EVAPOTRANSPIRATION PARTITIONING IN SEMIARID
CREOSOTEBUSH DOMINATED ECOSYSTEMS:
CLIMATE CHANGE IMPLICATIONS OF SOIL MOISTURE
CONTROL ON SHRUBLAND TRANSPIRATION

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Figure 2. Time series of precipitation (bars), $ET$, and $T$ at SRER (1) and WGEW (2).

Figure 3. Site map of both SRER and WGEW study sites.
This thesis reports the results of a field study examining the soil moisture controls on the partitioning of evapotranspiration ($ET$) at the Santa Rita Experimental Range and the Walnut Gulch Experimental Watershed in southeastern Arizona. This study looks at how precipitation inputs are partitioned into evaporation ($E$) and transpiration ($T$) within these two creosotebush ($Larrea tridentata$) dominated ecosystems and the implications of climatic shifts on the functioning of semiarid systems.

Results show that following the first summer rains, $E$ initially dominated $ET$ due to a lagged plant response to available soil moisture. $T$, associated with increased moisture at deeper soil layers, peaked after a series of large precipitation inputs at both sites. Under the current precipitation regime, soil moisture will remain low. However, if climatic changes provide less frequent but larger precipitation events, these sites could see more moisture at deeper soil depths favoring deeply rooted plants such as creosotebush.
1. INTRODUCTION

1.1 Why study evapotranspiration partitioning in semiarid ecosystems?

In dryland ecosystems, which account for over a third of the Earth’s land surface, productivity has been shown to be particularly sensitive to precipitation inputs (Fay 2009; Huxman et al. 2004a). These precipitation inputs tend to come in pulses, and therefore vegetation in drylands is largely dependent on pulses of moisture to infiltrate the soil (Huxman et al. 2004b; Ogle and Reynolds 2004). The result is a delicate balance of frequent small precipitation events (<5 mm) interspersed with infrequent larger events. This precipitation regime supports the great diversity and healthy ecosystem functioning characteristic of these semiarid ecosystems (Fay 2009; Golluscio et al. 1998; Sala and Lauenroth 1982).

Most global climate models predict changes in the intra-annual variability of precipitation (IPCC 2007; Knapp et al. 2008). Given that average annual precipitation in semiarid areas worldwide is expected to experience major fluctuations (IPCC 2007), the associated changes in timing, frequency, and magnitude of precipitation events will have ecological implications for semiarid ecosystems (Heisler-White et al. 2008; Knapp et al. 2008). Further, critical to predicting and understanding the ecological implications of these precipitation fluctuations is a better understanding of how dryland vegetation currently uses water resources.

Species such as creosotebush (*Larrea tridentata*), mesquite (*Prosopis sp.*), and juniper (*Juniperus sp.*) have been locally dominant in the semiarid southwestern United
States, including Arizona, New Mexico, and Texas, for at least 4,000 years (Grover and Musick 1990; Van Auken 2000); however, in the last 100 years, these species have encroached upon native grasslands, expanding in range and in land cover density (Archer et al. 1988; Abrahams et al. 1995; Bahre and Shelton 1993; Wilcox et al. 2006). The encroachment of these species is the result of a combination of changes in land use such as fewer, less intense wildfires, heavy grazing, and elimination of native herbivores (Van Vegten 1983; Archer et al. 1988; Dugas et al. 1998), as well as changes in atmospheric conditions including precipitation, temperature, and CO₂ (Van Auken 2000; Scott et al. 2006b). Surely, more of these dramatic land cover changes are possible under current global change scenarios.

A shift to more winter season precipitation, for example, might favor woody plant encroachment (Browning et al. 2008). Additionally, because of these changes in the landscape, grasses and woody plants will compete directly for available resources, such as soil moisture or plant available water. The competition of these plants depends on root biomass, density, other root characteristics, and timing of growth (Van Auken, 2000). While grasses reduce the success of woody plants during germination and establishment, once the woody plants have a well established root zone, the success of the grasses is inhibited (Brown and Archer, 1989, Van Auken, 2000).

Because most precipitation events in semiarid ecosystems have traditionally been small (<5 mm, Sala et al. 1992), often only the top few centimeters of the soil are wetted. Figure 1 illustrates this response of soil moisture to different sized precipitation events at SRER (1.1) and WGEW (1.2). During times of large precipitation pulse, there are
distinct spikes in the available soil moisture at shallower soil depths, while there is little change at deeper soil layers. Due to high evaporative demand and the large amount of bare soil, evapotranspiration ($ET$) accounts for more than 90% of all precipitation inputs to the system in semiarid environments (e.g. Carlson et al. 1990; Wilcox et al. 2003; Huxman et al. 2005), where $ET$ is the sum of soil evaporation ($E$) and transpiration ($T$).
Due to the shallow nature of this moisture reservoir associated with these small rainfall events, surface soil moisture is typically used up rapidly by $E$ (Kurc and Small 2007, Scott et al. 2006a). In contrast to $E$, $T$ is attributed to the soil moisture deeper in the root zone. Usually only large precipitation events are capable of wetting the root zone beyond the depth of evaporative demand (Kurc and Small 2007), and these events are likely in times when $T/ET$ is larger than $E/ET$. Figure 2 illustrates the partitioning of $E$ and $T$ in relation to precipitation inputs. $ET$ spikes immediately following precipitation events at
both sites, while the spike in $T$ is lagged. This suggests that immediately following precipitation inputs, $E$ dominates the first several days until the newly available moisture reaches the plant root zone ($T$). When compared to Figure 1, there is a clear relation between increases in $T$ and increases in soil moisture at greater depths.

While $ET$ in dryland ecosystems has been successfully estimated using Bowen ratio (e.g. Dugas et al. 1998; Scott et al. 2006a; Kurc and Small 2004) and open path eddy covariance techniques (e.g. Scott et al. 2006b, Kurc and Small 2007), alterations of the ecohydrological processes in these systems associated with isolated, episodic precipitation events, or pulses remain largely unresolved (Loik et al. 2004; Potts et al. 2006). The frequency and intensity of pulses has been shown to influence soil moisture and thus the partitioning of $E$ and $T$ within the system (Potts et al. 2006); yet, how and when the vegetation uses this soil moisture still needs to be addressed.

1.2 About the Field Sites

This document reports the research and data collected from the Creosote Site at SRER and the Lucky Hills field site at WGEW (Figure 3). The SRER lies entirely within the Sonoran Desert while WGEW is in the transition zone between the Sonoran and Chihuahuan Deserts. The semiarid climate is characterized by cool winters and warm summers with a bimodal precipitation pattern with the majority of precipitation falling during the summer monsoon season around the months of July through September.

