experiment I and actual yields were similar. Cool and hot temperatures reduced yield when compared to intermediate temperatures, as expected.

Harvest index was slightly improved in this study compared to the previous one. It ranged from 0.3 to 0.5. The harvest index was significantly better for 1-MCP treated plants grown at 25.4 °C than for untreated plants. However, this trend was not observed at other temperatures. Harvest index decreased as temperature increased or decreased from optimum temperatures.

In this experiment, temperature stress in either direction negatively impacted the growth parameters evaluated, with the exception of total dry biomass, panicles per container and mass per seed. Total dry biomass and mass per seed didn't seem to be affected by cold stress as much as by heat stress. Both parameters varied little, but decreased slightly as temperature increased. The explanation for this seeming lack of response most likely lies in the fact that the difference between the two most extreme mean temperatures was less than 5 °C. Even though there was an isolated instance where 1-MCP-treated plants were significantly improved, there was not a major overarching 1-MCP effect.

Experiment III. Overall, total dry biomass in this experiment was intermediate to that in Experiments I and II. This is again likely because of harvest dates. The biggest difference between this experiment and the first two is in the trend of total dry biomass. Opposite of Experiment I, biomass decreased slightly with increasing stress, though none of the differences were significant. No 1-MCP effects were detected.

The distribution of biomass was similar to that in Experiment I, but was more extreme. Plants grown at the hottest temperature had around 30% mature panicle biomass in both experiments, but plants grown at the coolest temperature in this experiment actually contained less mature panicle biomass than immature panicle biomass—a trend unique to this experiment. That being said, the delay in maturity mediated by temperature stress and the comparatively early harvest date likely explain this observation.

As in Experiment II, despite no noticeable difference in emergence of the first panicle, panicle emergence for the hottest (32.2 °C) and coolest (22.8 °C) rice plants was slower than those grown at more moderate temperatures, in some cases taking as many as 16 days longer to reach 50 panicles per container. At harvest, all containers produced at least 150 panicles.

Final panicle counts per container ranged from 167 to 375. Once again, there is a more than two-fold difference. The sustained temperature stress over the entire experiment partly explains this difference because of the delay in maturity it causes. At first the results of this experiment seem to contradict those of the Experiment I because the heat- or cold-stressed plants did not produce more panicles overall. However, since all rice was harvested within 5 days (110 to 114 DAP), rice delayed by either too cool or too warm of temperatures was not given the time to produce more panicles.

As before, fewer of the panicles on plants grown at 22.8 °C mean temperature were mature than panicles from plants grown at other temperatures. Rice grown at this temperature was harvested at 114 DAP—the last to be harvested in this experiment—but only about 10% of panicles were mature at harvest. Rice grown at 32.2 °C was less mature than rice grown at 29.0 °C and 29.8 °C but was more than 65% mature. Cold stress seems to have delayed maturity more than heat stress.

At 26.9 °C mean temperature, there were more seeds per immature panicle than for the other treatments. A corresponding decrease in seeds per mature panicle suggests that experimental error, rather than a temperature effect, is responsible for this deviation. Still, immature panicles contained fewer than 20 seeds, while mature panicles contained

at least 45. The number of seeds per panicle was similar for all but those rice plants grown under the highest temperatures. This indicates that extreme heat had more of an effect on seed set than extreme cool. There were no significant positive effects from 1-MCP.

In this experiment, the mass of a single seed from an immature panicle was about 5 mg less than that of a seed from a mature panicle, similar to Experiment I. The mass of a seed decreased as temperature increased for both immature and mature panicles. Still, there were no significant positive effects from 1-MCP treatment.

Yield at 26.9 °C and 29.0 °C was over three times greater than that at 22.8 °C and nearly double that at 32.2 °C. This large decrease in yield was likely due to a delay in maturity coupled with a reduction in the mass of a seed and the number of seeds per panicle. No significant 1-MCP effects were observed.

Harvest Index was very poor for plants grown at the coolest temperature (about 0.1). Harvest index for the middle three temperatures was near 0.5, while that for the hottest temperature was near 0.2. These significant differences in harvest index at extreme temperatures seem to be explained by maturity. As discussed previously, temperature-mediated delays coupled with too early of harvest date resulted in decreases in several measures of growth for the two extreme temperatures in this experiment. There were no differences in harvest index correlated with 1-MCP treatment.

With the exception of panicles per container and mass per seed, all measured parameters were negatively impacted by extreme temperatures. In this experiment some of the trends are exaggerated because of earlier harvest dates for similar temperatures

than in other experiments. Nevertheless, the effects of cold and heat stress can readily be seen. The number of panicles per container seemed to be either more affected by heat stress than cold stress or cold stress positively affected the number of panicles while heat stress negatively impacted panicle count. The same seems to hold true for the mass of a seed.

At first glance, there appears to be a positive 1-MCP effect in the rate of panicle emergence for the 26.9 °C mean temperature treatment. Panicles emerged more quickly for treated plants than for the untreated controls and the panicle count was significantly greater between 10 and 89 days after planting. However, overall yield was not different and other harvest measures for this temperature were similar. Accordingly, even if there were a positive 1-MCP treatment effect, it did not translate into an increase in yield upon harvesting.

Experiment IV. Overall total dry biomass in this experiment was similar to that in Experiments II and III (around 600 g). Biomass decreased slightly with decreasing temperature and even more with increasing temperature. No significant 1-MCP effects were observed.

Biomass distribution was about 60% stems and 40% mature panicles with very little biomass found in immature panicles at 26.7 °C and 28.1 °C. As temperature increased, immature panicle biomass and stem biomass increased, while mature panicle biomass decreased. At 30.3 °C, mature panicle biomass was just above 20% with immature panicle biomass approaching 15%. The delay in maturity caused by temperature stress most likely explains these trends because this hottest temperature

treatment was harvested at 123 DAP, which should have provided ample time for maturation.

The acute stress applied for 14 days during this experiment brought out an interesting trend. Plants grown at the hottest temperature (30.3 °C) had a similar number of panicles to other chambers at 75 DAP, but comparatively few additional panicles emerged from 75 DAP to 91 DAP (15 additional, on average, compared to a maximum of 48 for plants grown at 29.0 °C). In fact, plants grown at 30.3 °C didn't reach 50 panicles per container until 16 days after temperature stress was relieved. Though not as extreme, a similar trend can be observed for the plants grown at the two coolest temperatures. Eventually, all containers reached at least 150 panicles.

The range in panicle count for this experiment was 161 to 360, which is very similar to that of Experiment III despite the fact that the temperatures were different. However, the shape of the graph is much different. Given the extra days, rice grown at intermediate temperatures (28.1 °C and 28.7 °C) produced similar panicle counts to rice grown at intermediate temperatures (25.0 °C, 25.5 °C and 30.3 °C) in Experiment I. Harvest dates do not seem to explain this trend. It may be that all of the rice grown in this experiment was delayed because of the initial stress temperatures. The initial stress in this experiment was more extreme, but was relieved after 14 days while the stress in Experiment I was not relieved.

All rice in this experiment was at least 65% mature, except that grown at 30.3 °C mean temperature, which was only around 40% mature.

Once again, rice grown at the hottest mean temperature produced fewer seeds per mature panicle than the other temperatures. This trend did not occur with the coolest treatment, which provides more evidence that heat stress affects seed set more than cold stress. However, more factors are involved in seed set than just temperature. In this experiment, the rice grown at the hottest temperature was also late to mature, which would affect seed set. It appears that experimental error more likely explains the increase in seeds per immature panicle observed at 29.8 °C than a temperature or treatment effect. Most mature panicles contained 50 to 80 seeds while immature panicles contained fewer than 30, on average. No clear effect of 1-MCP treatment is apparent.

The mass of a single seed decreased as temperature increased. However, in this experiment, the mass of a seed from a mature panicle was relatively constant and then decreased for the two hottest temperatures rather than steadily decreasing. The mass of a seed from an immature panicle remained relatively constant at about 15 mg. The mass of a seed from both immature and mature panicles was similar to that from the other experiments. No significant 1-MCP effects were observed.

Similar to Experiment III, yield at the hottest temperature was one third of that at more moderate temperatures. No significant difference in yield occurred based on 1-MCP treatment.

Harvest index remained similar over the first two temperatures and then decreased as temperature increased. Harvest index for the hottest treatment was just over 0.2, while the harvest index of the other treatments was between 0.4 and 0.5. This indicates a

reduction in grams of yield per gram of dry biomass correlated with increasing temperature stress.

The response of growth parameters to temperature was somewhat different in this experiment. This is most likely because of the severity of the temperature stress. All parameters responded negatively to increased heat stress. There seemed to be no corresponding response to cold stress which makes sense when comparing the mean temperatures in this study to that in the others. The lowest mean temperature in this study was 26.6 °C, which is more similar to the intermediate temperatures in the other experiments. The mean cold temperatures that produced responses in other experiments were in the low 20s.

E.2.4 Synthesis

With the exception of Experiment I, where total biomass was greater for heat- or cold-stressed plants than those at more moderate temperatures, temperatures higher or lower than the optimum range resulted in a slight reduction in total biomass. Overall total dry biomass was approximately 600 g for all treatments and temperatures in all experiments (Fig. E.2.11). This metric seemed to be relatively unaffected by temperature stress. The accumulation of days after planting seemed to be more influential on total biomass than temperature.

We would expect that a greater percentage of the total biomass would be found in mature panicles as the rice plants mature. Thus, the distribution of biomass could be used as an indicator of maturity. A high temperature-induced delay in maturation is evident in all of the experiments, but is particularly evident in Experiment IV for the highest level of

heat stress. Despite having the longest growing season, the rice produced at this temperature still contained a significantly lower percentage of mature panicle biomass than any other temperature. This delay in maturation was not limited to heat stress, because the coldest treatment in Experiment III actually resulted in a greater percentage of immature panicle biomass than of mature panicle biomass, though this trend was likely exaggerated by the comparatively early harvest date. However, around 50% of the biomass for the intermediate treatments in that experiment was found in mature panicles, which is evidence of a temperature-mediated delay in maturation (Fig. E.2.12).

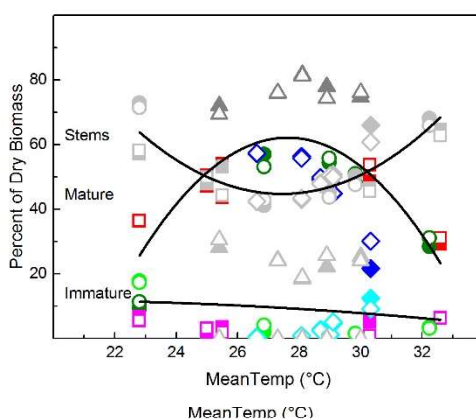


Fig. E.2.12. Rice Combined Biomass Distribution. When mature, the immature panicle biomass was near zero and both the stem and mature panicle biomass were around 50%. When immature, stem biomass and immature panicle biomass increased at the expense of mature panicle biomass. (Trend lines added for ease of interpretation.)

Heat and cold stress are also evident in the rate of panicle initiation. In some cases, the first panicles appeared later when temperatures were extreme, and, in other cases, the number of days required to reach 50 panicles per container was greater for extreme temperatures. It is evident that other-than-optimal temperatures will result in some combination of a delay in the appearance of the first panicles and the rate of panicle

initiation thereafter. Eventually the rice from all temperatures, treatments and experiments contained over 150 panicles per container, indicating that eventually typical panicle numbers will develop even under less-than-ideal conditions (Fig. E.2.13).

The fact that rice, if allowed more days to grow, is capable of sustained panicle initiation when conditions are favorable. In Experiment I, an extra 12 days resulted in more than a two-fold increase in the number of panicles per container. Environmental factors likely played a role in this increase in panicles, however, because it is unlikely that the number of panicles doubled in the last 12 days of the growing season. Perhaps this increase can be explained by a response to temperature where conditions delayed maturity so new panicles continued to emerge. The range in panicle count was much less when mean temperatures and harvest dates were more similar as in Experiment II. In Experiments III and IV the trend was similar to Experiment I with the exception that the rice was harvest over a much shorter period, resulting in more similar panicle counts in Experiment III, while more extreme temperature stress in Experiment IV resulted in greater variation in the number of panicles.

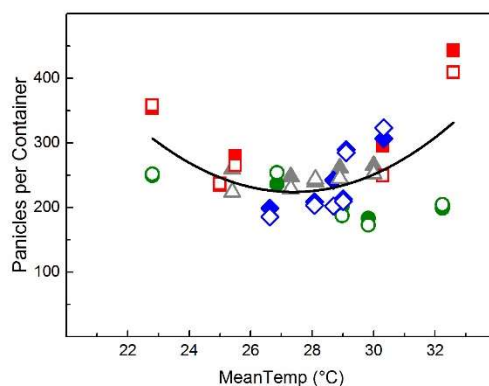


Fig. E.2.13. Rice Combined Total Panicles. Generally, there were between 200 and 300 panicles per container. When harvest was later, panicle count increase to near 500 in some cases.

