May 2019

# Tree to Grass Water Use Ratios; Assessing Turfgrass' High Water Use in the Urban Landscape

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# TREE TO GRASS WATER USE RATIOS; ASSESSING TURFGRASS' HIGH WATER USE IN THE URBAN LANDSCAPE

By

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Bachelor of Science in Plant Science
Cornell University
2009

A thesis submitted in partial fulfillment
of the requirements for the

Master of Science - Biological Sciences

School of Life Sciences
College of Sciences
The Graduate College

University of Nevada, Las Vegas
May 2019

# Thesis Approval

The Graduate College
The University of Nevada, Las Vegas

November 18, 2018

This thesis prepared by

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entitled

Tree to Grass Water Use Ratios; Assessing Turfgrass' High Water Use in the Urban Landscape

is approved in partial fulfillment of the requirements for the degree of

Master of Science - Biological Sciences
School of Life Sciences

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## Abstract

Water demand in the southwestern United States continues to rise. The population of the Las Vegas Valley doubled from 2000-2010 and now more than two million people call it home. The residential sector uses 60% of all water consumed in the valley. Outdoor urban landscape irrigation is responsible for 70% of all residential use. These landscapes are dominated by trees and turf grass. Although the water use of turf grass species is well studied, there are few published results about the water use of landscape trees in the desert southwest USA. To obtain a more complete picture of the tradeoffs between grasses and trees in urban landscapes in Southern Nevada, we conducted a tree to grass water use ratio study focusing on 10 common landscape trees and four turf grass species grown in the valley. We estimated water use by closing hydrologic balances (Evapotranspiration=water input-drainage-change in soil water storage) on mature trees planted in the ground and turf grass grown in lysimeters. We estimated transpiration of trees using Granier probes and estimated conductive tissue with a novel dye injection system. Sapflow was lower than the hydrological balance estimated evapotranspiration (ET) because of significant evaporation rates associated with irrigating trees in a desert environment. The values for sapflow ranged from 10 to 50 cm per year. Trees used less water than grass in nine out of 10 cases with an ET 38-88 cm/year determined by a hydrological balance. The exception was *Lagerstroemia indica* that used 196 cm year$^{-1}$ which was similar to the grass ET (106-262 cm year$^{-1}$) again determined by hydrological balance. We also developed models that predicted the tree water use based on reference evapotranspiration ($ET_{ref}$) and morphological characteristics such as tree height, canopy volume, basal canopy area, leaf area index (LAI) and leaf area. Replacing turf grass and planting trees can save water, if the right

species are selected. However, turf grass serves its purpose in many areas by providing aesthetics and recreational use. Water use values are listed to help assist in making landscape tradeoffs.

## Acknowledgments

I’d like to first acknowledge God, who makes all things possible. Thank you also to my parents and family that have been my biggest cheerleaders, best volunteers, and a source of love. Without Dale Devitt and his help, none of this would be possible, so thank you Dale! His kindness and father like leadership has kept me working and enjoying science. Lastly, I’d like to thank my committee for their support and guidance through the Master’s program.

## Table of Contents

## List of Tables

**List of Figures**

## Introduction

The Mojave Desert in the southwestern U.S.A. receives very little rain during the year. Even though water supplies are limited, people in the Las Vegas Valley and surrounding areas continue to place nonnative landscape plants that consume a lot of water in the ever expanding housing developments. Most (60 percent) of the water used in the valley is used outdoors (Southern Nevada Water Authority 2018) and 66 percent of residential water is used to irrigate the urban landscape (Devitt et al. 2008). To save water, the common trend now is to remove turfgrass and plant landscape trees to save water but do landscape trees use less water than the grass?

A study conducted Devitt et al. (1995) recorded young landscape trees used more water than turfgrass with tree to grass water use ratios ranging from two to four. But what about water use by mature trees, which have higher water use efficiency and canopy aerodynamic resistance than young trees (e.g. *Quercus rubra*, a temperate forest species; Cavender et al. 2000)? Landscape trees in the desert may demonstrate a similar characteristic. Few scientists have recorded the water use of landscape trees, although many scientists have measured the water use of turfgrasses, even fewer studies show a direct comparison of the tradeoffs between landscape trees and grasses, and none in Southern Nevada.