The SRER, established in 1903, was first managed by the U.S. Forest Service before being turned over to the University of Arizona in 1987. The property consists of
215 km² 35 miles south of Tucson, Pima County, Arizona. The SRER lies at the foot of the northwestern Santa Rita Mountains. The Creosote Site at SRER (31.9083N, 110.8395W) is at an elevation of about 1000 m and is characterized by a sandy loam soil. The average annual precipitation is about 345 mm (1971-2008) and average annual temperature is about 20°C (WRRC 2007). During the period from 1971 - 2008, the field site received approximately 50% of all annual precipitation during the summer monsoon season (June to September) and 45% during the winter (October to February). The results of a 2008 vegetation survey indicated that the total percent cover of vegetation at this site was around 24% with the dominant vegetation being creosotebush (14%) followed by small grasses, forbs, and cactus accounting for the remaining 10% of total cover.
The 150 km² WGEW has been managed by the USDA-ARS since 1951. The watershed is located just outside Tombstone, Cochise County, Arizona. WGEW extends from the Dragoon Mountains to the east to the San Pedro River to the west. The Lucky Hills Site at WGEW (31.7438N, 110.0522W) is located at an elevation of about 1375 m and is dominated by a gravelly loamy soil with rocks and a calciferous layer. The mean annual temperature is about 17°C and average annual precipitation is about 322 mm (Goodrich et al. 2008). From 1964-2007, the WGEW received approximately 70% of annual precipitation in the summer and 25% in the winter months (Goodrich et al. 2008). A vegetation survey conducted in Fall of 2008 indicated that total percent cover at the site was about 27%, with creosotebush being the dominant species (9%) followed by acacia (Acacia constricta; 9%) as well as small grasses and forbs (10%).

1.3 Objectives

This thesis reports the research and data collected at the SRER and the WGEW field sites during the summer of 2008. The following were the two objectives of the study. The first objective was to understand the unique water use of creosotebush under different environmental conditions within the semiarid southwestern United States. To gain a better understanding of ET partitioning, the two study sites were chosen due to their differences in soil type and seasonal distribution of precipitation. The second objective was to compare transpiration losses from the dominant vegetation at both sites by using the heat balance method of sap flow measurement. Additional measurements of
soil moisture and ecosystem $ET$ were made to determine how $ET$ was partitioned at each site.

Appendix A, *Evapotranspiration partitioning in semiarid creosotebush dominated ecosystems: Climate change implications of soil moisture control on shrubland transpiration*, presents and addresses the following three hypotheses regarding evapotranspiration partitioning at the two study sites. Firstly, it was predicted that there would be no transpiration responses for storms less than 5 mm at both sites. Secondly, at both sites there would be a lagged response of $T$ to large precipitation events, with evaporation being the dominant component of $ET$ for the first few days. Thirdly, it was hypothesized the ratio of plant transpiration to total evapotranspiration ($T/ET$) will be less at WGEW due to the smaller average shrub size at this site.

1.4 Structure of the Following Chapters

My Masters research is presented as an individual research paper which appears in its entirety in Appendix A of this document. The paper titled *Evapotranspiration partitioning in semiarid creosotebush dominated ecosystems: Climate change implications of soil moisture control on shrubland transpiration* is expected to be submitted to the journal Oecologia for peer review and publication in May 2009. Tables and figures associated with this appendix appear at the end of the appendix section. Appendix B is a manual for the construction of heat-balance sap flow sensors. All photos and diagrams are included within the appendix itself. Both appendices were prepared by the author herself who is responsible for all data analysis and interpretation. Significant
contributions were received by the second and third authors in Appendix A; those noted in the Acknowledgements section of Appendix A also helped as noted there.

The following section, Present Study, summarizes the methods, results, and conclusions of my research.
2. PRESENT STUDY

The methods, results, and conclusions of this study are appended to this thesis. The following are two abstracts; the first abstract describes of the most important findings of this document, while the second abstract describes in detail the theory, assembly, and installation of the major method used for the research presented in Appendix A.

2.1 Abstract of Appendix A: Evapotranspiration partitioning in semiarid creosotebush dominated ecosystems: Climate change implications of soil moisture control on shrubland transpiration

The vegetation of dryland ecosystems is sensitive to precipitation pulses. In future climate scenarios, precipitation patterns are expected to be altered, impacting the functioning of these ecosystems. How and to what extent these impacts will be felt are less understood. Creosotebush (*Larrea tridentata*) is the dominant shrub in all three North American deserts, yet there is little information regarding precipitation controls on transpiration in this shrub. We address how changes in precipitation dynamics might affect creosotebush dominated ecosystems. In this study, we look at how precipitation inputs are partitioned into evaporation (*E*) and transpiration (*T*) within two creosotebush dominated ecosystems which differ in precipitation regime: the Santa Rita Experimental
Range (SRER) and the Walnut Gulch Experimental Watershed (WGEW). During the 2008 summer rainy season, we measured $ET$ using eddy covariance techniques, whole plant $T$ using heat-balance sap flow sensors, and soil moisture at several depths at both sites. Prior to the onset of summer rains, $ET$ and soil moisture were very low. After the start of the rains, $E$ dominated $ET$ as the plants did not respond to the available soil moisture for approximately 3 weeks. $T$, associated with increased moisture at deeper soil layers, peaked after a series of large precipitation inputs at both sites. $ET$ was correlated to shallow soil layers typical of semiarid ecosystems dominated by dry conditions, high evaporative demand, and poor soil infiltration. Under the current precipitation regime of smaller, less intense storms, soil moisture at SRER and WGEW will remain low with most water lost to $E$. However, if climatic changes provide less frequent but larger precipitation events, SRER and WGEW could see increased available moisture at deeper soil depths that will favor deeply rooted plants such as creosotebush enabling them to thrive and expedite encroachment on native grasslands.


This document provides a brief theory of and thorough instructions on how to construct and install sap flow sensors in woody plants. A measurement of transpiration can be made using sap flow sensors on plant stems to measure heat transport along a
branch section. Using the heat balance method of sap flow measurement, mass sap flow is considered equal to transpiration of all leaves on the stem upon which the heating sensor is installed. Advantages to the sap flow method are (1) that it is easily automated for continuous data collection and (2) can be set up in the field with ease and little disturbance.
3. REFERENCES


APPENDIX A: EVAPOTRANSPIRATION PARTITIONING IN SEMIARID CREOSOTE BUSH DOMINATED ECOSYSTEMS: CLIMATE CHANGE IMPLICATIONS OF SOIL MOISTURE CONTROL ON SHRUBLAND TRANSPIRATION

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Introduction

In dryland ecosystems, which account for over a third of the Earth’s land surface, productivity has been shown to be particularly sensitive to precipitation inputs (Fay 2009; Huxman et al. 2004a). These precipitation inputs tend to come in pulses, and therefore vegetation in drylands is largely dependent on pulses of moisture (Huxman et al. 2004b; Ogle and Reynolds 2004). The result is a delicate balance of frequent small precipitation events (<5 mm) interspersed with infrequent larger events that supports the great diversity and healthy ecosystem functioning characteristic of these dryland ecosystems (Fay 2009; Golluscio et al. 1998; Sala and Lauenroth 1982).