Further evidence of the effects of extreme temperatures on rice maturation and development is found in the percentage of panicles that had matured at harvest. Temperatures higher- or lower-than the optimum range resulted in a smaller percentage of mature panicles, assuming similar harvest dates. This is particularly evident in Experiment III, where similar harvest dates resulted in approximately 10% of panicles being mature for the coldest temperature while more than 60% of the panicles were mature for all of the other temperatures (Fig. E.2.14).

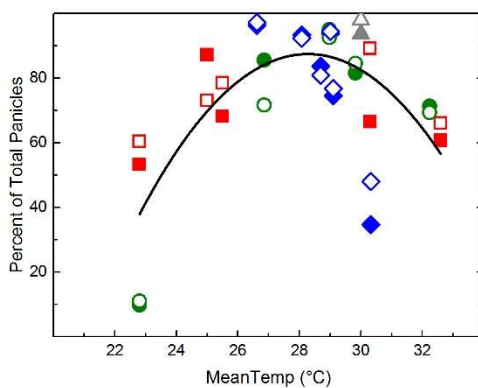


Fig. E.2.14. Rice Combined Mature Panicles. When grown at extreme temperatures, the percentage of mature panicles decreased, assuming that growth periods were equal. In the optimum temperature range at least 70% of the panicles were mature at harvest.

The number of seeds per mature panicles was always greater than that for immature panicles at the same mean temperature. This provides evidence that, not only was a visual classification of panicles as mature or immature informative, it was also fairly accurate. The number of seeds per panicle, whether mature or immature, declined as temperatures became more extreme in either direction (Fig. E.2.15).

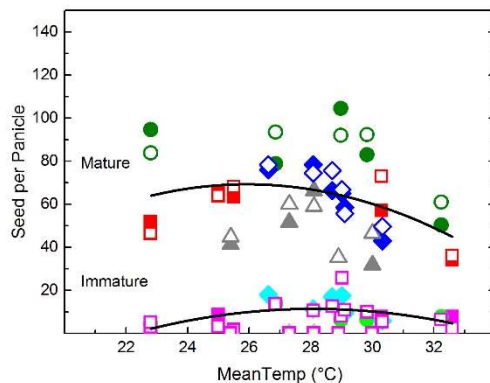


Fig. E.2.15. Rice Combined Seeds per Panicle. Mature panicles in all experiments contained around 60 seeds, while immature panicles contained fewer than 20. Under identical conditions, immature panicles always contained significantly fewer seeds than did mature panicles.

It is clear that the mass of an individual seed was affected by temperature.

However, the trend lines of this parameter were linear rather than parabolic as they were for most of the other parameters. Seeds from rice grown at cooler temperatures had larger seeds while rice grown from warmer temperatures had smaller seeds in all experiments, whether the seed was from mature or immature panicles. Seed from immature panicles was generally about 5 mg smaller than that of mature panicles from corresponding temperatures (Fig. E.2.16).

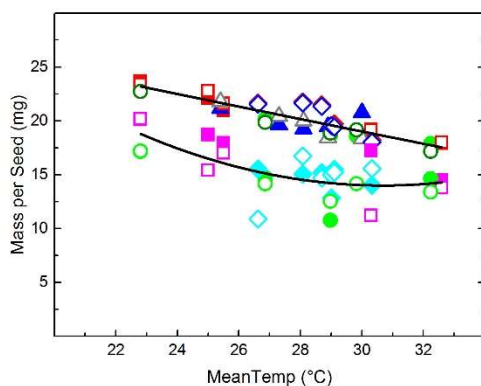


Fig. E.2.16. Rice Combined Mass per Seed. For both mature and immature panicles, the mass of a single seed decreased as temperature increased. Seeds from immature panicles weighed about 5 mg less than those from mature panicles in all experiments.

Temperature stress also resulted in a decrease in yield. Yield was reduced as temperatures deviated from the optimum range. Extreme heat stress such as the 40 day/30 day in Experiment IV resulted in significantly reduced yield (one third of the yield obtained in the optimum temperature range) (Fig. E.2.17).

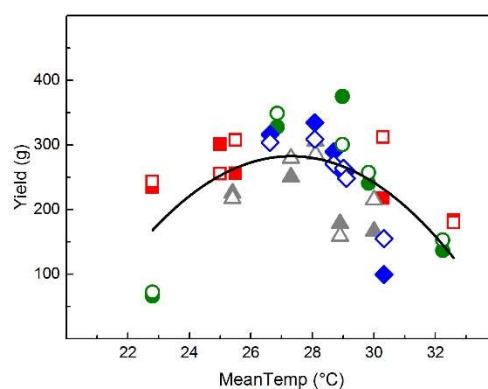


Fig. E.2.17. Rice Combined Yield. Yield was generally above 200 g per container. When cold or heat-stress, yield reductions occurred. When grow in the optimal temperature range, yield approached 300 g.

Harvest index followed similar trends to yield, as would be expected. Extreme cold stress (Experiment III) and extreme heat stress (Experiments III and IV) resulted in greatly reduced harvest indices (Fig. E.2.18). Rice grown within the optimal temperature range generally had a harvest index of 0.5, which is comparable to the suggested value suggested by Yoshida (1977).

Under the conditions tested and at the rates applied, 1-MCP produced no significant positive effects on Ai Nan Tsao rice.

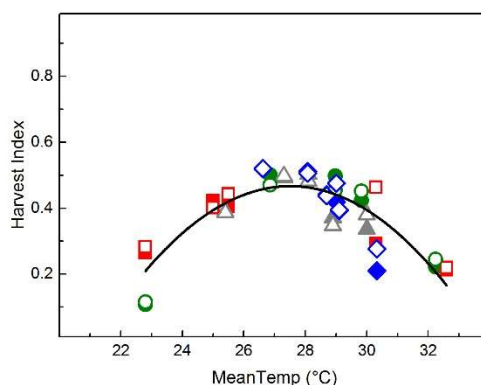


Fig. E.2.18. Rice Combined Harvest Index. Under optimal temperatures, the harvest index was about 0.5, comparable to good field-grown rice. As temperature increased or decreased so did harvest indices.

E.3 Transplant Shock Experiments

E.3.1 Materials and Methods

For each experiment, Seeds of Ai Nan Tsao rice were germinated on blotter paper then transplanted into 6 o 6s with soilless media. Plants were watered with 50 ppm nitrogen fertilizer solution daily for 3 weeks. After three weeks, stresses were applied as described within each dated subsection. All plants were placed into soggy soilless media in a 10 cm by 10 cm by 10 cm white plastic container. A plastic bag was placed around the entire container and tied around the rice plant stem to reduce evaporation from the soil surface to as near zero as possible. The excess bag was trimmed off. A white paper “hat” was placed over around the stem of each rice plant and over the pot to reduce the radiation heat load on the container.

Treated plants were sprayed at a rate of 144 g of AI/Acre and allowed to remain in the chamber. After 20 minutes, they were removed and allowed to air dry before being placed back into the growth chamber.

Initially, each leaf of each plant was measured using the rim of the container as the reference. Each subsequent measurement was taken in like manner and the leaf elongation rate (LER) was determined. The initial mass of each container was taken and subsequent mass measurements used to determine the transpiration rate of each plant.

To prevent water stress from dry media, the amount of water transpired was replaced using a syringe when transpiration totals approached 250 grams.

Multiple 1-MCP Sprays, Soilless Media to Soilless Media. *16 July 2014.* Rice plants were removed from the 6 packs and the **entire rootball was planted intact**. Sixteen plants were placed in each of three chambers and subjected to “cool” (23 °C day/18 °C night), “optimal” (30 °C day/25 °C night) or “hot” (35 °C day/30 °C night) temperatures. Half of the plants (4) from each temperature were **treated with 1-MCP each day for 4 consecutive days**. Plants were **grown for 5 days**.

21 July 2014. Plants were removed from the 6 packs and the **entire rootball was dried overnight then planted intact**. Sixteen plants were placed in each of three chambers and subjected to “cool” (23 °C day/18 °C night), “optimal” (30 °C day/25 °C night) or “hot” (35 °C day/30 °C night) temperatures. Half of the plants from each temperature were **treated with 1-MCP each day for 4 consecutive days**. Plants were **grown for 8 days**.

29 July 2014. Rice plants were removed from the 6 packs and **half of the rootball was removed, dried overnight and planted.** Sixteen plants were placed in each of three chambers and subjected to “cool” (23 °C day/18 °C night), “optimal” (30 °C day/25 °C night) or “hot” (35 °C day/30 °C night) temperatures. Half of the plants from each temperature were **treated with 1-MCP each day for 4 consecutive days.** Plants were **grown for 6 days.**

5 August 2014. Plants were removed from the 6 packs and the **entire rootball was planted intact.** Sixteen plants were placed in each of three chambers and subjected to “cool” (23 °C day/18 °C night), “optimal” (30 °C day/25 °C night) or “hot” (35 °C day/30 °C night) temperatures. Half of the plants from each temperature were **treated with 1-MCP each day for 3 consecutive days.** Plants were **grown for 6 days.**

25 September 2014. Rice plants were removed from the 6 packs and **67% of the rootball was removed.** Sixteen plants were placed in each of three chambers and subjected to “cool” (23 °C day/18 °C night), “optimal” (30 °C day/25 °C night) or “hot” (35 °C day/30 °C night) temperatures. Half of the plants from each temperature were **treated with 1-MCP each day for 4 consecutive days.** Plants were **grown for 6 days.**

2 October 2014. Plants were removed from the 6 packs and **67% of the rootball was removed and the rootball dried in a diaper** until plants began to wilt (about 3 hours). Sixteen plants were placed in each of three chambers and subjected to “cool” (23 °C day/18 °C night), “optimal” (30 °C day/25 °C night) or “very hot” (**40 °C day/35 °C night**) temperatures.

Half of the plants from each temperature were **treated with 1-MCP each day for 4 consecutive days**. Plants were **grown for 6 days**.

25 October 2014. Rice plants were removed from the 6 packs and **67% of the rootball was removed and the rootball dried in a diaper** until they started to wilt. Sixteen plants were placed in each of three chambers and subjected to “cool” (23 °C day/18 °C night), “optimal” (30 °C day/25 °C night) or “hot” (35 °C day/30 °C night) temperatures.

Half of the plants from each temperature were **treated with 1-MCP each day for 4 consecutive days**. They were sprayed at a rate of 144 g of AI/Acre and allowed to remain **in the chamber overnight** before being returned to the growth chambers. Plants were **grown for 6 days**.

Dipped in 1-MCP, Calcined Clay to Soilless Media. Seeds of Ai Nan Tsao rice were germinated on blotter paper then transplanted to flats of calcined clay (Profile). Plants were watered with 50 ppm nitrogen fertilizer solution daily. After 3 weeks, the rice roots were carefully removed from the calcined clay, rinsed and treated as described under each date subheading. The bare roots were then transplanted into a 10 cm by 10 cm by 10 cm container filled with soggy soilless media. The entire container was placed into a plastic bag and the bag was tied around the rice plant stem to reduce evaporation from the soil surface to as near zero as possible. Initially, each leaf of each plant was measured using the rim of the container as the reference. Each subsequent measurement was taken in like manner and the leaf elongation rate (LER) was determined. The initial

mass of each container was taken and subsequent mass measurements used to determine the transpiration rate of each plant.

12 August 2014. The **bare roots were dipped once in a solution of 3.6 g/L 1-MCP** Sixteen plants were placed in each of three chambers and subjected to “cool” (23 °C day/18 °C night), “optimal” (30 °C day/25 °C night) or “hot” (35 °C day/30 °C night) temperatures. Plants were **grown for 6 days**.

19 August 2014. Rice **roots were clipped** approximately 3” from the base of the plant, then **dipped once in a solution of 3.6 g/L 1-MCP**. Sixteen plants were placed in each of three chambers and subjected to “cool” (23 °C day/18 °C night), “optimal” (30 °C day/25 °C night) or “hot” (35 °C day/30 °C night) temperatures. Plants were **grown for 6 days**.

26 August 2014. **Bare roots were clipped** approximately 3” from the base of the plant and **air dried overnight**. They were then **dipped once in a solution of 3.6 g/L 1-MCP**. Sixteen plants were placed in each of three chambers and subjected to “cool” (23 °C day/18 °C night), “optimal” (30 °C day/25 °C night) or “hot” (35 °C day/30 °C night) temperatures. Plants were **grown for 6 days**.

2 September 2014. The **roots were rinsed** with tap water then **dried in a diaper** until they started to wilt and **dipped once in a solution of 3.6 g/L 1-MCP**. Sixteen plants were placed in each of three chambers and subjected to “cool” (23 °C day/18 °C night), “optimal” (30 °C day/25 °C night) or “hot” (35 °C day/30 °C night) temperatures. Plants were **grown for 6 days**.