The arid desert region of Southern Nevada is an excellent place to quantify the water use of trees and grass due to the region’s minimal precipitation. Because trees in urban areas obtain most of their water as irrigation, water balances can be accurately closed using a hydrologic approach. In this study, evapotranspiration (ET) estimates were found by closing a hydrological balance (ET=Irrigation/Precipitation-Drainage-Change in soil water storage) on ten different mature landscape tree species. The hydrological balance was closed by measuring each one of the parameters in the equation and plugging the numbers into the equation to get the estimate for evapotranspiration. This estimate was then compared to transpiration estimates attained with sap flow sensors inserted into the trunk. Trees can vary their water use dependent on water availability, widely known to be true for native species (opportunistic species) (Devitt et al. 1994). Trees and grass were provided irrigation amounts based on how much water was used on a weekly basis. Four turfgrass species were also used in the study to determine water usage. Based on inherent species differences in water use efficiency ($C_3$ vs. $C_4$ grasses) we postulated significant differences in water use of the four grass species and this should lead to significant differences in the tree to grass water use ratios. If this is true, significant tradeoffs between trees and grasses should be possible in the urban landscape.

Devitt et al. (1995) assessed the comparative water use of turfgrass and ornamental trees in an arid environment. Their results demonstrated that young ornamental trees used more water than turfgrass based on basal canopy area. The tree evapotranspiration rate of *Q. virginiana* ‘Heritage’ (oak) compared to low fertility *Cynodon dactylon* (Bermuda) grass had a 3:1 ratio. *Prosopis alba* (Mesquite) and *Chilopsis linearis* (Desert Willow) showed similar ratios. When comparing tree water use to *Festuca arundinacea* (Fescue) water use, the trees used more water, although at a smaller average rate throughout the year. It was estimated that larger trees could possibly use even more water than turfgrass, but questions associated with accurate scaling were noted.

## I. Water Use of Ornamental Landscape Trees

Few scientists have approached the subject of water use of ornamental trees. Ansley (1994) compared stem flow gauges with porometry to estimate transpiration of *Prosopis glandulosa* (honey mesquite). These trees grew in a large tree stand of *P. glandulosa* with 200 trees ha$^{-1}$. Human destruction of the trees in the 1960s caused coppice growth since that time. When the study was performed the trees stood 3.5 m tall. Using stem flow gauges (Dynamax), the team of scientists estimated that in June and October, 30 km south of Vernon, TX (a semi arid region), the tree's transpiration was 108 kg (108 L) day$^{-1}$ in June. The measurements taken with porometry compared somewhat to sap flow gauge estimations of transpiration, however, the accuracy of the porometer declined with increased transpiration. This study did not include a hydrological balance method to cross check the values obtained with the stem flow gauges. The values for transpiration were relatively high compared to turfgrass in Southern Nevada, although this reading only reflected summer time water use.

Zajicek and Heilman (1991) studied the transpiration of four different varieties of *Lagerstroemia indica* (crepe myrtle) under different land cover in College Station, TX on the 16th of August 1989. The scientists used sap flow gauges in addition to weighing the trees to estimate the amount of water each tree used during the course of the study. Trees ranged in height from 20 cm to 65 cm, depending on the variety, and were one-year-old plants. Plants grew in pots placed in holes in a plot of land with undescribed distances between trees, watered to saturation daily at sunset. Sapflow was estimated for only two 2-day intervals. The results revealed the water use rates per unit of leaf area over a course of 24 hours for the four varieties were somewhere between 4.63 to 3.55 kg m$^{-2}$ day$^{-1}$. If the values are extrapolated, the trees used as much as 1690 kg per year. Most likely *L. indica* uses less water per year, since the estimate was based on the summer period. The short interval of measurements may not have accurately reflected the water use of *L. indica* (crepe myrtle) on a yearly basis. However, this plant is native to tropical East Asia (Rohwer, 2000) suggesting it grows naturally with large amounts of available water.

Interestingly, evapotranspiration (ET) and growth can vary based on different irrigation regimes (Devitt et al., 1994). *Prosopis alba*, *C. linearis,* and *Q. virginiana* grew in lysimeters in Southern Nevada while watered based on three different leaching fractions (+0.25, 0, -0.25) to see if evapotranspiration varied dependent on irrigation amount. The lysimeters were weighed once a week to determine the water use of the young one to two meter tall trees. The trees growing in tanks (lysimeters) were placed in the ground in concrete sleeves with insulation placed in between the lysimeter and the concrete sleeves with five meters separation between trees. The area between the trees was planted to turfgrass with drip irrigation. Based on the size of the trees and openness of the experimental plot, turbulent wind moved unimpeded and no shading of trees occurred. The analyses showed that the average yearly ET showed significant differences between leaching fractions for all three species. Also, the size of the tree influenced the ET of the oak and willow, with the oak ET closely correlating with all growth parameters. These trees varied their water use based on the amount of water irrigated.