Most global climate models predict changes in the intra-annual variability of precipitation (IPCC 2007; Knapp et al. 2008). Given that average annual precipitation in semiarid areas worldwide is expected to experience major fluctuations (IPCC 2007), the associated changes in timing, frequency, and magnitude of precipitation events will have ecological implications for dryland ecosystems (Heisler-White et al. 2008; Knapp et al. 2008). Further, critical to predicting and understanding the ecological implications of these precipitation fluctuations is a better understanding of how dryland vegetation currently uses water resources.

Species such as creosotebush (Larrea tridentata), mesquite (Prosopis sp.), and juniper (Juniperus sp.) have been locally dominant in the semiarid southwestern United States for at least 4,000 years (Grover and Musick 1990; Van Auken 2000); however, in the last 100 years, these species have encroached upon native grasslands, expanding in range and in land cover density (Archer et al. 1988; Abrahams et al. 1995; Bahre and
Shelton 1993; Wilcox et al. 2006). The encroachment of these species is the result of a combination of changes in land use such as fewer, less intense wildfires, heavy grazing, and elimination of native herbivores (Van Vegten 1983; Archer et al. 1988; Dugas et al. 1998), as well as changes in atmospheric conditions including precipitation, temperature, and CO\textsubscript{2} (Van Auken 2000; Scott et al. 2006b). Surely, more of these dramatic land cover changes are possible under current global change scenarios. A shift to more winter season precipitation, for example, might favor woody plant encroachment (Browning et al. 2008). Additionally, because of these changes in the landscape, grasses and woody plants will compete directly for available resources, such as soil moisture or plant available water.

Because most precipitation events in semiarid ecosystems have traditionally been small (<5 mm, Sala et al. 1992), often only the top few centimeters of the soil are wetted. Due to high evaporative demand and the large amount of bare soil, evapotranspiration (\textit{ET}) accounts for more than 90\% of all precipitation inputs to the system in semiarid environments (e.g. Carlson et al. 1990; Wilcox et al. 2003; Huxman et al. 2005), where \textit{ET} is the sum of soil evaporation (\textit{E}) and transpiration (\textit{T}). Due to the shallow nature of this moisture reservoir associated with these small rainfall events, surface soil moisture is typically used up rapidly by \textit{E} (Kurc and Small 2007, Scott et al. 2006a). In contrast to \textit{E}, \textit{T} is attributed to the soil moisture deeper in the root zone. Usually only large precipitation events are capable of wetting the root zone beyond the depth of evaporative demand (Kurc and Small 2007), and these events are likely in times when \textit{T/ET} is larger than \textit{E/ET}. 

While \( ET \) in dryland ecosystems has been successfully estimated using Bowen ratio (e.g. Dugas et al. 1998; Scott et al. 2006a; Kurc and Small 2004) and open path eddy covariance techniques (e.g. Scott et al. 2006b, Kurc and Small 2007), alterations of the ecohydrological processes in these systems associated with isolated, episodic precipitation events, or pulses remain largely unresolved (Loik et al. 2004; Potts et al. 2006). The frequency and intensity of pulses has been shown to influence soil moisture and thus the partitioning of \( E \) and \( T \) within the system (Potts et al. 2006); yet, how and when the vegetation uses this soil moisture still needs to be addressed.

The objective of this study is to understand the unique water use of creosotebush under different environmental conditions within the semiarid southwestern United States. To gain a better understanding of \( ET \) partitioning, two study sites were chosen which differ primarily in their soil type and seasonal distribution of precipitation. The objective of this study was to compare transpiration losses from the dominant vegetation at both sites by using the heat balance method of sap flow measurement. Sap flow methods have proven to be effective in measuring water use in a variety of semiarid plant species (e.g., Gazal et al. 2006, Carlson et al. 1990, Scott et al. 2006a).

We address three hypotheses in regards evapotranspiration partitioning at the two study sites. Firstly, we predicted that there would be no transpiration responses for storms less than 5 mm at both sites. Secondly, at both sites there would be a lagged response of \( T \) to large precipitation events, with evaporation being the dominant component of \( ET \) for the first few days. Thirdly, we hypothesized the ratio of plant transpiration to total
evapotranspiration ($T/ET$) will be less at WGEW due to the smaller average shrub size at this site.

**Materials and Methods**

**Site Description**

Our study was conducted at two locations in semiarid southeastern Arizona: the Santa Rita Experimental Range (SRER) and Walnut Gulch Experimental Watershed (WGEW) (Figure 1). The SRER lies entirely within the Sonoran Desert while WGEW is in the transition zone between the Sonoran and Chihuahuan Deserts. The semiarid climate has cool winters and warm summers. This region experiences a bimodal precipitation pattern with the majority of precipitation falling during the summer monsoon season around the months of July through September.

The Creosote Site at SRER (31.9083N, 110.8395W) is at an elevation of about 1000 m. Laser diffraction particle size analyses (Arriaga et al., 2006) conducted in 2008 confirmed that the soil at this creosotebush ecosystem is sandy loam at least to 1 m in depth; no calcite layer was encountered within this 1 m. The average annual precipitation at the SRER is about 345 mm (1971-2008) and average mean annual temperature is about 20°C (WRRC 2007). During the period from 1971 - 2008, the field site received approximately 50% of all annual precipitation during the summer monsoon season (June to September) and 45% during the winter (October to February). In the Fall of 2008 a
vegetation survey indicated that the total percent cover of vegetation at this site was around 24% with the dominant vegetation being creosotebush (14%) followed by small grasses, forbs, and cactus accounting for the remaining 10% of total cover. Average plant area index (PAI) for the months June to November was 0.45 with a maximum PAI of 0.55 occurring in September.

The Lucky Hills Site at WGEW (31.7438N, 110.0522W) is located at an elevation of about 1375 m and is dominated by a gravelly loamy soil with rocks and a calciferous layer. The average annual temperature is about 17°C and average annual precipitation is about 322 mm (Goodrich et al. 2008). From 1964-2007, the WGEW received approximately 70% of annual precipitation in the summer and 25% in the winter months (Goodrich et al. 2008). A vegetation survey conducted in Fall of 2008 indicated that total percent cover at the site was about 27%, with creosotebush being the dominant species (9%) followed by acacia (*Acacia constricta*; 9%) as well as small grasses and forbs (10%). The average PAI for June to November was 0.46 with a maximum LAI of 0.66 in September.