9 September 2014. Bare **roots were clipped** approximately 3” from the base of the plant, **dried in a diaper** until they started to wilt and then **dipped once in a solution of 3.6 g/L 1-MCP**. Sixteen plants were placed in each of three chambers and subjected to “cool” (23 °C day/18 °C night), “optimal” (30 °C day/25 °C night) or “hot” (35 °C day/30 °C night) temperatures. Plants were **grown for 6 days**.

Hydroponic Solution with 3.6 g/L 1-MCP. *3 September 2014.* Seeds of Ai Nan Tsao rice were germinated in rag dolls then transplanted to hydroponic container culture. 1-MCP was added to the stock **hydroponic solution at a rate of 3.6 g/L**. Containers were placed in growth chambers and subjected to either “optimal” (30 °C day/25 °C night) or “hot” (35 °C day/30 °C night) temperatures.

Initially, each leaf of each plant was measured using the rim of the container as the reference. Each subsequent measurement was taken in like manner and the leaf elongation rate (LER) was determined. The initial mass of each container was taken and subsequent mass measurements used to determine the transpiration rate of each plant. Plants were **grown for 13 days**.

Hydroponic Study—Aerenchyma. *17 September 2014.* Seeds of Ai Nan Tsao rice were germinated in rag dolls then transplanted to **hydroponic culture**. **No 1-MCP** was added to the solution. One container was aerated and the other was not.

Initially, each leaf of each plant was measured using the rim of the container as the reference. Each subsequent measurement was taken in like manner and the leaf elongation rate (LER) was determined. Plants were **grown for 23 days**.

Stress Level Quantification Experiments. Due to the apparent resiliency of rice transplants, comparisons of the level of stress induced by the different treatments needed to be quantified. For the following three experiments rice seeds were started and transplanted into soilless media as before. At three weeks, they were transplanted into soilless media. **No 1-MCP was applied.**

15 December 2014. Twelve rice plants were transplanted from cell packs into soilless media with rootballs intact. Twelve more rice plants were removed from cell packs and **67% of their rootball was removed** before transplanting into soilless media. **No 1-MCP** was applied. Four of each treatment were placed into growth chambers and subjected to either “optimal” (30 °C day/25 °C night) or “hot” (35 °C day/30 °C night) temperatures. Plants were grown for 6 days.

6 January 2015. Identical to the 15 December 2014 study except that the rootballs were not cut, but were **dried in a diaper** for until they started to wilt before transplanting. Plants were **grown for 6 days.**

10 February 2014. The treatments in this experiment were a combination of the previous two treatments. **Two thirds of the rootball** of half the plants were **removed** and then **dried in a diaper** until they started to wilt.

Follow-Up Studies. Because of the differences in transpiration rates between treated and untreated plants in the 9 September 2014 study, three other studies were conducted to attempt to duplicate the results. Rice seeds were started as before, transplanted to cell packs in soilless media and grown until three weeks old. LER was

not determined for these studies because of the large labor input. Transpiration rates were measured every other day.

31 March 2015. Twelve rice plants were removed from the 6 packs and **half of the rootball was removed and planted**. Four of these plants were not treated. Four of these plants were **treated with 1-MCP each day for 4 consecutive days**, while the last four plants were **treated with 1-MCP once**. Another four plants were transplanted intact to make an untreated control group for a total of 16 plants. These 16 plants were placed in a growth chamber and subjected to 40 °C day/35 °C night temperatures. Then the procedure was repeated and placed in a chamber at 40 °C day/40 °C night temperatures. Plants were **grown for 6 days**.

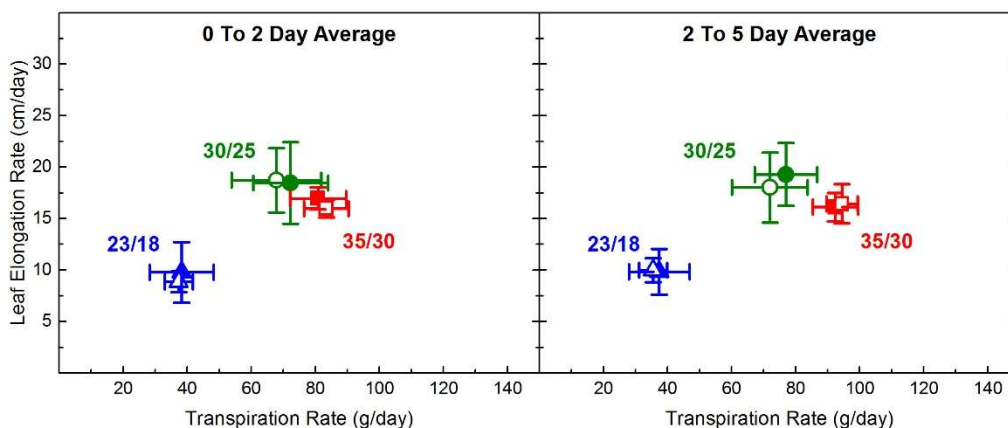
7 April 2015. The study from 31 March 2015 was repeated, but the daily treatment of 1-MCP was excluded. Five untreated control plants and ten plants with **half of the rootball removed** were planted. Half of the plants whose rootballs had been removed were **treated with 1-MCP once**. These 15 plants were placed in a growth chamber and subjected to 40 °C day/35 °C night temperatures. The procedure was then repeated and placed in a chamber at 40 °C day/40 °C night temperatures. Plants were grown for 6 days.

14 April 2015. This study was identical to the study from 7 April 2015, but 15 plants were placed in a growth chamber and subjected to 38 °C day/33 °C night temperatures. The procedure was then repeated and placed in a chamber at 35 °C day/30 °C night temperatures. Plants were **grown for 6 days**.

21 April 2015. The study from 14 April 2015 was duplicated, with the exception that instead of transplanting into soilless media, the rice plants were **transplanted into sandy loam top soil**. Five untreated control plants and ten plants with half of the rootball removed were planted. Half of the plants whose rootballs had been removed were **treated with 1-MCP once**. These 15 plants were placed in a growth chamber and subjected to 40 °C day/35 °C night temperatures. The procedure was then repeated and placed in a chamber at 40 °C day/40 °C night temperatures. Plants were **grown for 6 days**.

E.3.2 Results

Multiple 1-MCP Sprays, Soilless Media to Soilless Media. 16 July 2014. No significant differences in transpiration or LER occurred at any temperature in this study (Fig. E.3.1).



16 July 2014
 Transplanted whole rootball
 Spayed with 1-MCP 4 times
 Grown for 5 days

Fig. E.3.1. Multiple 1-MCP sprays: 16 July 2014.

21 July 2014. Some small differences in LER and transpiration rate occurred at 35/30 from transplant to 3 days after, but differences were not significant (Fig. E.3.2).

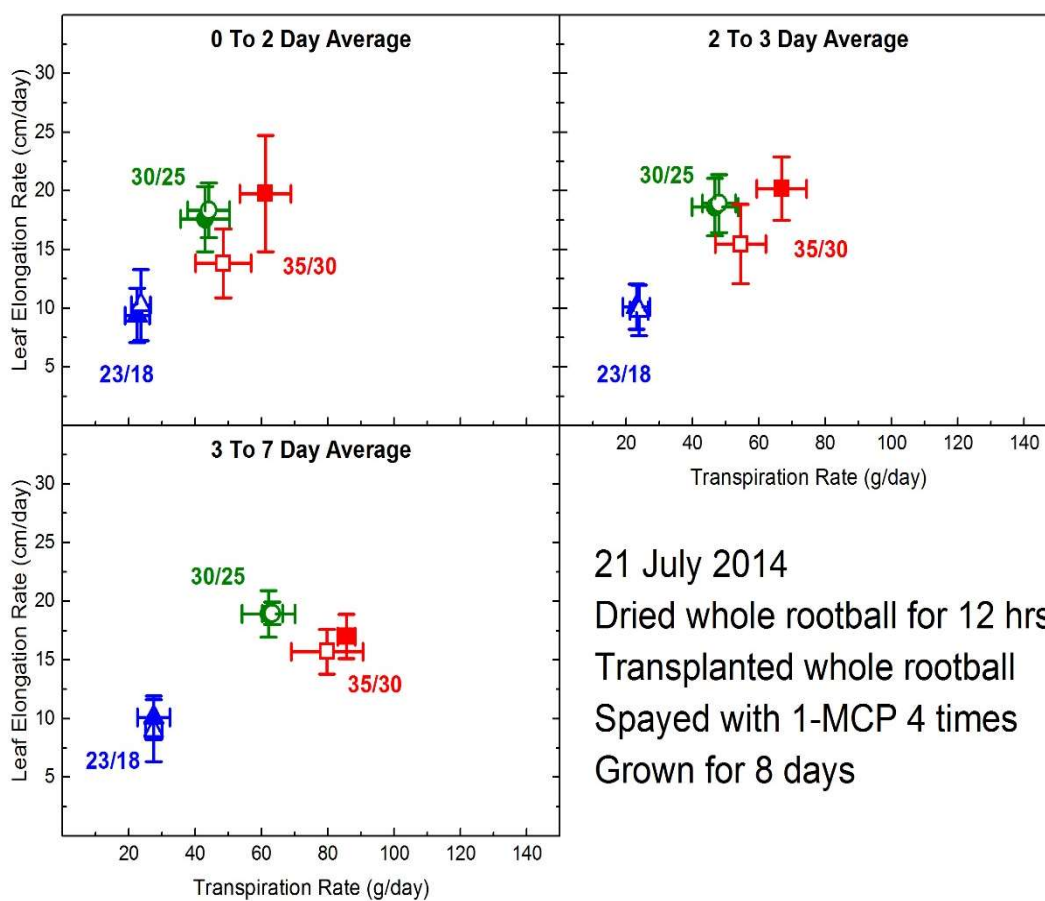


Fig. E.3.2. Multiple 1-MCP sprays: 21 July 2014.

29 July 2014. No significant difference in LER or transpiration rate was found at any temperature or for any time-frame in this experiment (Fig. E.3.3).

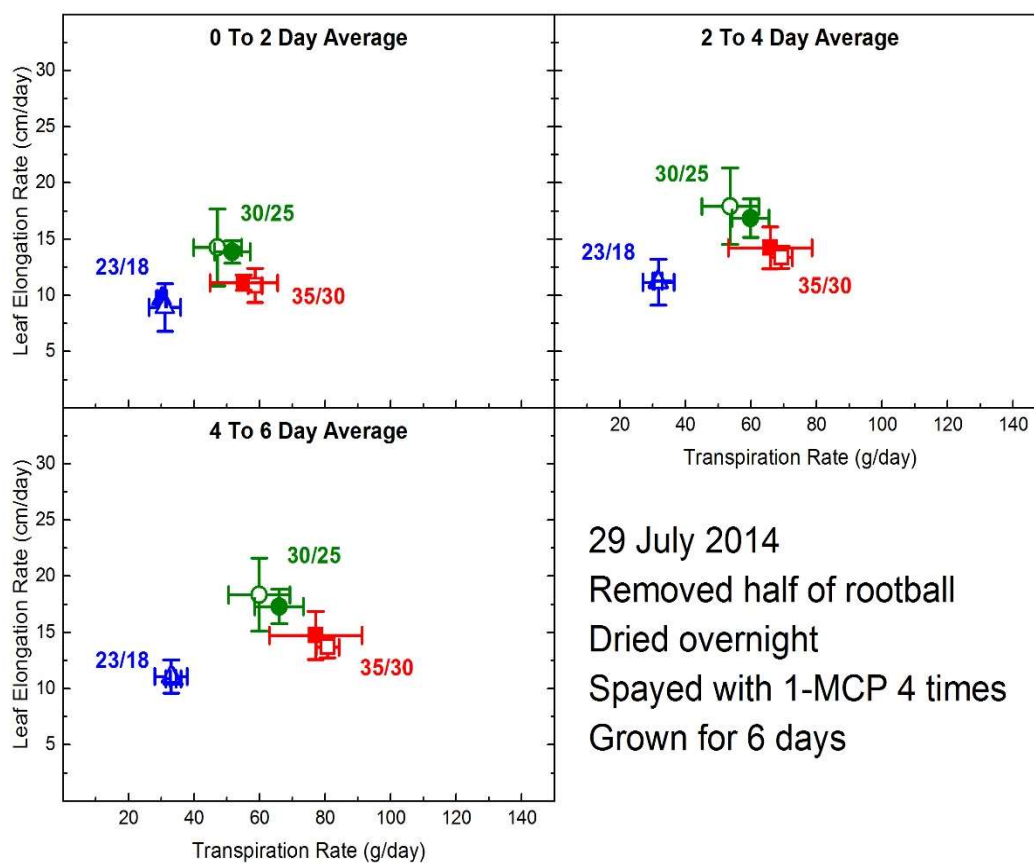


Fig. E.3.3. Multiple 1-MCP sprays: 29 July 2014.

5 August 2014. LER nor transpiration rate differed significantly during this experiment for any temperature (Fig. E.3.4).