An earlier study done by Devitt et al. (1993) demonstrated that stem flow gauges could accurately estimate transpiration by using a hydrologic balance approach. The three young tree species were grown in lysimeters and hoisted onto a top loading balance to measure water loss during a period from May to August. The average estimate of the three species was about one centimeter per day. If we extrapolate that estimate for the May to August period the value exceeds 120 cm, which greatly exceeds the water use of most turfgrass species.

A similar study done in Arizona, demonstrated *P. alba* used more water than *Q. virginiana* when given unlimited water (Levitt et al., 1995). Again, similar to Devitt et al. 1994, the trees ranged between 1-2 m tall, were placed in a grid with the trees spaced 4m apart, and weighed to determine the ET. The experiment only ran for four months and their basic statistics showed a significant difference between mesquite water use (0.55 to 4.07 L per day) and oak water use (0.35 to 5.50 L per day), again with unlimited irrigation applied.

The question whether tall mature trees use more water per area than short trees remains unanswered. Bennett et al. (2015) compiled data from other studies that measured tree growth (n=13) and tree mortality (n=14) on trees from natural wooded areas experiencing drought. The findings showed that tall trees exhibited a greater decrease in growth rate and a greater increase in mortality in drought.  The paper suggested that the patterns may be attributed to responses of canopy versus understory species. They were unable to substantiate whether small and tall trees in the studies were of the same species.  Within the compilation of 40 drought events that occurred worldwide, the study did not mention the age of the trees, which plays an important role in the determination of water use efficiency and ability to survive drought. From the results, it seems that large trees use more water than short trees, although results may have been skewed with confounding factors.

Pataki et al. (2011) recorded estimates of the water use of landscape trees in southern California, with the caveat that the estimates really were specific to that region with its particular climate. The study used Thermal Dissipation Probes in 14 tree species in the Los Angeles Metropolitan area and found the water use per tree ranged from 0.8 kg tree$^{-1}$ day$^{-1}$ to 176.9 kg tree$^{-1}$ day$^{-1}$, depending on the tree species. These trees grew as single trees in several different urban areas such as a University campus, the zoo, an arboretum, and as plantings adjacent to the street. The trees had a range of diameters at breast height (dbh) ranging from 12.1 cm to 61 cm, with most trees in the 40-50 cm range, therefore the study encompassed mature trees. The largest water user grew near the street, *Platanus hybrida* (London Sycamore), and the lowest water user grew in an unirrigated landscape at the zoo, *Malosma laurina* (Laurel Sumac), a native to Southern California. Likely street trees that stand alone use more water due to their increased surface area exposed to the wind and sun, as opposed to trees planted in a denser stand. Also, the region of origin of these species may have contributed to their water use. Several trees used in our study were used by Pataki et al. (2011): *L. indica* (crepe myrtle) used 45.3 kg tree$^{-1}$ day$^{-1}$, *U. parvifolia* (elm) used 67.7 kg tree$^{-1}$ day$^{-1}$, and *G. tracanthos* (locust) used 89.9 kg tree$^{-1}$ day$^{-1}$. It should be noted that, these trees did not get watered according to their respective evapotranspiration rates. Rather, the irrigation amounts generally went unknown. It is unknown how the trees in the Pataki et al. study (2011) might have responded with different irrigation amounts.

## II. Water Use of Turfgrass

Many have studied the water use of different kinds of turfgrasses in the southwest in the 1980s and 90s. However, none directly compared the use of tree and grass water use at the same field site. Kim and Beard (1988), Salaiz et al. (1991), Bowman and Macaulay (1991), and DaCosta and Huang (2006) all used mini-lysimeters to measure turfgrass actual ET ($ET_a$). Mini-lysimeters tend to overestimate the amount of water used by the plant due to the soil matrix discontinuity at the bottom of the lysimeter to the soil underneath restricting drainage (Devitt personal observation). Kim and Beard identified the ET of 12 different turfgrasses grown with nonlimiting water and fertilization at rates applied to golf courses. Despite using mini-lysimeters, they found that *C. dactylon* (Bermudagrass) used about 180 cm year$^{-1}$ from measurements done for three months and *F. arundinacea* used 219cm year$^{-1}$. The grass ET was determined by the water balance method by weighing the mini-lysimeters on a daily basis. *Lolium perenne* (Creeping Bentgrass) varied between 3.2mm day$^{-1}$ to 10.7 mm day$^{-1}$ throughout 1987 and 1988 in Nebraska (Salaiz et al, 1991). The grasses were mowed five times a week to keep the grass short and watering was determined by weighing minilysimeters 14 times between May and October. Some of the variation in ET may have been driven by the infrequent weighings. Bowman and Macauley in Reno, NV estimated water use *F. arundinacea* cultivars in April. Scientists estimated ET by using mini-lysimeters weighed on a daily basis for a week. *F. arundinacea* 'Monarch' used 6.23 cm for the week measured. This paper did not provide explicit information about fertilizer input, which may have influenced ET in an unknown way.