**Micrometeorology**

Both the SRER and WGEW sites are instrumented with standard eddy covariance systems (Moncrieff et al., 2000); at SRER this system is 4.25 m tall, while at WGEW it is at a height of 6.4 m. With adherence to Ameriflux protocol (http://public.orl.gov/ameriflux/), both sites offer 30 minute-averaged CO$_2$ and H$_2$O fluxes that are calculated using 10 Hz measurements from a LiCor 7500 and Campbell
Scientific CSAT 3-D Sonic Anemometer. The 30 minute flux data were filtered to screen out points associated with rain events, outlier spikes, periods of low turbulence, and other noise. To calculate daily ET, using all “good” half hour data over the course of a day, an average ET in mm half hour$^{-1}$ is calculated and then multiplied by 48 half hours to obtain units of mm day$^{-1}$, given that much of the missing data is likely associated with nighttime when ET is low. The authors caution that this averaging scheme likely results in a slight overestimate of ET at the daily scale.

Precipitation at SRER is measured with a Texas Electronics TE525-L tipping bucket rain gauge. A digital weighing rain gauge developed by the USDA Agricultural Research Service measures precipitation at WGEW. At SRER, volumetric water content ($\theta$) or soil moisture is estimated using Campbell Scientific CS616 Water Content Reflectometers in 6 profiles: 3 profiles under creosote canopies and 3 profiles in bare areas. In each profile, probes are placed at 7 depths: 2.5, 12.5, 22.5, 37.5, 52.5, 67.5, and 82.5 cm. At WGEW, soil moisture is estimated with one profile of Campbell Scientific TDR100 time domain reflectometry sensors also installed at 7 depths: 5, 15, 30, 50, 75, 100, and 200 cm.

**Sap Flow**

Sap flow was estimated using the heat balance method (HBM) at both of our sites (Senock and Ham 1993; Kjelgaard et al. 1997). In the heat balance method, thermocouples are placed along a plant stem - one at the heating element, one upstream of the heating element, and one downstream. A second set of thermocouples wired in
series are wrapped around the stem on top of the first set of thermocouples to measure heat lost radially away from the stem. The thermocouples measure the heat lost by conduction along the stem as well as radially away from the stem (Kjelgaard et al., 1997). The HBM uses the principle of energy balance to interpret heat fluxes in sap flow, defined as:

\[ Q = Q_f + Q_{rad} + Q_{up} + Q_{dn} \]  

(1)

where the heat input \( Q \) is equal to the sum of heat transported by convection in the sap flow \( Q_f \), heat lost radially away from the stem \( Q_{rad} \), and heat lost up \( Q_{up} \) and downstream \( Q_{dn} \) through the plant stem. The authors refer the reader to the work of Kjelgaard et al. (1997) for a more complete discussion of HBM sensor theory.

Traditionally, the thermocouple component of HBM sensors is installed just under the bark for the best readings of conductive heat flow along the stems. However, we found that for creosotebush and acacia, the very thin bark was severely damaged using this procedure. As a result, thermocouples were placed on top of the bark, perpendicular to the branch and secured with electric tape to ensure sufficient contact. Gravimetric comparisons performed in a greenhouse setting in May 2008 suggested that this modification did not impact the measurements.

In order to measure sap flow prior to, during, and after the green-up associated with the summer monsoon season, sensors were installed during the first week of June 2008 and data were collected from mid-June to mid-October 2008. We installed fifteen probes at each site. At SRER, nine creosotebush were chosen to include a variety of stem diameters ranging from 5.3 to 16.0 mm. Of the nine plants, six had two sensors installed
on two separate stems, while three plants had a single sensor. At WGEW, sensors were installed on both creosotebush and acacia, with eight sensors in four creosotebush, and seven sensors on four acacia plants. A variety of stem diameters were chosen from 6.5 to 11.8 mm for creosotebush and 5.5 to 9.7 mm for acacia. Data was collected every 5 minutes was averaged and stored at 30 minute intervals using a Campbell Scientific CR10 datalogger at SRER and Campbell Scientific CR10X at WGEW. Half-hourly data was downloaded and general maintenance preformed every two weeks. The data was filtered to remove errors caused by sensor malfunction. Approximately one half of all sensors were working at any given time during the study.

Stem-level sap flow per cross-sectional stem area was determined for each branch on which a sensor was installed and functioned. In Fall 2008, an estimate of stems per unit area was determined through a survey of twenty 35 m transects at each site. Average sap flow velocity was calculated using quality controlled data and then scaled up using average stem density and percent cover to estimate shrub-level transpiration based on the average number of stems per unit area of land surface.

**Ancillary Measurements**

Supplementary measurements included monthly pre-dawn measurements of leaf water potential and PAI at both sites. Each month during the study period, average PAI at each site was determined from a series of 22 PAI measurements taken every 6 m along a 150 m transect from east to west using a LiCor 2000 between civil twilight and sunrise. Each measurement consisted of two above canopy readings and three below canopy
readings. In addition to PAI measurements, pre-dawn plant water potential ($\Psi_{pd}$) was determined for both creosotebush and acacia using a PMS 1000 pressure chamber. We used 10 clipped samples from shrubs at the field sites to determine a representative the pre-dawn plant water potential of the ecosystem.

**Results**

**Precipitation and Soil Moisture**

Both sites had small, infrequent storms in the spring prior to the onset of the summer rainy season. Following the commencement of the rainy season on DOY 176 at SRER (Figure 2a) precipitation events were recorded on 33 days with daily rainfall ranging from 0.25 to 40.4 mm (259.6 mm total) from DOY 176 and 285. At WGEW summer rains beginning on DOY 174 and lasted until DOY 285 (Figure 2b); the approximate monsoon period had 48 rainy days with daily precipitation ranging from 0.25 to 38.6 mm/day (211.8 mm total).

Surface soil moisture at both sites fluctuate with precipitation inputs spiking after large events and showing a distinct dry down at the end of the summer rains (Figure 2). At SRER (Figure 2a), with the onset of the summer monsoon on DOY 176, $\theta_{2.5cm}$ and $\theta_{37.5cm}$ increase markedly, while deeper in the soil profile, $\theta_{52.5cm}$ and $\theta_{67.5cm}$ increase only slightly. Later in the monsoon, e.g. DOY 237-244, precipitation events elicit a similar increase in $\theta_{2.5cm}$ and $\theta_{37.5cm}$ but unlike early in the monsoon, $\theta_{52.5cm}$ and $\theta_{67.5cm}$ remain
unchanged. At WGEW (Figure 2b), $\theta_{5\text{cm}}$ and $\theta_{30\text{cm}}$ also increase in response to precipitation events starting on DOY 191 with a slight increase at $\theta_{50\text{cm}}$. However deeper in the soil profile, following three large precipitation events on DOY 201, 204, and 207 $\theta_{70\text{cm}}$ remains essentially unchanged. Near the surface, $\theta_{5\text{cm}}$ and $\theta_{30\text{cm}}$ gradually dry down following large storms, while $\theta_{50\text{cm}}$ remains elevated.