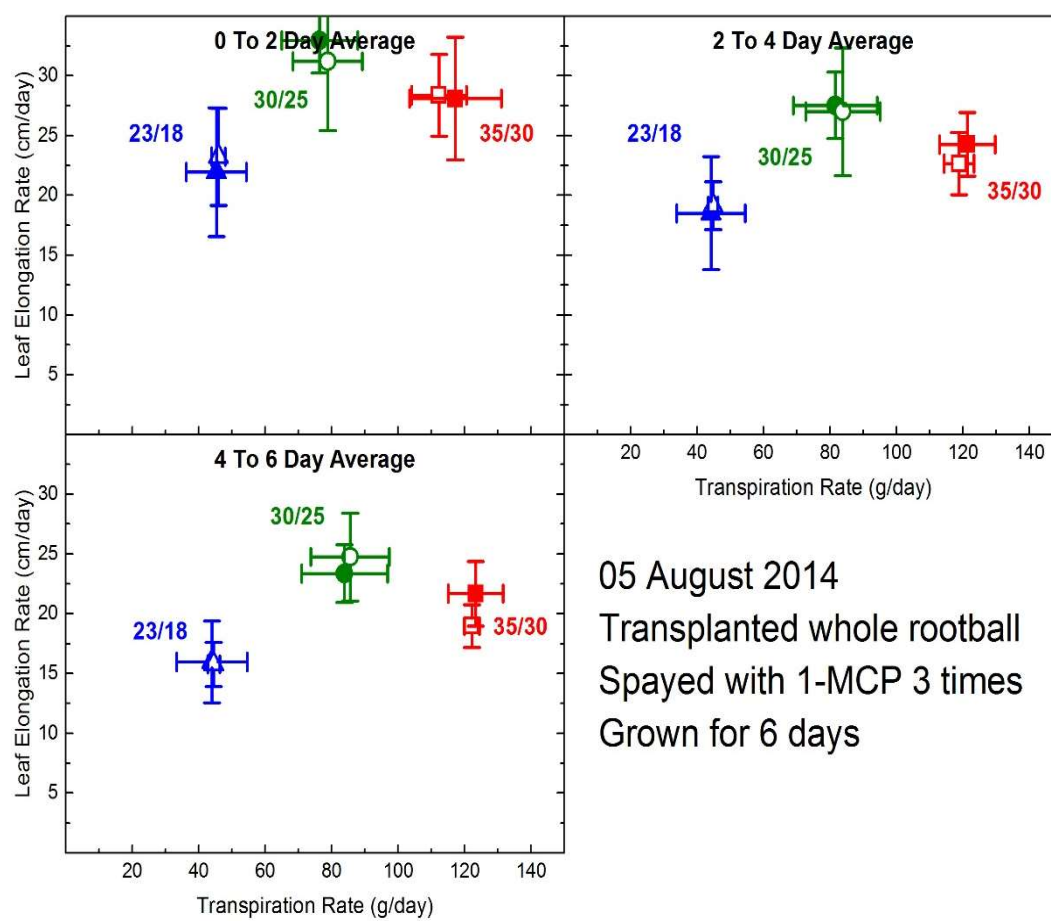


Fig. E.3.4. Multiple 1-MCP sprays: 5 August 2014.

25 September 2014. While a significant difference in LER occurred for the 35/30 over the first two days after transplanting, the difference did not persist. It was also not accompanied by a corresponding difference in transpiration rate. (See Fig. E.3.5).

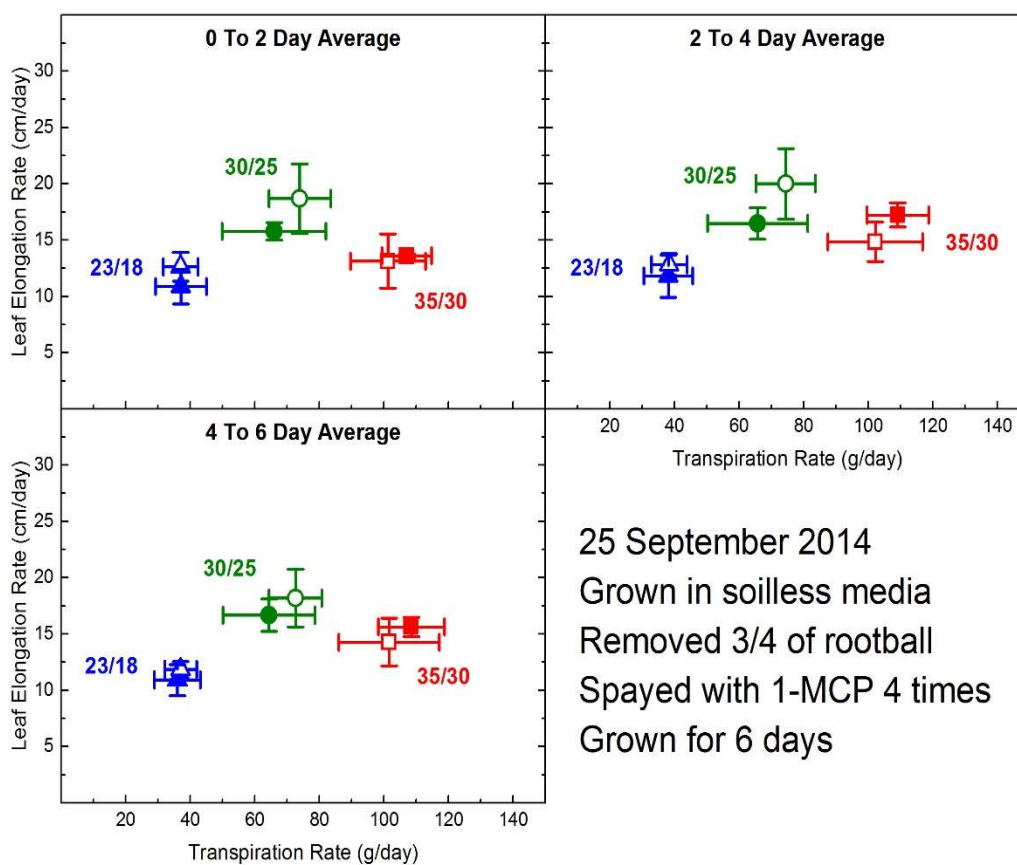


Fig. E.3.5. Multiple 1-MCP sprays: 25 September 2014.

2 October 2014. Some differences in transpiration and LER occurred in the very hot treatments over the course of the experiment, but were not statistically significant. For the cool and warm treatments, no differences were observed (Fig. E.3.6).

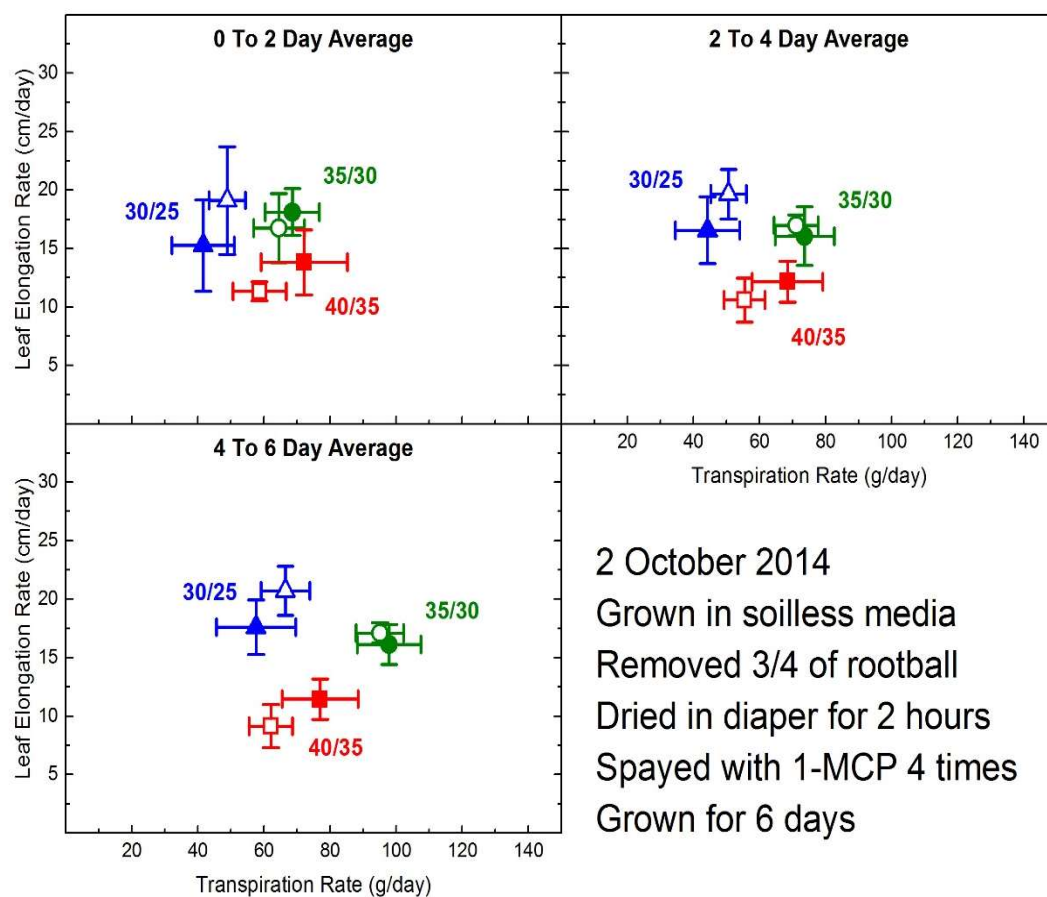


Fig. E.3.6. Multiple 1-MCP sprays: 2 October 2014.

25 October 2014. No significant differences occurred between treatments for any temperature in this experiment (Fig. E.3.7).

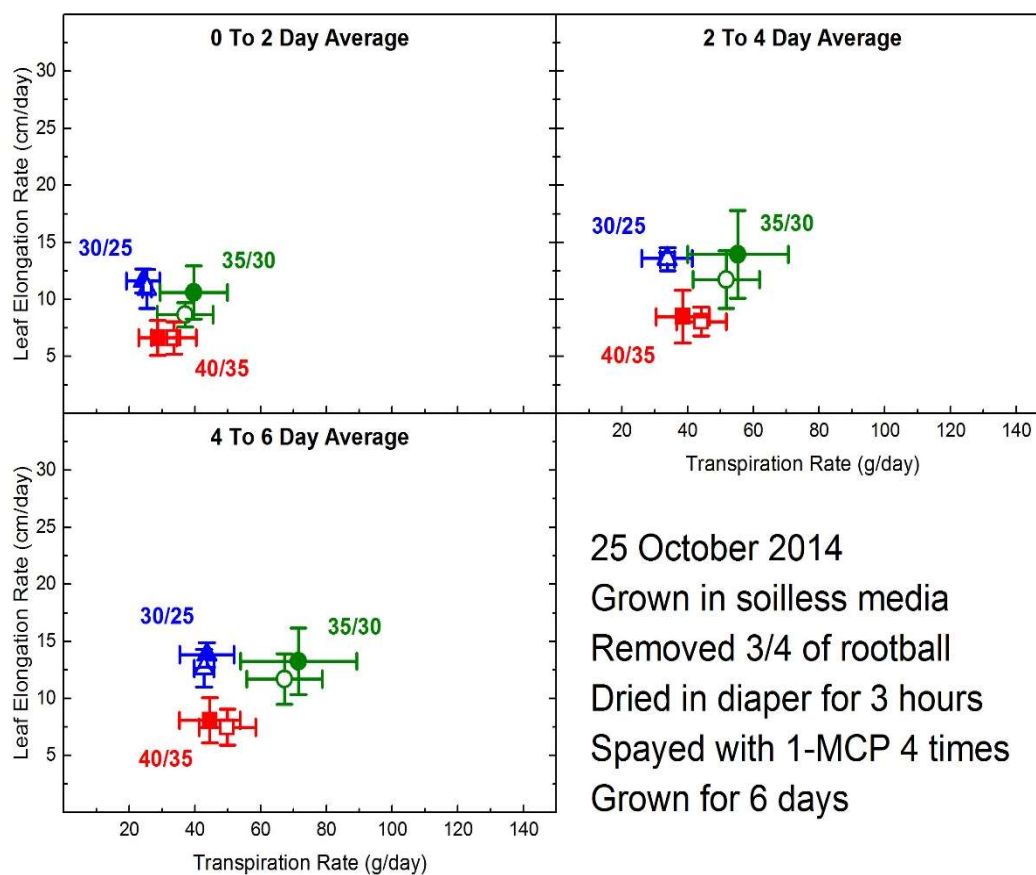


Fig. E.3.7. Multiple 1-MCP sprays: 25 October 2014.