Schiavon et al. (2017) used a plot of perennial ryegrass to assess performance and to measure ET, without the use of lysimeters. Unfortunately, the adjacent plots were not provided with buffer to isolate roots, and horizontal water movement under sprinkler irrigated conditions.

The reference ET ($ET_{ref}$) for the study was 147 cm year$^{-1}$ and the scientists found that even watering at 100% $ET_{ref}$, the cool season grass did not do well in the summer at UC Riverside.

Another recent study, Litvak et al. (2016), studied the ET of grass in metropolitan Los Angeles area. This study did not control irrigation, fertilization, or drainage at any site, but simply took data from the grass being managed by a third party. The numbers from this study predicted an ET of 165 cm year$^{-1}$ for *C. dactylon*.

Devitt (1992) determined ET for desert turfgrasses. The research included *C. dactylon* over seeded with ryegrass at three sites within Las Vegas, NV. The golf course *C. dactylon* was estimated to use 150 cm vs. 106 cm for *C. dactylon* in a park setting due to increased fertilization at the golf course. This fertilization response agreed with the 1989 study by Devitt and Morris that showed that increased nitrogen fertilization increased evapotranspiration.

## III. Turfgrass and Trees

Litvak et al. (2017a) modeled differences between urban landscape trees and urban turfgrass in Southern California. The authors measured ET based on Land Data Assimilation System and in situ measurements from a previous study Litvak et al. (2017b). From the modeled ET, grass used more water in mm per year when compared to the trees per each city council district. Water use in this study and the previous study mentioned by Litvak assumed nonlimiting irrigation and did not measure fertilizer inputs. Given these conditions, it is unclear what were the exact water needs of both urban landscape trees and turfgrass and what the possible tradeoffs were between these plant forms.

Our study aimed to determine possible water use tradeoffs in urban landscapes based on comparing water use of turfgrass on an area basis equivalent to the basal canopy area of the trees. These ratios will vary based on turfgrass species, with cool season *F. arundinacea* using significantly more water than warm season *C. dactylon*. Also, given that this current study included the morphological assessment of the trees, such as tree height, basal canopy area, canopy volume, leaf area density, and trunk diameter we believe it may be possible to estimate monthly and yearly actual evapotanspiration of tree species. The accuracy of these estimates will be species dependent and dependent on the inclusion of reference evapotranspiration.

The environment, people’s livelihood, and the quality of life depend on the efficient use of water in urban places, especially with continually sprawling metropolises and dwindling water supplies (Hilaire et al., 2008). Reducing the total amount of water used in the urban landscape will act as a critical component of balancing supply and demand. Landscapers will need to choose the proper tree and grass species to achieve these lower water use rates in urban landscapes.