**ET and ET Partitioning**

At both sites, response in evapotranspiration $ET$ follows most precipitation events (Figure 3). However, the relationship between $T$ and precipitation is not as clear. For instance, at the SRER, even though summer rains commenced on DOY 176, the plants did not respond to the available moisture until DOY 200 (Figure 3a); peak $T$ rates occurred between DOY 205-216 during which time there was no rainfall. Maximum daily $T$ was 1.9 mm/day which occurred on DOY 210. The length of the growing season was 85 days from DOY 200 to 285. Total $ET$ for the growing season was 147.1 mm and total $T$ was 54.7 mm. The PAI and PWP results (Figure 4a) reflect the monsoonal precipitation pattern with increased PAI and decreased PWP during the period of greatest rainfall.

At WGEW peak $T$ rates for both creosotebush and acacia occurred between DOY 210 and 229 with a maximum ecosystem value of 1.53 mm/day on DOY 220 (Figure 3b). The shrubs began actively transpiring around DOY 205 or about 25 days after the monsoon onset. The growing season lasted approximately 69 days from DOY 205 to 274. While creosotebush and acacia were the two dominant species, there were other
plants contributing to total $T$ within the system; total $T$ is estimated using average vegetation characteristics and included in Figure 3b. Total $ET$ for the growing season was 102.2 mm and total $T$ was 44.5 mm. PAI and PWP results (Figure 4b) are similar to those at SRER. However, DOY 209 measurements (July) of PAI are still relatively low despite the fact that monsoon rains had been occurring for 35 days. PWP measurements decreased, suggesting the plants were beginning to respond to available moisture, but PAI results do not reflect this.

Figure 5 illustrates the relationship between weekly $T$ and $ET$ at each site. At SRER (Figure 5a), the ratio was higher with an average ratio value of 0.41 while at WGEW (Figure 5b) the average value was 0.36. Weekly $T/ET$ time series values (Figure 5c) at SRER were higher throughout nearly the entire study period with the exception of the period between DOY 240 and 260 when $T/ET$ values at WGEW are slightly higher.

Linear regressions were performed between the moisture fluxes ($ET$, $T$, and $E$) and soil moisture at all depths (Table 1); for this analysis, $E$ was calculated as the residual of $ET$ and $T$. At SRER, the strongest correlation between $ET$ and $\theta$ was at 37.5 cm ($R^2=0.78$, Figure 6a, Table 1). At this depth, $T$ and $\theta$ were also most strongly correlated ($R^2=0.65$, Figure 6b, Table 1). The depth of greatest correlation for $E$ and $\theta$ was 2.5 cm ($R^2=0.57$, Figure 6c). Table 1 includes $R^2$ values for $\theta$ at each depth. At WGEW, $ET$ and $\theta$ have the strongest correlation at depth 5 cm ($R^2=0.61$, Figure 6d). $T$ is most strongly correlated to $\theta_{75cm}$ with an $R^2$ value of 0.21 (Figure 6e). At WGEW, both $ET$ and $E$ are most strongly correlated with surface soil moisture ($\theta_{5cm}$).
**Timing of \( T \)**

At SRER, no isolated precipitation events of 5 mm or less could be identified in the record. In fact, only a single isolated event which was not preceded or immediately followed by another precipitation event was found within the record (DOY 227 Figure 2a). Likewise, no isolated precipitation events at WGEW which are not preceded or followed by another event within 2 days (Figure 2b) were identified within the record. Figures 7a and 7c illustrate response to events or series of events less than 10 mm at SRER and WGEW respectively. Following the precipitation event on DOY 227 (7.62 mm) at SRER, there is an immediate increase in \( ET \); however, \( T \) remains constant, not responding to the precipitation inputs. At WGEW following a series of two events totaling 5.64 mm, \( ET \) increases immediately following the storms and again there is no change in \( T \).

Figures 7b and 7d illustrate the response to series of events at SRER and WGEW respectively. At SRER (Figure 7b), following a series of 9 events totaling 78 mm of precipitation from DOY 236 to 245, \( ET \) begins to increase immediately following the first event and continues to increase for the next 10 days. \( T \) does not show a strong response to the inputs until approximately DOY 243 or seven days following the first precipitation event. \( T \) continues to increase for approximately 5 more days before decreasing along with \( ET \). At WGEW (Figure 7d), a series of 9 events from DOY 200 to 208 provided 110.7 mm of rain to the system. This was at the beginning of the growing season just as the plants were beginning to respond to the available soil moisture. Following the first
event, $ET$ responds immediately while there is a lag in the $T$ response by several days with a clear increase in $T$ by DOY 209; $T$ then begins to decrease on DOY 214.

**Discussion**

**Soil Moisture Controls on $T$ and $ET$**

Soil moisture dynamics were mainly confined to the upper 37.5 cm of soil at SRER and 30 cm at WGEW (Figure 2). In a previous study, Scott et al. (2000) found that during the summer rainy season only very infrequently was there wetting to 50cm and often no response even at 30cm at WGEW. $ET$ is correlated with 37.5 cm at SRER and 5 cm at WGEW (Figure 6). The correlation of $ET$ to shallow soil layers is typical of semiarid ecosystems which are dominated by the dry conditions, high evaporative demand, and poor infiltration (Scott et al. 2000; MacCracken et al. 2003; Kurc and Small 2004). Kurc and Small (2004) suggest water for $ET$ is found in the surface soil layer (0-5cm) during the period of summer rains. This is the case for $E$ at both sites as well as $ET$ at WGEW which are correlated to shallow surface soils; however, $T$ at both sites and $ET$ at SRER are correlated with deeper soils (Figure 6). As suggested by Kurc and Small (2004), most $ET$ loss is the result of $E$ from the soil due to the deeper roots of the plants and the large amount of bare soil surface. In contrast, at SRER the increased correlation between $T$ and deeper soil moisture could be due to larger average shrub size, soil differences, or a combination of the two (Donovan and Ehleringer 1992; De Soyza et al.
SRER has a sandier soil composition allowing for better drainage and increased infiltration, while WGEW experiences greater runoff due to the gravelly soil composition and presences of a calcite layer which prevents water from passing through it to greater depths. Because $E$ has the greatest influence on shallow surface soils (Yamanaka and Yonetani 1999), $T$ will dominate at the deeper soil layers (Kurc and Small 2007).