Dipped in 1-MCP, Calcined Clay to Soilless Media. 12 August

2014. Responses for treated and untreated plants were similar throughout this experiment (Fig. E.3.8).

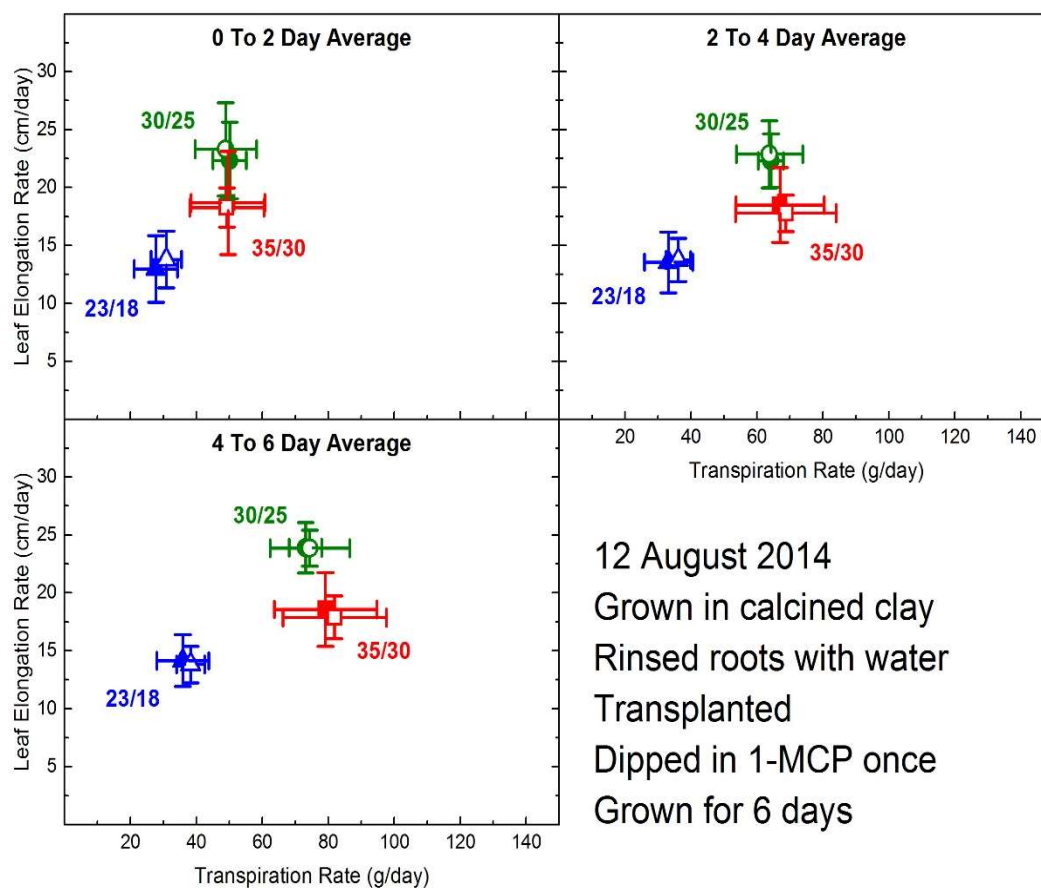


Fig. E.3.8. Roots dipped in 1-MCP: 12 August 2014.

19 August 2014. No significant differences in LER or transpiration rates occurred for any temperature in this experiment (Fig. E.3.9).

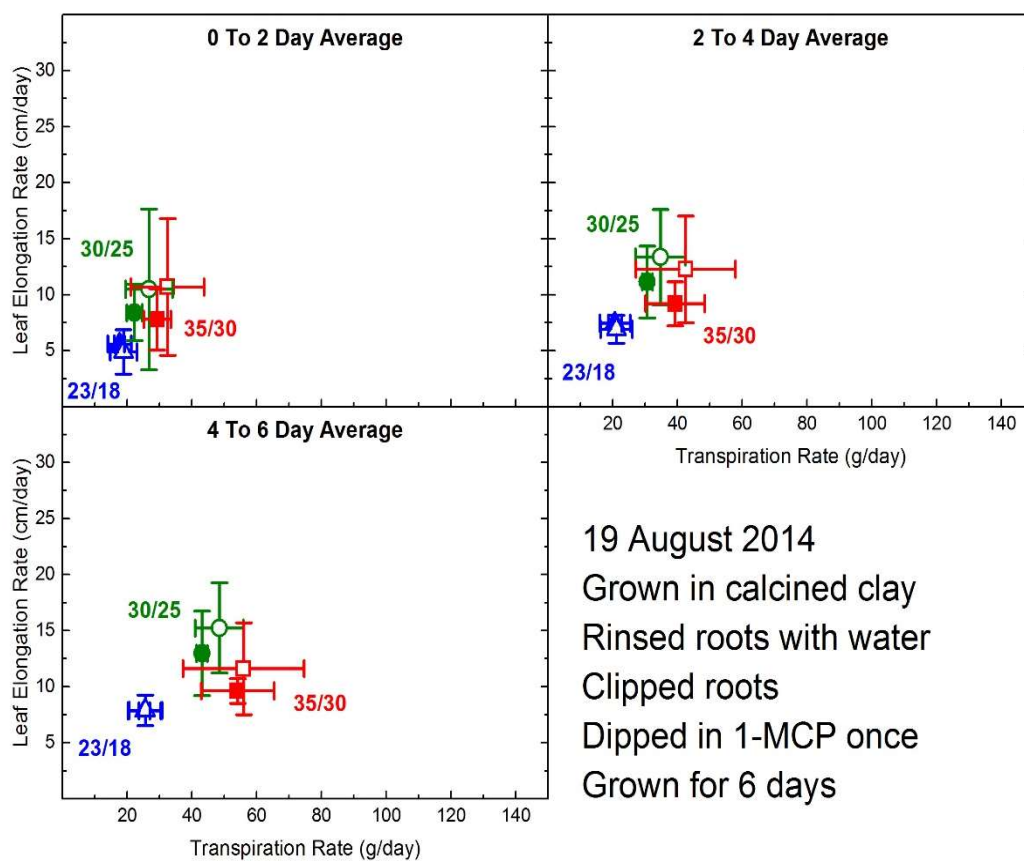
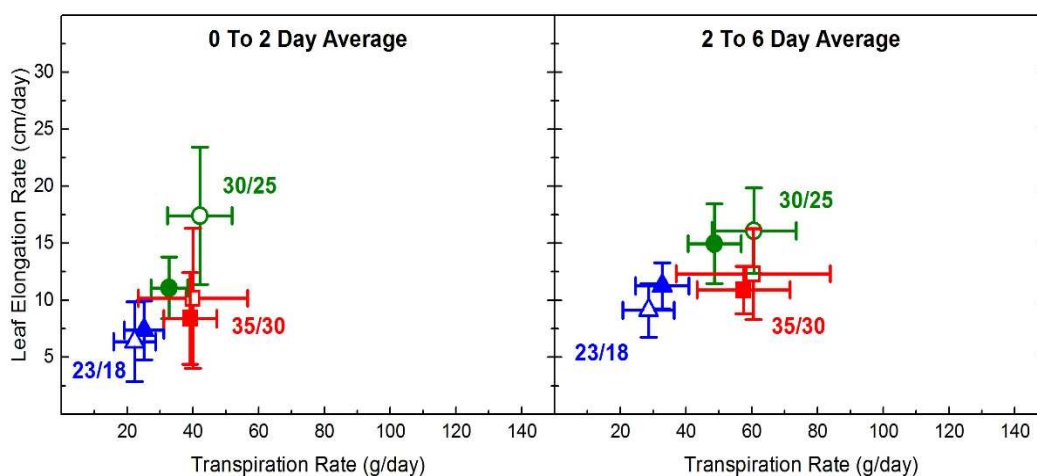


Fig. E.3.9 Roots dipped in 1-MCP: 19 August 2014.

26 August 2014. No significant differences were found in this experiment between treated and untreated rice plants (Fig. E.3.10).



26 August 2014
 Grown in calcined clay
 Rinsed roots with water
 Clipped and dried roots
 Dipped in 1-MCP once
 Grown for 6 days

Fig. E.3.10. Roots dipped in 1-MCP: 26 August 2014.

2 September 2014. No significant difference occurred between treated and untreated rice plants at any of the temperature (Fig. E.3.11).

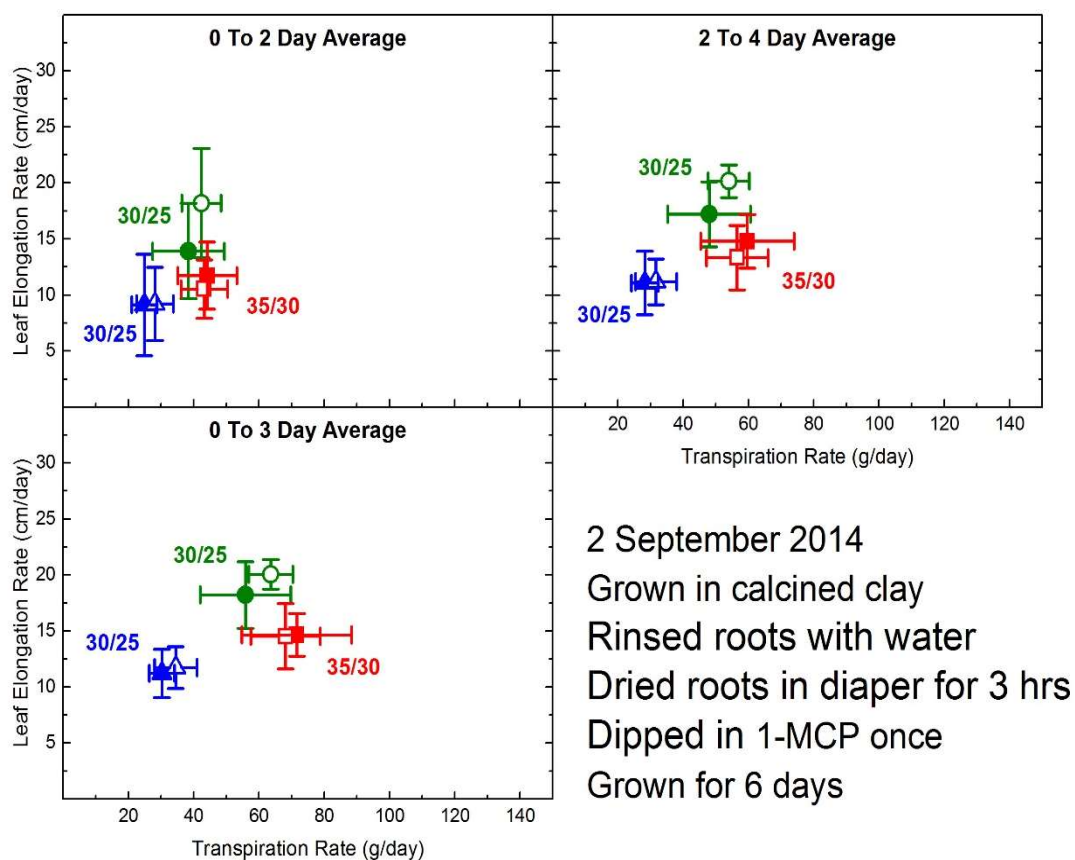


Fig. E.3.11. Roots dipped in 1-MCP: 2 September 2014.

9 September 2014. The average transpiration rate of treated plants exceeded that of untreated plants at 35/30. A similar response was observed for the 30/25, but was not statistically significant. No other differences in LER or transpiration rate occurred (Fig. E.3.12).

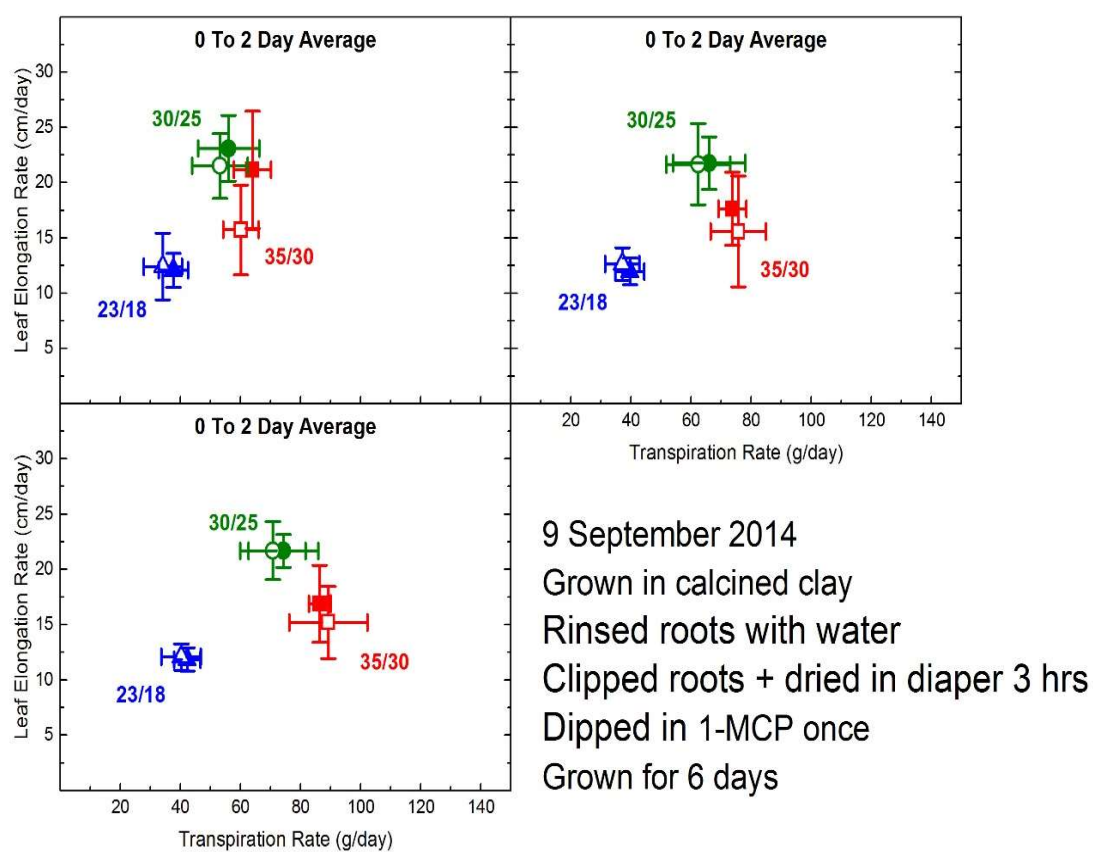


Fig. E.3.12. Roots dipped in 1-MCP: 9 September 2014.