## Methods

The research was conducted at the University of Nevada's Center for Urban Water Conservation in North Las Vegas, NV. A large tall fescue plot containing lysimeters was selected for the study. Six of the existing lysimeters were selected; three with tall fescue (*Festuca arundinacea* var. Monarch*)* and three converted to perennial ryegrass (*Lolium perenne* var. Palmer Prelude). The lysimeters size was 0.5m diameter and 1.22m deep. These lysimeters were centrally located in the larger fescue plot surrounding a weather station that monitored atmospheric conditions, enabling estimates of reference evapotranspiration (ETref) using the empirical based Penman Monteith equation (Allen et al. 1998). In an area 100 m north east of the tall fescue plot, an additional turfgrass plot planted to bermudagrass 5 years earlier was also selected for the study. This turfgrass plot also contained lysimeters of which 6 were selected; three with the existing bermudagrass (*Cynodon dactylon* var. Tifway) and three converted to bentgrass (*Agrostis stolonifera* var. TI Creeping*)*. The lysimeters were placed there in 2009 and filled with the native North Las Vegas soil attained from the hole dug for the lysimeters, which was leveled to the ground. A stand of 100 landscape trees was also included in the study. The trees had been planted twenty years earlier. The tree plot contained (Mesquite *Prosopis alba* Grisebach, Ash (Modesto and Arizona) *Fraxinus velutina* 'Modesto' and *Fraxinus velutina* 'Arizona', Desert Willow *Chilopsis linearis*, Oak *Quercus virginiana*, Palo Verde *Parkinsonia florida*, Vitex *Vitex agnus-castus*, Locust *Gleditsia tricanthos*, Elm *Ulmus parvifolia* and Crepe Myrtle *Lagerstroemia indica*). Three trees of each species were selected out of the ten by ten tree grid where trees were planted on 4.88 m center to center spacing. All of the trees were surrounded with 1.8 m diameter irrigation basins, however in the case of the 30 trees selected for this study all irrigation lines were capped off such that water was only delivered via a metered hose. Prior to the start of the study, a trencher dug 1.2 m down every row in all directions cutting all roots leaving or entering each watering basin.

Each of the watering basins surrounding the 30 trees and all of the lysimeters selected for this study had access tubes inserted to a soil depth of one meter to allow a PR2 Theta Probe (Dynamax, Houston, TX) to be inserted to estimate soil volumetric water content at depths of 10, 20, 30, 40, 60 and 100 cm. Measurements were taken on a weekly basis during the study. These soil moisture estimates were then entered into a hydrological balance equation to determine evapotranspiration (ET=Input-Output-Change in Soil Water Storage). The input in the equation signifies the irrigation or precipitation that occurred during the previous week. This irrigation was applied with a hose attached to a digital pvc water meter (TM075 Great Plains Industries, Inc) and the water shot into a bucket that sat on a mat, to prevent the basin from eroding. The output in the equation denotes the drainage which was determined in the trees to be negligible based on little or no change in soil water content estimates (time domain reflectometry probe) at a depth of 150 cm (one tree of each species). Change in water storage reflects the soil moisture change in the entire one meter profile from week to week. With the grass, drainage was determined by a vacuum pump pulling water from ceramic extraction cups from the bottom of the lysimeter. All plants then received irrigation water for the next week based on the previous weeks ET, thus minimizing the possibility of a drainage component.

Thermal Dissipation Probes (Dynamax, Houston, TX) were inserted into the trunks of all experimental trees to continuously measure sap flow. The sensors were all inserted on the north side and at a height of 0.75m off the ground. The probes selected were one centimeter in length to minimize the entry of the probe beyond the sapwood that would otherwise distort the measurement. These probes were connected to a data logger (CR1000, Campbell Scientific, Logan, UT) in the middle of the stand of trees that recorded measurements every thirty seconds, storing 30 minute averages. The data were downloaded to a laptop and analyzed by converting the sap velocity measurements to transpiration. First the dimensional parameter K needed to be defined as $K=(\Delta TM-\Delta T)/\ \Delta T$, where $\Delta T$ is the difference in temperature between one heated probe and the other non-heated probe. The other value $\Delta TM$ is the value of $\Delta T$ when there is no sap flow. Sap flow velocity V (cm/s) can be related to K by V=0.0119*K^1.231. The sapflow of the tree was determined by the equation $F_s = A_s{}^{*}V*3600$ (s/h), where $F_s$ ($cm^3$/h) is the sap flow, V is the average sap flow velocity, and $A_s$ is cross sectional area of sapwood (active) as described below.

In order to convert the sap flow velocities to transpiration, the area of conductive xylem tissue needed to be quantified. The sapwood area was estimated by injecting a colored dye into the conductive tissue. To accomplish this, a small area of bark was removed and a rubber stopper was affixed to the trunk of each tree (strong adhesive). The stopper had a 1 cm diameter hole drilled into the middle of the stopper and a second smaller hole drilled as a vertical hole between the outside of the stopper and the inside hole of the stopper to purge air bubbles from the system. A hole was then drilled though this central hole in the stopper into the tree to a depth of approximately 10 cm. A plastic bottle with a bent nozzle on the top was filled with water and placed into the hole and sealed with silicone glue and supported with elastic bands. A small hole was drilled into the top of the plastic bottle to properly vent the bottle to allow the water to freely move into the sapwood under natural tension in the xylem. Once the hole was fully charged with water and water was observed flowing from the vertical hole in the stopper, a nail was inserted into the top of the stopper. After a two-day period in which water was flowing into the tree at a somewhat constant rate, we switched the water to a red dye (Kool-Aid, a mixture of 2 packets per liter of water). This bottle then stayed on the tree for a week. Levels of dye in the bottle were observed daily and additional solution was added as needed to maintain a constant head. At the end of the one week period the stopper and dye injection system were removed and a core was taken 2.5 cm above the hole injected with red dye. The cores were dried and mounted on wood and the sapwood area was estimated based on the length of the core stained red. Photos were taken of the cores under a microscope (Leica M27s, Leica, Buffalo Grove, IL), with a Nikon D60 camera (Nikon, Melville, NY) and analyzed with ImageJ (Schneider, et al., 2012) and measured with Photoshop (Adobe).