A common model used to estimate $ET$ and leakage losses from soil moisture uses averaged soil moisture for the entire soil profile (Rodriguez-Iturbe et al. 1999; Rodriguez-Iturbe 2000; Laio et al. 2001). Vivoni et al. (2008) suggest that in semiarid sites, the relation between $ET$ and $\theta$ is dependent upon seasonal precipitation and vegetation response. Our data show that a single averaged root zone soil moisture is likely not able to capture the dynamics of the $ET$ in these systems, because it will not be able to parse out $T$ or $E$. Precipitation rarely wets below 10 cm during the summer rains and therefore, most roots below this depth are not wetted following most events (Kurc and Small 2004). Surface soil is the primary source of $ET$ losses within the system with $E$ from bare soil being a larger contributing factor than $T$ losses from plants (Dugas 1996; Kurc and Small 2004). If surface soil moisture (within the top 10 cm) were averaged across the entire root zone, the tight coupling between surface soil moisture and $ET$, in periods when $E$ dominates $ET$, will be lost.
Partitioning of $ET$ into $E$ and $T$

The $ET$ and $T$ trends at both sites reflect the precipitation pattern with increased $ET$ and $T$ following rainfall (Figure 3). As was suggested by Scott et al. (2006a), prior to the summer rains, both SRER and WGEW $ET$ was near zero. A $T$ response was not seen until about three weeks following the commencement of summer rainfall as the plants came out of a dormant state to respond to the available soil moisture. At SRER, the plants responded after 16 precipitation events totaling 145.5 mm, while at WGEW there was a response after 22 events totaling 116.8 mm of precipitation inputs. It appears that the plant response was driven by the cumulative total of all events rather than a single large event. For the remainder of the season, $T$ remained a larger part of total $ET$ at SRER, while at WGEW $E$ continued to dominate the system. Following large pulses or precipitation, $T$ remained elevated for 2 to 10 days at both sites.

At SRER following the series of precipitation events from DOY 236 to 244, $ET$ began to increase immediately following the first event, but $T$ did not show a strong response until approximately DOY 243. Soil moisture during this time peaked at 10.7% ($\theta_{37.5\text{cm}}$) on DOY 243 from 8.8% on DOY 237. Soil moisture decreased to 9.5% by DOY 255 preceding more rain. At WGEW, from DOY 200 to 208, a period of precipitation, there is a dry down of the soil moisture at 75 cm, which is the depth of greatest relation between $ET$ and $\theta$. Soil moisture begins to increase on DOY 209 from 12.04% ($\theta_{75\text{cm}}$) and then peaks on DOY 215 at 12.94%. This coincides with the increase on $T$ on DOY 209 and peak on DOY 214. Scott et al. (2006a) found similar results stating that peak $T$ rates were lagged compared to $ET$ which peaks immediately after storms. Consistent with our
findings, the authors also showed that the length of lag increased with larger precipitation inputs and ET responses. Furthermore, similar to the findings of Scott et al. (2006a) in our study peak T rates were rarely sustained for more than a day. This suggests that the plants are almost always functioning in a water-limited state (Kolb and Sperry 1999; Schwinning and Sala 2004; Scott et al. 2006a).

At SRER, T comprised 42% of the total ET for the study period. At WGEW, T comprised only 20% of total ET. In 2003, Scott et al. (2006a) found that T accounted for 58% of total ET during the months July-October for the same study area at WGEW. For the present study, sap flow techniques were implemented on creosotebush and acacia plants, the two dominant species, however there were other woody plant species present at the WGEW field site. The combined measured T of creosotebush, acacia, and estimated T of the other species is 47% of total ET. At SRER, creosotebush is the only woody plant within the ecosystem and therefore can be said to be the majority of T within the site. The creosotebush at SRER were larger with an average height of 1.7 m as compared to 0.9 m at WGEW. This difference in size as well as the species composition between the two sites may have played a role in the differences in the T/ET partitioning (Donovan and Ehleringer 1992; De Soyza et al. 1996; Allen et al. 2008). Additionally, it should be noted that creosotebush T was a much smaller fraction of ecosystem T as compared to acacia T at WGEW. Because ecosystem T was estimated for WGEW based on the combined measure of T for creosotebush and acacia, this estimate could be an under or over estimate depending on whether other woody plant species were more or less active as compared to the species used for measurement.
Seasonal $T/ET$ can be highly variable from year to year at the same site due to climate variability and differential plant responses (Scott et al. 2006a; Reynolds et al. 2000; Knapp and Smith 2001). Similar to the 2003 study, the majority of rainfall was received in July at both sites when the shrubs were not fully able to respond to and utilize the available soil moisture. This suggests that years with more precipitation events later in the summer (August and September) would have a higher $T/ET$ ratio (Scott et al. 2006a). Dugas et al. (1996) found that average $T/ET$ values ranged from 40 to 70% in different desert sites in New Mexico. In a comparative modeling study, Kemp et al. (1997) found that annual $T/ET$ was approximately 40% for a site dominated by creosotebush with 30% cover. The amount of bare space and percent cover by woody plants will affect the $T/ET$ ratio, but these findings are comparable to our results of 42% at SRER and 47% at WGEW.

**Pulse Dynamics and Climate Change**

As a result of changes in global atmospheric conditions and hydrologic processes, it has been predicted that mean annual precipitation will be modified and that there will be increases in intra- and inter-annual variability in precipitation (Easterling et al. 2000; IPCC 2007). One of the key predictions of this shift in hydrologic processes is the increases probability of more intense precipitation events (Knapp et al. 2008) and greater inter-annual variability in summer rain (Diffenbaugh et al. 2008). These intensified intra-annual events would result in longer periods of dry conditions in between larger individual events than currently occur in these systems (Easterling et al. 2000; IPCC
With fewer precipitation events, this is likely to lead to shifts in ET dynamics, reduce infiltration, and increase runoff (MacCracken et al. 2003; Knapp et al. 2008).

Rainfall in semiarid landscapes such as SRER and WGEW are characterized by a few large pulses of rainfall and many small precipitation events that wet only the soil surface (Loik et al. 2004). This leads to rapid evaporation of the surface soil layers leaving the surface soil dry between events. Because the soil water content is low, small precipitation events are not sufficient enough to increase water content to the point of reducing plant stress (Knapp et al. 2008). If a more intense rainfall regime were to occur, water would be able to reach deeper soil layers past the zone of evaporation which could then be utilized by plants (Knapp et al. 2008).

Under the current regime of smaller, less intense storms, soil moisture at SRER and WGEW will remain very low with most water lost to E. However, if these climate predictions hold true, SRER and WGEW will have a precipitation regime including more intense storms resulting in increased volumetric water content within the soil. This increase in available moisture at deeper soil depths will favor deeply rooted plants such as the creosotebush enabling them to thrive and expedite encroachment on the grasslands.

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Journal of Hydrology 217:135-148
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APPENDIX B: HEAT BALANCE METHOD OF SAP FLOW MEASUREMENT
CONSTRUCTION MANUAL

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Theory

The stem heat balance method (HBM) is one of several methods which can be used to measure sap flow. Other methods include the heat pulse and heat probe methods (see Cohen et al. 1981, Kluitenberg and Ham 2004, Lu et al. 2004). To employ the heat balance method, thermocouples are placed along a plant stem - one at the heating element, one upstream of the heating element, and one downstream. The thermocouples measure the heat lost by conduction up and down the stem as well as radially away from the stem (Kjelgaard et al., 1997). One set is installed directly to the branch to measure conduction along the stem while a second set of thermocouples wired in series are wrapped around the stem on top of the first set of thermocouples to measure heat lost radially away from the stem.