Hydroponic Solution with 3.6 g/L 1-MCP. 3 September 2014. Very little growth or transpiration occurred during non-aerated liquid hydroponic culture. By the end of 13 days, nearly all of the rice plants had died. Anecdotally, the treated plants died more quickly, but there were no significant differences in LER or transpiration rate between 1-MCP treated plants and untreated controls at either temperature (Fig. E.3.13).

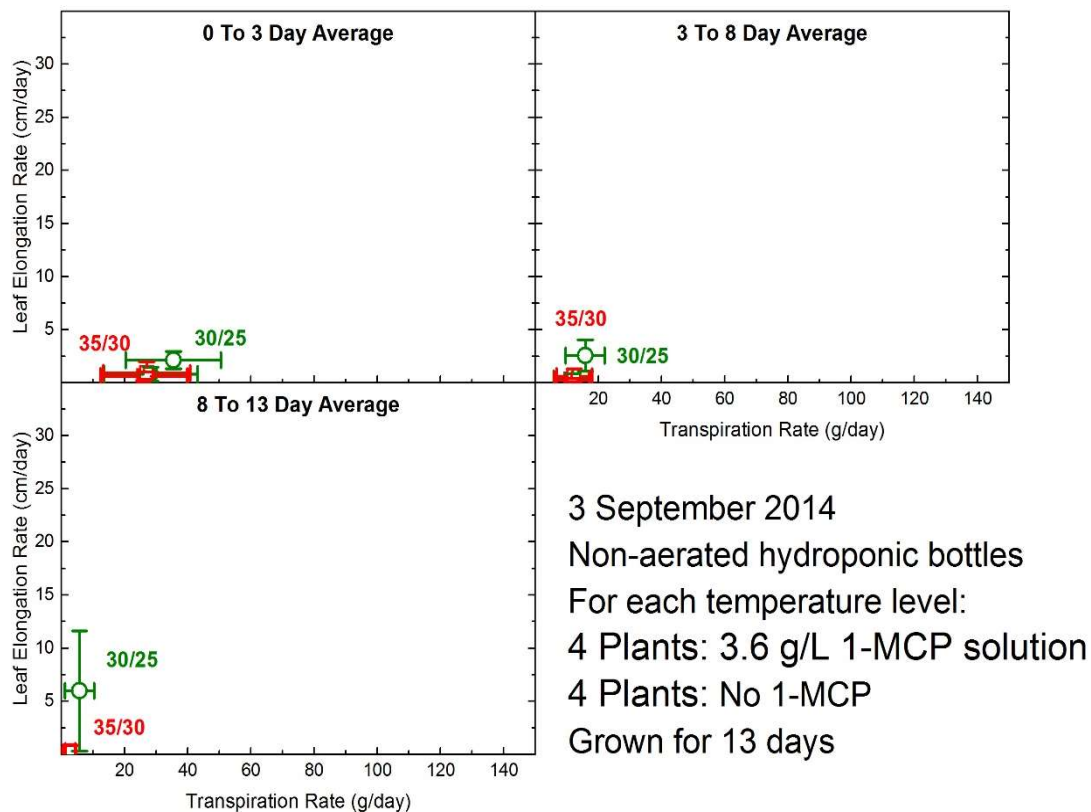


Fig. E.3.13. Roots dipped in 1-MCP: 3 September 2014.

Hydroponic Study—Aerenchyma. *17 September 2014.* Seeds of Ai Nan Tsao rice were germinated in rag dolls then transplanted to hydroponic culture. No 1-MCP was added to the solution. One container was aerated and the other was not.

Initially, each leaf of each plant was measured using the rim of the container as the reference. Each subsequent measurement was taken in like manner and the leaf elongation rate (LER) was determined (Fig. E.3.14). Plants were **grown for 8 days**.

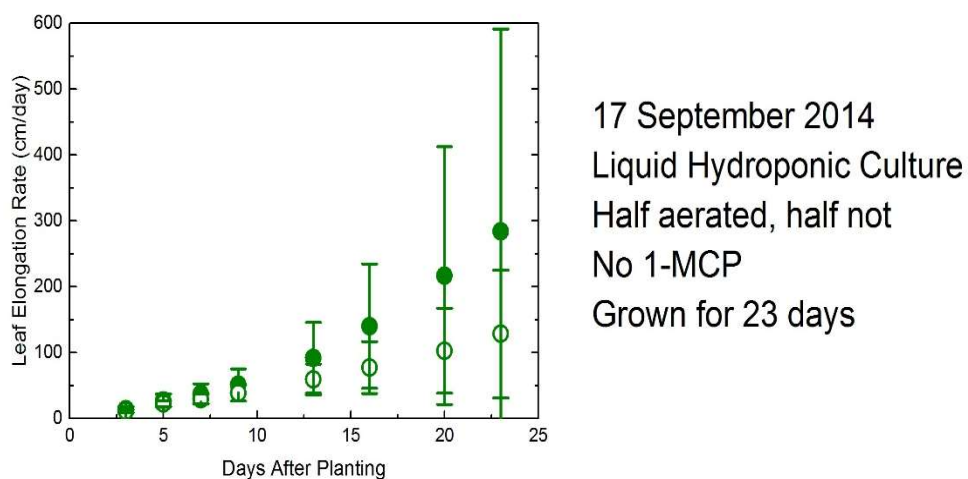
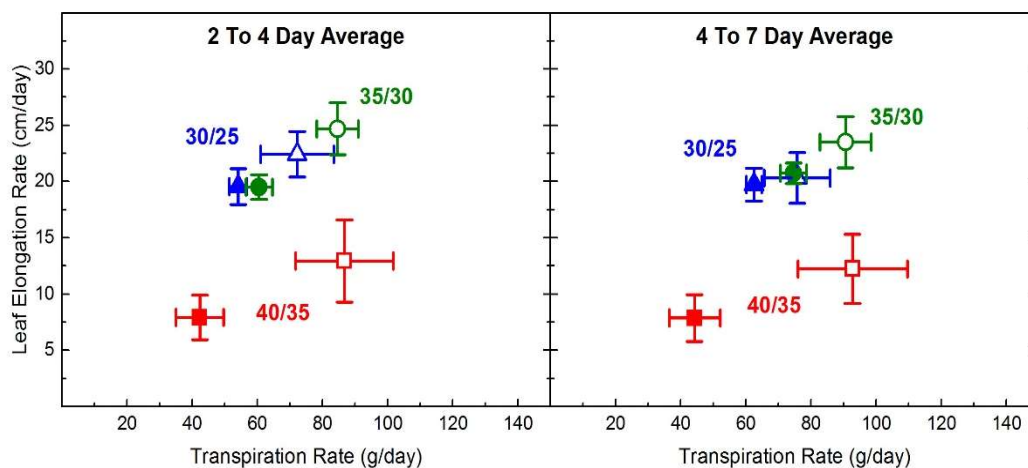


Fig. E.3.14. Aerenchyma study: 17 September 2014.

Stress Level Quantification Experiments. 15 December 2014. Untreated plants transpired slightly more than treated plants grown at 35/30 in the first 4 days. This differences disappeared by 7 days. At 40/35, the untreated controls transpired significantly more for the duration of the experiment than the plants whose rootballs had been truncated. No significant difference in LER or transpiration rate could be detected at 30/25 (Fig. E.3.15).



15 December 2014
 12 Plants: Cut 67% of plants
 12 Plants: Untreated control
 No 1-MCP
 Grown for 7 days

Fig. E.3.15. Stress level quantification: 15 December 2014.

6 January 2015. Two significant differences in LER occurred in this study. At 40/35, dried rice plants had a smaller LER than untreated controls in the first 2 days. From 2 to 4 days, the untreated control plants had a greater LER than the dried plants. No other significant differences in LER occurred. There were no significant differences in transpiration rates between treatments (Fig. E.3.16).

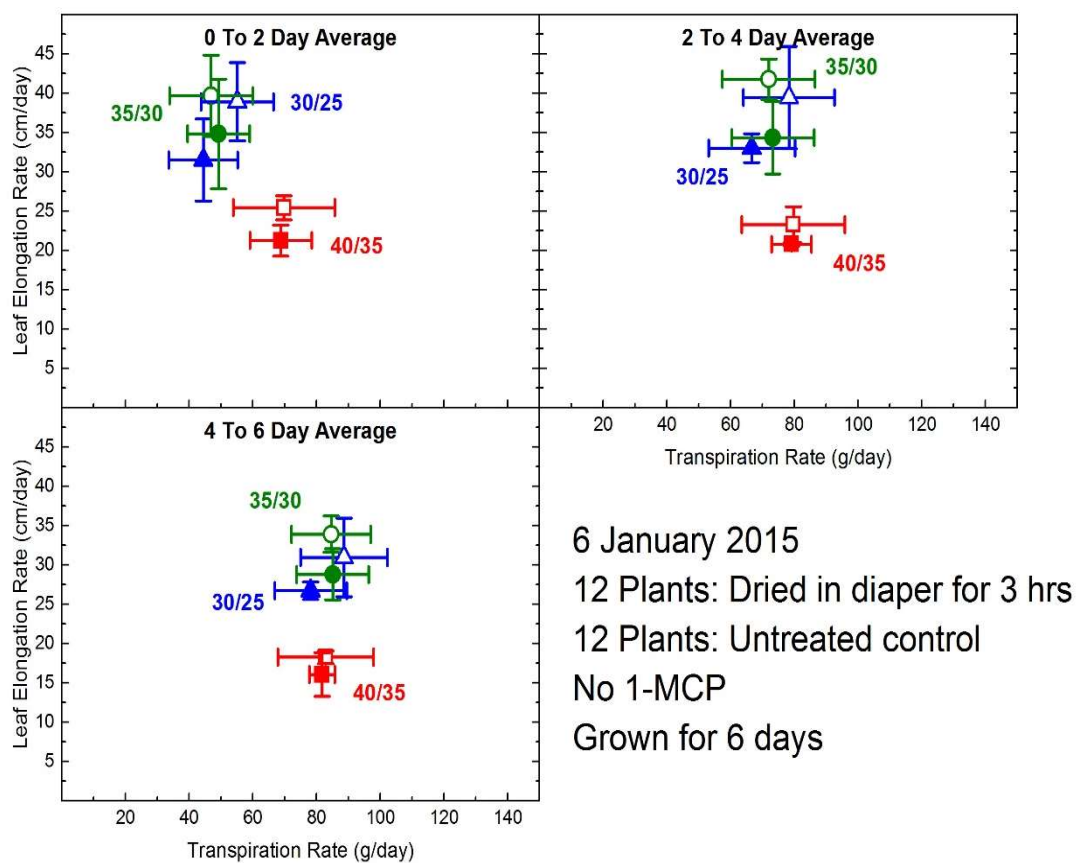


Fig. E.3.16. Stress level quantification: 6 January 2015.

10 February 2015. When rootballs were both cut and dried, untreated controls had significantly greater LERs and significantly higher transpiration rates than their treated counterparts for the first two days. From day 2 to day 4, the differences in LER were not significant. Transpiration rates were significantly greater for the 40/35 and 35/30 plants, but not for the 30/25 plants (Fig. E.3.17).