Morphological measurements of the trees were taken using a hydraulic lift. This lift enabled accurate measurements of height, canopy rib (start at the top of the canopy and descend down to the base on the outer edge of the canopy) length in four cardinal directions. The diameter of the canopy was also measured at the top, middle and bottom of each tree on a north, south east and west basis. Trunk diameters were measured at a height of one meter. In addition, leaf area index was assessed with a leaf area index wand (Li-cor 2100, Li-Cor, Lincoln, Nebraska). Monthly physiological measurements (see below) were taken to verify that the trees were not under water stress based on irrigating at the previous weeks ET rate.  Physiological measurement included: canopy temperatures (39800 Infrared Thermometer, Cole Palmer, Vernon Hills, IL), stomatal conductance (SC-1 Porometer, Meter Group, Pullman, WA) leaf xylem water potential (Pressure Chamber, PMS Instruments, Albany, OR) and chlorophyll index (FieldScout CM1000 Chlorophyll Meter, Spectrum Technologies, Aurora, IL). Canopy density was assessed by measuring Photosynthetic Active Radiation (PAR) (LI-190R, Li-Cor, Lincoln, Nebraska) in open areas and comparing that to measurements taken at the base of the canopy of each tree, allowing for a PAR ratio to be generated.

Trees received fertilizer once per year in the early spring (same regiment as the last 21 years). Nitrogen was applied at a rate of 325 g tree$^{-1}$ with a 15-15-15 (N-P-K) fertilizer. Iron chelate was applied 30 g tree$^{-1}$ and sulfur was applied at 225 g tree$^{-1}$. The grass had fertilizer applied once a month on each lysimeter with ammonium sulfate 21-0-0 at a rate of 227 g of nitrogen 1000 sq. feet$^{-1}$. Clipping height was 5.08 cm for *F. arundinacea* and *L. perenne*; height was kept at 2.54 cm for *A. stolonifera* and *C. dactylon*. The grass was clipped using hand shears on a weekly basis.

Data was analyzed using descriptive statistics, analysis of variance, linear and multiple regression analysis (Sigmaplot, Systat Software, San Jose, CA).

## Results

### I. Climate

Climatic conditions reported for the study were obtained from a weather station located in a larger *F. arundinacea* ‘Monarch’ plot. Ambient temperature ranged from 45.3° C in the summer to -3.9° C in the winter, with a mean temperature of 26.5 ± 9.6° C. Rainfall at the site was 87.36 mm for November through June 2016, and 64.01 mm for July to June 2017. The mean wind speed was 1.9 ± 0.8 $ms^{-1}$. The reference ET estimated from weather station parameters was 156.19 cm for July 2016- June 2017 and 136.44 cm for July 2017 to May 2018.

## II. Morphology of Trees

The mature trees ranged in height from 3.37 ± 0.38 m to 6.95 ± 0.35 m (means with standard deviations, Table 2). The smallest trees in the study were *L. indica* and *F. velutina* 'Modesto', whereas *F. velutina* 'Arizona' and *Q. virginiana* stood the tallest in the grove of trees. The maximum trunk diameter at 1 m from the soil surface was 22.25 ± 2.02 cm for *Q. virginiana* with the smallest trunk diameter measured was for *C. linearis* at 10.52 ± 5.05 cm, with an overall average trunk diameter for all species of 15.35 ± 4.63 cm. Most of the trees had basal canopy areas between 17 and 25 $m^2$. The tree with the maximum basal canopy area was *P. florida* at 29.62 $m^2$ and the smallest was 4.95 $m^2$ for *L. indica*, with an overall average basal canopy area for all species of 19.78 ± 7.18 $m^2$. The canopy volume also varied greatly based on species with a maximum of 108.19 $m^3$ for *Q. virginiana*, a minimum of 6.65 $m^3$ for *L. indica* with an overall canopy volume average for all species of 48.17 ± 28.38 $m^3$.