The theory of HBM of sap flow measurement is well described by Senock and Ham (1993). The HBM uses the principle of energy balance to interpret heat fluxes in sap flow, defined as:

\[ Q = Q_v + Q_r + Q_f + S \]  \hspace{1cm} (3)

where the heat input (\(Q\)) is equal to the sum of the heat lost by conduction along the stem (\(Q_v\)), heat lost radially away from the stem (\(Q_r\)), heat transported by convection in the sap flow (\(Q_f\)), and the rate of change in heat storage in the stem (\(S\)).

Furthermore, convective heat flux can be defined as:

\[ Q_f = cF(T_{so} - T_{si}) \]  \hspace{1cm} (4)
where \( c \) is the specific heat of water, \( F \) is the rate of water flow in the stem, and \( T_{so} - T_{si} \) is the temperature difference between the water flowing in to \( (T_{si}) \) and out \( (T_{so}) \) of the heated segment of the stem.

The calculation of mass sap flow or rate of water flow \( (F) \) within the heated stem can be determined by substituting equation (4) into equation (3):

\[
F = (Q - Q_p - Q_r)/[c(T_{so} - T_{si})] \quad (5)
\]

It should be noted that an estimate of radial conductance \( (K_{rad}) \) is necessary for determining the value of \( Q_r \). A value of \( K_{rad} \) can be found when mass sap flow is zero, which often occurs during the early morning hours (Baker and Nieber, 1989, Kjelgaard et al., 1997):

\[
K_{rad} = (Q_h - Q_{up} - Q_{dn})/(\delta T_{rad}) \quad (6)
\]

where \( K_{rad} \) is \( J \cdot s^{-1} \cdot ^oC^{-1} \) and \( \delta T_{rad} \) is the temperature difference between the heating element and the outside of the thermocouple.

After determining the \( K_{rad} \) value, the radial heat loss is calculated as:

\[
Q_{rad} = K_{rad} \delta T_{rad} \quad (7)
\]
Construction

THERMOPILE

Materials:

- Thermocouple wire 30 gauge (TT-T-30-SLE) (can be purchased from Omega Engineering)
- White 24 gauge wire (can be purchased at local building or electrical supply store)
- Brown 24 gauge wire (can be purchased at local building or electrical supply store)
- Craft foam - one color for each size being made (can be purchased at any craft store)
- Epoxy or glue - Gorilla Glue is recommended
- Solder resin core and flux

Tools:

- Scissors
- Marker
- Ruler
- Wire cutters
- Exacto blade
- Wire strippers
- L-pliers
- Needle nose pliers (no teeth)
- Soldering gun

Procedure:

*Consult Photos for Clarification*

1. Cut foam to 10 cm in length. Width will depend on the size of the stem, e.g. I made three different sizes: Green - 3cm wide, Blue - 5cm wide, and Red - 6.5cm wide, each 10cm long.

2. Mark a centerline, widthwise on the foam. This will be the location of the thermocouple junctions. There must be a minimum of two thermocouple junctions on each thermopile (two on inside, two on outside). For wider thermopiles, more junctions will be needed.

3. For 2 junctions, mark 5 locations equidistant along the centerline, with the outer two being 3-5mm from the edge. For 3 junctions, mark 7 locations; for 4 junctions, mark 9 junctions; etc.

4. For 2 junctions, cut three pieces of 30 gauge thermocouple wire each 3cm long (4 pieces for 3 junctions, 5 pieces for 4 junctions, etc).

5. Strip 0.5cm of plastic coating from each end of the newly cut thermocouple wire. This can be done using your fingernail against the tabletop and pulling firmly. Alternatively, you can hold the piece of wire with L-pliers and use 28 gauge wire strippers.
6. Using needle nose pliers, twist together one end of two of the three pieces of 3cm 30 gauge thermocouple wire.

7. Solder the twisted ends. Using soldering flux helps the solder material adhere better.

8. From the non-soldered end, separate the blue (copper) and red (constant) wires of the thermocouple wire. This can be done with an Exacto blade, being careful to only cut the clear coating and not the outer blue or red coating on the wires. The wire should now look like a wishbone.

9. For the third of the three 3cm pieces, remove the clear coat and separate the red and blue wires. You will only be using the blue (copper) wire.

10. Insert the non-soldered ends of the thermocouple wishbone through the foam at the pre-marked locations. Start with the blue wire. For 2 junctions, the sequence will be blue-red-blue-red-blue. The final blue is the single blue wire. This final blue wire should be inserted into the foam like a horseshoe with both ends ending up on the outside of the thermopile (the same side as the ends of the wishbone).

11. On the opposite (outside) of the foam, twist together the exposed ends, twisting blue to red to form junctions just as was done on the inside. Solder the connections. The result should be two soldered connections and two single blue wires at the edges of the foam (for 2 junctions).
12. On both the inside and the outside of foam, press soldered ends flat to the foam forming a “W” shape for each junction.

13. Cut both white and brown 24 gauge wires to 10cm in length.

14. Strip approximately 1cm from each end of the wire.

15. Wrap the stripped end of one of the blue 30 gauge wires around one of the stripped ends of the white 24 gauge wire, and the second around the brown wire. Solder this connection.

16. Glue the 30 gauge/24 gauge wire connections to the foam in the same directions using epoxy or glue.
Inside Thermopile

- Equidistant locations
- Single Blue Wire
- Junctions at 3-5cm from edge
- Centerline

Outside Thermopile

- 30/24 gauge connection with Glue
- Glued in same direction
- "W" shape junctions
THERMOCOUPLE

Materials:

- Thermocouple wire 36 gauge (TT-T-36-SLE) (can be purchased from Omega Engineering)
- Blue 24 gauge wire (can be purchased at local building or electrical supply store)
- White 24 gauge wire (can be purchased at local building or electrical supply store)
- Green 24 gauge wire (can be purchased at local building or electrical supply store)
- Heat shrink tubing HST250 (can be purchased at a local electrical supply store)
- Heat shrink tubing HST093 (can be purchased at a local electrical supply store)
- Solder resin core and flux

Tools:

- Wire cutters
- Wire strippers
- Exacto blade
- Needle nose pliers (no teeth)
- Soldering gun
- Heat gun
- Voltmeter

Procedure:
Consult Photos for Clarification

1. Cut blue, white, and green 24 gauge wire to 10cm lengths.

2. Strip plastic coating 1cm off one end and 0.5cm off the other end of each piece.

3. Cut three pieces of 36 gauge thermocouple wire to 10cm, 15cm, and 20cm lengths.

4. Strip 0.5cm from each end of each piece using 30/32 gauge wire strippers.

5. For each wire: at one end, tightly twist together and solder the exposed ends. At the other end, separate the blue and red wires a distance of 0.5cm (do not separate the entire length of the wire) by slicing the clear coating with an Exacto blade.