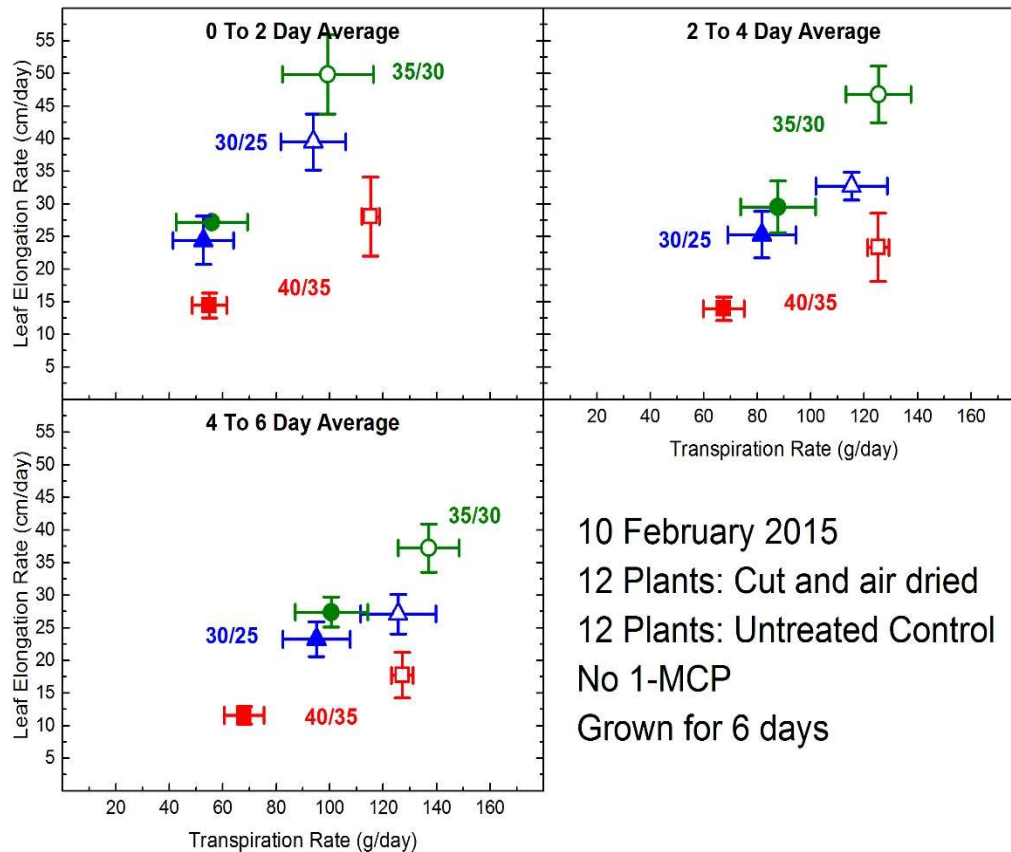


Fig. E.3.17. Stress level quantification: 10 February 2015.

Follow-Up Experiments. 31 March 2015. The average transpiration rate of treated plants exceeded that of untreated plants at both temperatures, but the difference was not statistically significant (Fig. E.3.18). Treating more than once with 1-MCP seemed to have no significant effect.

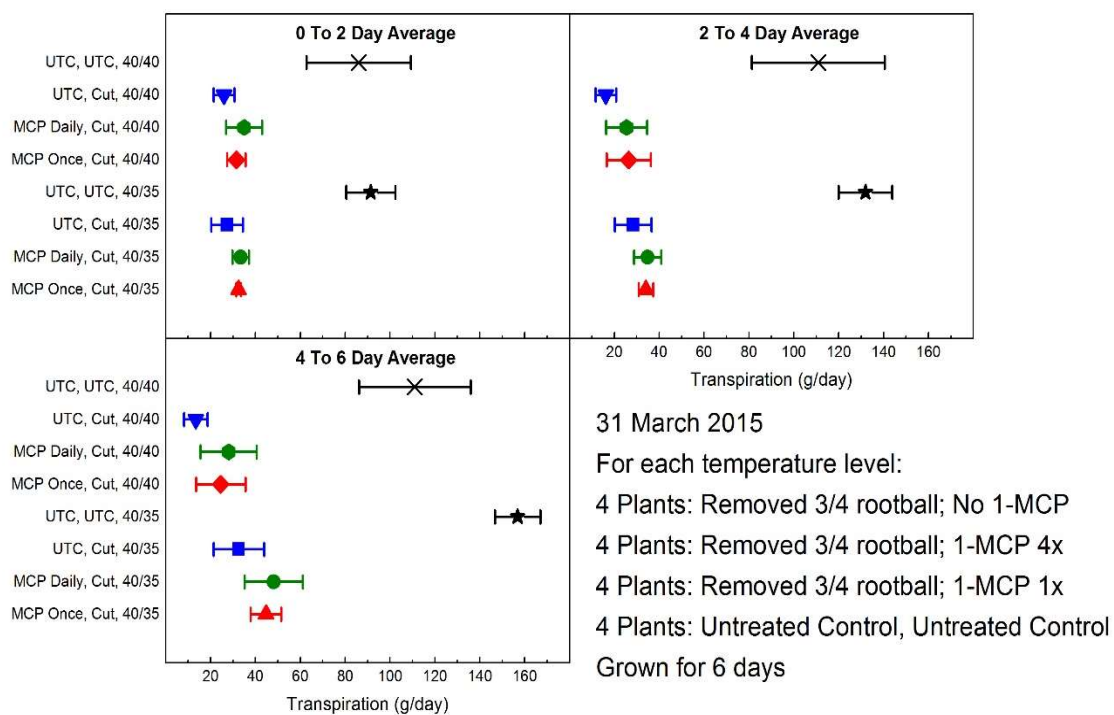


Fig. E.3.18. Follow-up experiment: 31 March 2015.

7 April 2015. A small, but not statistically-significant increase in the transpiration rate of treated plants can be observed at both temperatures (Fig. E.3.19).

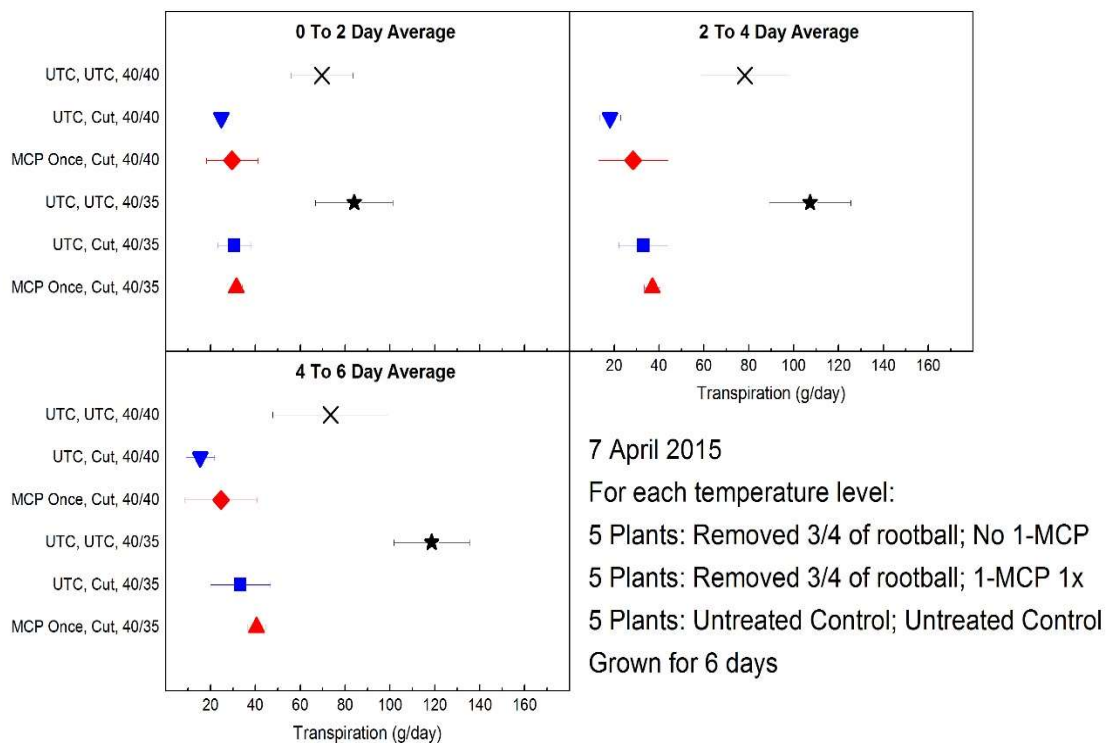


Fig. E.3.19. Follow-up experiment: 7 April 2015.

14 April 2015. A small increase in transpiration for treated plants can be observed at 38/30 but not at 35/30. The increase is not statistically significant (Fig. E.3.20).

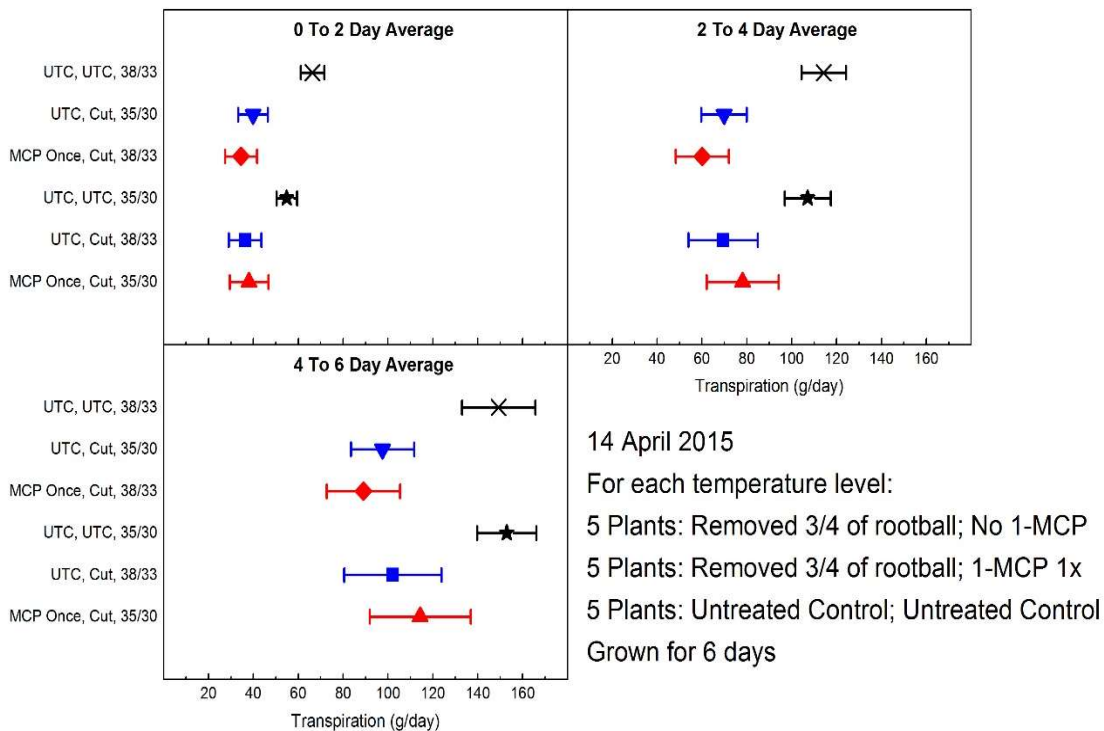


Fig. E.3.20. Follow-up experiment: 14 April 2015.

21 April 2015. Small, but not statistically-significant increases in the transpiration rate occurred at both temperatures in this study (Fig. E.3.21).

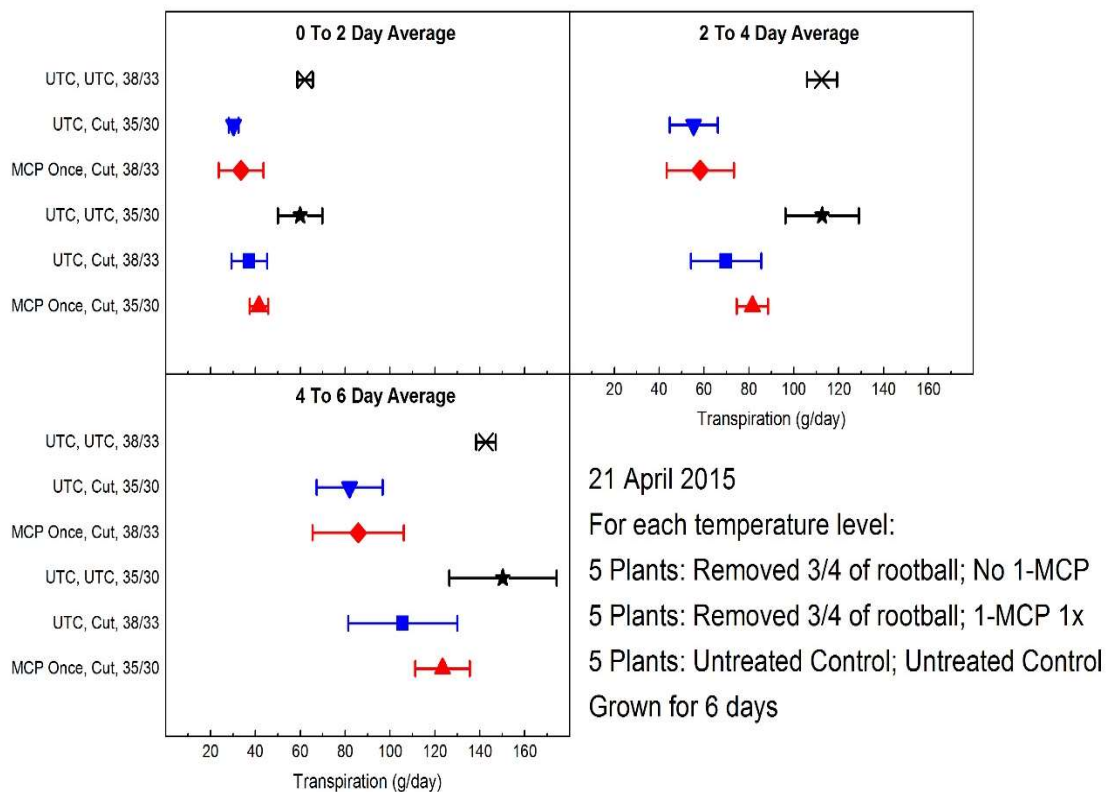


Fig. E.3.21. Follow-up experiment: 21 April 2015.