Leaf Area Index (LAI) is reported in Table 3. The lowest LAI was 0.49 for *P. alba*, which had a very open widespread canopy. Other low values included the *U. parvifolia* (0.53), *P. florida* (0.74), and *C. linearis* (0.75). Whereas, *Q. virginiana* (2.22) and *L. indica* (1.68) exhibited the highest LAI values. The area of the individual leaf played a significant role in determining LAI. The smallest individual sun leaf area averaged 0.5 $mm^2$ for *P. florida*. However, some trees had large sun leaves, such as the *G. tricanthos* at 51.5 $mm^2$ and *F. velutina* at 47.3 $mm^2$. Shade leaves ranged in size from 0.9 $mm^2$ to 46.4 $mm^2$ for *P. florida* and *F. velutina* 'Modesto' respectively.

Table 1. Tree morphological characteristics (Height (Ht), Trunk Diameter, Basal Canopy Area (BCA), and Canopy Volume) taken for all 10 species in 2016 in North Las Vegas. Values are means with one standard deviation.

| Tree Species | Ht (m) | Trunk Diameter (cm) | BCA ($m^2$) | Canopy Volume ($m^3$) |
|---|---|---|---|---|
| *Chilopsis linearis* | 5.97± 0.32 | 10.52± 5.05 | 24.75± 6.52 | 54.86± 15.51 |
| *Fraxinus velutina* ‘Arizona’ | 6.95± 0.35 | 17.60± 3.71 | 19.05± 0.97 | 59.11± 4.83 |
| *F. velutina* ‘Modesto’ | 4.18± 0.21 | 13.09± 0.80 | 16.61± 2.69 | 27.43± 3.11 |
| *Gleditsia tricanthos* | 4.62± 0.83 | 15.50± 1.30 | 17.72± 6.69 | 33.70± 18.55 |
| *Lagerstroemia indica* | 3.73± 0.45 | 8.90± 0.81 | 5.69± 0.64 | 3.14± 2.44 |
| *Prosopis alba* | 5.30± 0.11 | 21.40± 0.77 | 22.16± 2.27 | 52.71± 28.43 |
| *Parkinsonia florida* | 5.77± 0.38 | 17.86± 1.62 | 29.62± 4.70 | 93.10± 18.49 |
| *Quercus virginana* | 7.10± 0.27 | 22.25± 2.02 | 20.49± 6.57 | 74.53± 29.32 |
| *Ulmus parvifolia* | 5.57± 0.12 | 15.77± 0.81 | 22.85± 4.77 | 60.42± 15.25 |
| *Vitex agnus-castus* | 3.37± 0.38 | 12.13± 1.62 | 19.67± 4.95 | 27.30± 13.84 |

Table 2. Leaf Area Index (LAI) and Photosynthetically Active Radiation measured underneath the canopy (inverse, 1/PAR) and the leaf area for leaves in the shade and in the sun for all ten tree species in North Las Vegas. Data are means with one standard deviation.

| Tree Species | LAI | 1/PAR | Sun Leaf | Shade Leaf |
|---|---|---|---|---|
| *Chilopsis linearis* | 0.76± 0.01$_{a}$ | 2.33± 0.74$_{a}$ | 2.07± 0.23$_{a}$ | 2.47± 1.42$_{a}$ |
| *Fraxinus velutina* 'Arizona' | 0.76± 0.03$_{a}$ | 2.22± 1.30$_{a}$ | 42.75± 6.29$_{c}$ | 45.55± 10.54$_{b}$ |
| *F. velutina* 'Modesto' | 1.21± 0.22$_{a}$ | 2.71± 0.35$_{a}$ | 34.88± 8.55$_{c}$ | 37.9± 10.09$_{b}$ |
| *Gleditsia tricanthos* | 1.25± 0.38$_{a}$ | 2.05± 0.25$_{a}$ | 36.00± 14.31$_{c}$ | 32.9± 21.51$_{b}$ |
| *Lagerstroemia indica* | 1.22± 0.60$_{a}$ | 5.70± 3.19$_{a}$ | 5.33± 0.681$_{ab}$ | 6.23± 0.81$_{a}$ |
| *Prosopis alba* | 0.59± 0.09$_{ab}$ | 1.93± 0.34$_{a}$ | 12.7± 7.14$_{bc}$ | 16.07± 8.41$_{c}$ |
| *Parkinsonia florida* | 1.25± 0.56$_{a}$ | 3.86± 1.45$_{a}$ | 0.67± 0.15$_{a}$ | 0.97± 0.12$_{a}$ |
| *Quercus virginana* | 1.82± 0.43$_{ac}$ | 4.49± 2.18$_{a}$ | 6.23± 2.70$_{bc}$ | 13.33± 2.91$_{c}$ |
| *Ulmus parvifolia* | 0.85± 0.42$_{a}$ | 2.21± 0.50$_{a}$ | 2.53± 0.23$_{a}$ | 3.00± 0.79$_{a}$ |
| *Vitex agnus-castus* | 1.15± 0.02$_{a}$ | 4.17± 2.02$_{a}$ | 17.20± 4.09$_{c}$ | 23.93± 7.62$_{c}$ |