6. Twist together all three exposed red (constant) ends (one from each of the three pieces). Solder this connection, leaving the three blue (copper) ends separated and exposed.

7. Identify the blue exposed end of the 10cm piece and twist it around the 0.5cm stripped end of the green wire. Wrap as tightly as possible.

8. Identify the blue exposed end of the 15cm piece and wrap it around the 0.5cm stripped end of the white wire.

9. Identify the blue exposed end of the 20cm piece and wrap it around the 0.5cm stripped end of the blue wire.

10. Solder all three connections.
11. Cut 4 pieces of the narrower heat shrink about 1cm long.

12. Cut one piece of the wider heat shrink about 2cm long.

13. Cover the soldered connections made in Steps 6-9 with the narrower heat shrink. Apply the heat gun using the lowest setting to ensure that you do not melt the wire coating.

14. Slide the wider heat shrink over the now covered connections and apply the heat gun. Immediately after heating, use the needle nose pliers to squeeze the ends of the heat shrink around wires to limit any gaps between the wires and wrap.

15. Be sure to test the thermocouples to make sure that there are no breaks in the wires. Using the voltmeter set to 200 ohms, test each combination of pairs of wires: Blue-White, Blue-Green, and White-Green. Resistances should be between 9-15 ohms with Blue-White having the highest and White-Green having the lowest resistance.
Thermocouple

Internal Thermocouple Connections

- 20 cm thermocouple wire connected to Blue
- 15 cm to White
- 10 cm to Green
- Narrow Heat Shrink
- Wide Heat Shrink

Narrow Heat Shrink

- 3 Red (constant) ends
- Soldered

Blue (copper) wires soldered to corresponding 24 gauge

Soldered ends
HEATER

Materials:

- Red 24 gauge wire (can be purchased at local building or electrical supply store)
- Heat Constant Wire (TFCC-003) (can be purchased from Omega Engineering)
- PVC pipe (1/2” x 10’) (can be purchased at a local building supply store)
- Heat Shrink tubing HST093 (can be purchased from local electrical supply store)
- Electrical tape
- Soldering resin core and flux

Tools:

- Hand saw
- Wire Cutters
- Wire Strippers
- Needle nose pliers
- Soldering gun
- Heat gun

Procedure:

Consult Photos for Clarification

1. Cut PVC into pieces approximately 5cm long.

2. Cut 2 pieces of Red 24 gauge wire to 10cm in length.

3. Strip 1cm off one end and 0.5cm off the other for both pieces.
4. Cut heating wire to 3m in length. Avoid kinks in wire which will increase chances of it breaking.

5. Fold the wire in half and tape the folded end near one end of the PVC using electrical tape. Begin wrapping the wire around the PVC. Try not to wrap over tape, as it makes installation easier. When about 10cm of wire remains, tape wire to PVC.

6. Strip 1-2cm off each end of the heating wire. This can be done using your fingernail or blunt end of an Exacto blade.

7. Wrap each stripped end of heating wire around one of the 0.5cm stripped end of the Red 24 gauge wires.

8. Solder these connections.

9. Cover connections with heat shrink and apply heat gun being careful not to melt wire coating. Using pliers, flatten the tube end around the heating wire to close the end.

10. Carefully insert 24 gauge wire into the PVC tube and tape to inside wall. Be sure to tape well as this will easy the installation process. Also, be careful as the connection between the heating wire and the 24 gauge wire can easily break.
Heater

Heating wire/ 24 gauge connection

3m of Heating wire

Heating wire folded and taped

24 gauge wire taped inside PVC
Installation

Materials:

- Ruler
- Electrical tape
- Small plastic wire nuts - 7 per sensor
- Double-sided Velcro strips (can generally be purchased at hardware stores in the plant section or local craft store)
- Pipe installation (5/8” and 11/8”) (can be purchased at local building supply store)
- Aluminum foil
- Foil-lined bubble wrap (can be purchased at select local hardware or building supply store)

Tools:

- Wire Cutters
- Wire Strippers
- Exacto blade
- Straight Pin

Procedure:

Consult Photos for Clarification

HEATER

1. Heater should be installed at least 30cm above the soil surface. Starting with the folded end of the heating wire, tape the fold onto the branch and begin to wrap the wire around the branch moving downward. Be sure to wrap as tightly as possible
while creating minimal gaps and overlap, not pulling the wire too tight as it will break.

2. When all the wire has been wrapped around the branch, the two red wires should be at the bottom. Tape wire and connections to branch securely.

**THERMOCOUPLES**

3. Thermocouples should be installed with the blue (longest) above the heating wire, white in the middle of the heating wire, and the green (shortest) below the heating wire. The thermocouples above and below should be placed the same distance from the heating wire. For example, 1.5cm above and below the wire. The middle thermocouple should be located in the middle of the heating wire.

4. Depending on the plant being used, the thermocouples can be installed above or below the bark.
   a. If installing above the bark, use electrical tape to secure the soldered thermocouple ends to the bark horizontally with respect to the direction of the branch ensuring good contact with the bark. The middle thermocouple should be installed beneath the heating wire.

   b. If installing under the bark, trim the soldered thermocouple ends to approximately 0.5cm in length. Use a straight pin to make a hole horizontally with respect to the direction of the branch under the bark in
the sapwood. Be sure to not rip the bark. Insert the thermocouple into the hole and secure with electrical tape.

**THERMOPILE**

5. Place the thermopile over the heating wire, lining up the inside soldered junctions with the middle thermocouple. The white and brown wires should be pointing downward in respect to the branch.

6. Wrap the foam thermopile around the branch and secure with Velcro strips.

**WIRING AND INSULATION**

7. 7 wires should now be at the bottom of the sensor - 2 Reds, 2 Whites, Blue, Green, and Brown. Wire these to the cable connected to the datalogger. One red should be wired to the black in the cable. The 2 white wires should be wired together to the white wire in the cable. These connections should be secured with wire nuts.

8. Cut pipe insulation to appropriate length to cover entire sensor with at least an additional 3cm on each end.

9. Wrap the 5/8” insulation with the opening opposite that of the thermopile. Secure with Velcro strips. Wrap the 11/8” over the 5/8” and secure with Velcro.

10. Wrap the pipe insulation with aluminum foil being sure to pinch the ends to prevent insects or water from getting in.
11. Wrap foil-lined bubble wrap around the aluminum foil and secure with Velcro.

Add a ‘cap’ of bubble wrap to the top of the sensor to prevent water from getting in. Silicon can also be used to make a ‘cap’ around seams to keep water out.
Thermocouples

Blue (Longest)

White (Middle)

Green (Shortest)

Thermopile

Secured with Velcro

White and Brown Wires Point Down
Pipe Insulation

Aluminum Foil

Connections with Wire Nuts
References and Useful Literature