E.3.3 Discussion

Multiple 1-MCP Sprays, Soilless Media to Soilless Media. In the 31 March 2015 experiment there was no significant difference between rice plants treated with 1-MCP once and those treated with 1-MCP multiple days in a row. Spraying rice plants on multiple consecutive days produced no significant differences in LER or transpiration rates in five studies (29 July 2014, 5 August 2014, 25 September 2014, 2 October 2014 and 25 October 2014), with the exception of an improvement in LER at 35/30 in the 25 September 2015 study. **Dipped in 1-MCP, Calcined Clay to Soilless Media.** No significant differences in LER or transpiration rate occurred between rice plants whose roots were dipped in 1-MCP and untreated rice plants at any temperature in any of the three experiments conducted (12 August 2014, 19 August 2014 and 26 August 2014).

Hydroponic Solution with 3.6 g/L 1-MCP. Because of poor plant performance, the study was discontinued and very little useful information was obtained.

Hydroponic Study—Aerenchyma. Poor plant performance made this study of little benefit. However, rice plants grown with aeration were larger than those without.

Stress Level Quantification Experiments. When intact rootballs were dried in a diaper until they started to wilt before transplanting, there were no significant stress effects evidenced by differences in LER or transpiration. However, when 67% of the rootball was removed, it provided a significant reduction in LER and transpiration. The combination of cutting and drying the rootball produced similar results. This indicates that removing two thirds of the rootball induces more stress in rice than drying the rootballs.

Follow-Up Studies. There is some evidence that treatment with 1-MCP aids rice in dealing with transplant stress in these studies. Generally, stressed rice treated with 1-MCP had a slightly higher transpiration rate than rice plants that were stressed only. This effect seems to be more pronounced at higher mean temperatures. However, none of these differences were statistically-significant. Whether or not they would be agronomically-important is beyond the scope of these experiments.

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APPENDIX F
CONTROLLED ENVIRONMENT MANAGEMENT
SYSTEM AND PROGRAM

F.1 Introduction

Plant growers have searched for a better method to create ideal environments for plant growth in greenhouses ever since the first glass house was invented. Nelson (1978) described the procession from manual controlling of valves and ventilators by night watchpersons in the 20th century to the computerized systems of today. Growth chambers require similar environmental control.

Growth chambers are expensive to replace and often the chamber itself does not wear out, but the control components become obsolete and can no longer be repaired or replaced. Some companies advertise retrofits for chambers to update these obsolete components (Conviron, 2013; Cycloptics, 2013; Luminessence Lighting Inc., (n.d.)). However, creative scientists can modify and retrofit chambers condemned by obsolete components and make them useable without the high cost of replacing them. In fact, there is enough current interest in this topic that a workshop was devoted to this topic at the 2013 American Society for Horticultural Science (ASHS) meetings (van Iersel and Massa, 2013).

The Utah State University Crop Physiology lab has a reputation for retrofitting and continuing to use older chambers (Hay, (n.d); J. Nelson and Bugbee, 2013a; J. Nelson and Bugbee, 2013b; Utah State University Crop Physiology Lab, (n.d.)). As the control systems of three early 1980s growth chambers failed, they were retrofitted with functional control systems. However, several devices and settings must be used to control the chambers. Separate day and night thermostats control temperatures, while the time clock controls lighting. Cooling valves meter water to flow through the cooling coils and are manually adjusted to provide the correct flow for daytime and nighttime

cooling. The requirement for cooling in the daytime is greater because of the heat load of the lighting. Even with the retrofit to LEDs, there is greater need for cooling when the lights are on.

The objective for this project was to use a datalogger to control the lighting and temperatures of three growth chambers so that they could all be controlled from a central user interface. Ideally, a controlled environment chamber should be able to hold different night and day temperatures and ramp slowly up or down when changing temperatures. Lighting should also be controlled by the same interface. The most difficult challenge was to create the capability of ramping smoothly from one temperature to another. Initially, this was done using a step-wise change in temperature, but ultimately, multipliers were used to create a moving target temperature, and, thus a smooth ramp between temperatures.

F.2 Materials and Methods

F.2.1 Current Control System

Three growth chambers manufactured in the early 1980s (Environmental Growth Chambers, Chagrin Falls, Ohio) had already been retrofitted to have high pressure sodium lighting (Fig. F.2.1).

A 120 V time clock (Fig. F.2.2) controlled lighting and whether the chamber temperature was controlled by the daytime thermostat or the

nighttime thermostat, which were set separately. All chambers were heated with electric heater bars and cooled by tap water passed through exchanger coils. The flow of water



Fig. F.2.1. Partially-retrofitted growth chamber

through these coils was controlled by solenoid valves triggered by the time clock via relays and metered with manually-adjustable flow valves. Each of these devices had to be set separately (Fig. F.2.3).



Fig. F.2.2. 120 V timeclock used to control chambers.



Fig. F.2.3. Separate day and night thermostats controlled each chamber.

F.2.2 New Control System

A datalogger (CR1000, Campbell Scientific, Inc., Logan, Utah) was programmed to control the heating, cooling and lighting by means of a solid-state relay (Dayton, Grainger, Ogden, Utah) (Fig. F.2.4). All times and settings are programmable in the datalogger and executed automatically.



Fig. F.2.4. Solid state relays interfaced datalogger DC signals with 120 V electricity.

F.2.3 Testing

To test the program prior to installing the system on the actual chambers, a simulated growth chamber (Fig. F.2.5) was fitted with a Type K thermocouple which was wired to a datalogger (CR-1000, Campbell Scientific, Inc., Logan, Utah) in order to measure temperature. The simulated growth chamber was fitted with a heater bar, a light socket and an exhaust fan. The heater bar and light socket were controlled by the datalogger via solid state relays. The exhaust fan was wired to the 12V switched port of the datalogger and used to simulate chamber cooling.

Using LoggerNet's CRBasic editor, the datalogger was programmed to monitor and control the temperature of the simulated growth chamber using the heater bar for the heat source and the exhaust fan as a source of simulated cooling. The datalogger program also controlled the lighting. A real time control interface was created using RTMC Pro to allow for quick changes of the settings. Several iterations of the program and the real time interface were tested.



Fig. F.2.5. Simulated growth chamber used to test programs and real-time interfaces.

F.3 Results

F.3.1 Implementation

All thermostats and 120 V clocks were removed from the chambers and replaced by solid state relays for heating, lighting and cooling. All three chambers are controlled

with the datalogger and real-time interface. After the initial implementation, LED lighting replaced the HPS lighting on top of the chambers to avoid problems associated with water leaks. The system was also expanded to include a fourth growth chamber which necessitated the use of a 16 channel control port module and minor changes to the program.

F.3.2 Real-Time Interface

The final version of the real-time interface made it impossible to set the clock in any order other than chronological and prevented blanks in the program caused by missing set points. Indicators for lighting, ramping, cooling and heating were included for each set point. The photoperiod was also calculated and displayed. In this real time interface, the background of each set point is black when lights are set to off, but turns yellow when they are set to come on, providing a visual reference for photoperiod on the real time interface. The final real-time interface is shown below in Fig. F.3.1.

F.3.3 Program

Four preliminary versions of the program were written prior to the final version. The final version overcame several issues encountered with the preliminary versions. The final program enabled smooth ramping of temperatures between set points by using a multiplier derived from the difference in time and the difference in temperature between set points. This multiplier greatly reduced the overall length of the code. A dead band was also added to keep heating and cooling from rapid cycling near the set point. The real-time interface was also updated to be more intuitive and have better graphics.

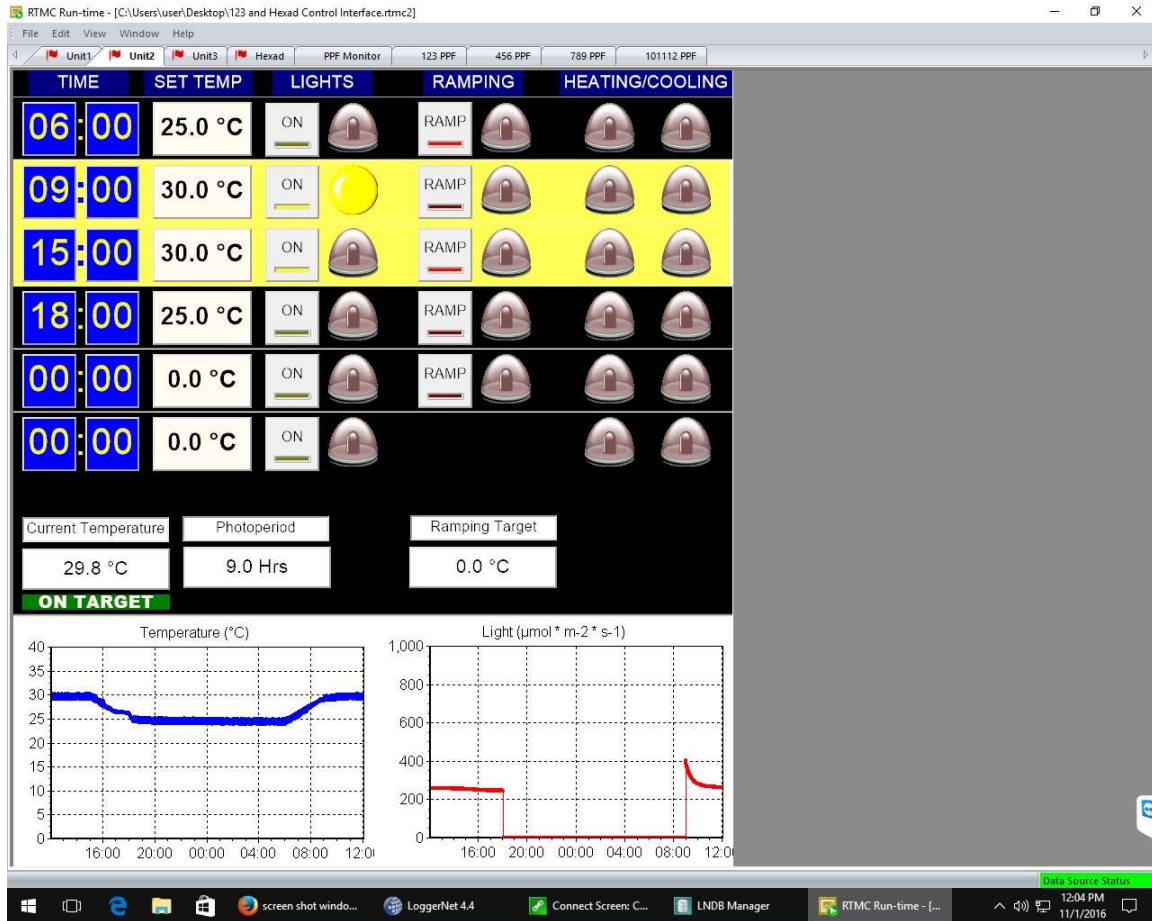


Fig. F.3.1. Real-time interface. The final real-time interface allows for six set points with ramping between the first five. It also shows the temperature and lighting history graphically.

F.4 Discussion

As Theroux discussed in the workshop at the 2013 ASHS meetings, one of the major reasons for upgrading the controller of a growth chamber is because of obsolete parts (van Iersel and Massa 2013). The most cost-effective method for upgrading the control system suggested was a DIY method. However, Theroux suggested that this option had several disadvantages, chiefly lack of expertise within a lab and the fact that generally only one person understands how the system works. The cost of installation for

this system is limited to the cost of a datalogger, the software and the sensors and wiring. The universal programming language for the datalogger and the simple-to-program user interface make this a viable option for controlling growth chambers.

The final program was able to provide adequate control of the growth chambers both when ramping and when controlling a square wave pattern. The addition of the dead band feature should be useful, but more experimentation will be required in order for it to be fine-tuned. With some changes, the program was even flexible enough to simulate an orbital photoperiod by turning the lights on for one hour and off for one-half hour around the clock.

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