Small letters denote significant differences within each column, α=0.05

## III. Assessing Physiological Status of the Trees

During the active growing period of each year we assessed the physiological status of the trees (Table 4). Measurements of chlorophyll index, leaf xylem water potential ($\psi_L$), and canopy-ambient temperature differentials ($T_c$-$T_a$) were taken at midday (1100-1300 hours). These measurements were taken to document that irrigation to meet the previous weeks ET (thereby not having to assess drainage) did not lead to stressful conditions that might reduce the amount of water used. Although there was a certain amount of variation with each parameter all trees had similar values (differences were nonsignificant $p>0.05$) for the chlorophyll index, leaf water potential, and $T_c$-$T_a$. When $T_c$-$T_a$ values are positive it indicates increased plant water stress. Only on a few days for a few species did positive $T_c$-$T_a$ values occur, suggesting that irrigations to replace ET did not lead to a systematic rise in canopy temperatures relative to ambient temperatures.

Table 3. Physiological measurements for all ten trees in North Las Vegas reported as a mean with one standard deviation. $T_c$-$T_a$ represents the temperature differential between canopy temperature ($T_c$) and ambient temperature ($T_a$).

| Tree Species | Chlorophyll Index | Xylem Water Potential(MPa) | $T_c$-$T_a$ (°C) |
|---|---|---|---|
| *Chilopsis linearis* | 170.20± 32.07$_a$ | -1.79± 0.12$_a$ | -1.88±1.05$_a$ |
| *Fraxinus velutina* ‘Arizona’ | 172.20± 23.95$_a$ | -2.18± 0.47$_a$ | -1.42±0.88$_a$ |
| *F. velutina* ‘Modesto’ | 156.93± 18.22$_a$ | -2.46± 0.67$_a$ | -2.65±1.32$_a$ |
| *Gleditsia tricanthos* | 163.33± 37.33$_a$ | -2.44± 0.33$_a$ | -1.55±0.81$_a$ |
| *Lagerstroemia indica* | 170.64± 21.80$_a$ | -2.19± 0.44$_a$ | -2.70±1.32$_a$ |
| *Prosopis alba* | 154.44± 28.61$_a$ | -2.66± 0.42$_a$ | -1.93±0.74$_a$ |
| *Parkinsonia florida* | 136.31± 11.67$_a$ | -2.17± 0.12$_a$ | -1.10±1.68$_a$ |
| *Quercus virginana* | 165.98± 18.32$_a$ | -2.44± 0.33$_a$ | -0.84±1.16$_a$ |
| *Ulmus parvifolia* | 150.40± 7.29$_a$ | -2.86± 0.64$_a$ | -2.97±1.79$_a$ |
| *Vitex agnus-castus* | 156.18± 17.63$_a$ | -2.56± 0.62$_a$ | -3.14±1.32$_a$ |

Different small letters denote significant differences within each column, $\alpha$=0.05

## IV. Soil Water Storage

Soil water storage generally went the opposite direction as reference ET, as was clearly demonstrated with *V. agnus-castus*. This fluctuation between the soil water being up when reference ET was down and soil water storage down when reference ET was up can be explained by the watering regime. Trees received water based on the values of ET in the previous week, therefore when temperatures declined in the fall and ET declined, soil water rose because we were irrigating based on the previous weeks higher ET. This same phenomenon occurred in the spring/summer, as we irrigated based on the previous weeks' lower ET and the soil water storage declined. However, closing the water balance required an estimate of drainage. We assumed drainage was zero based on no change in the soil water content at the 150 cm depth (Figure 1 and 2). *Quercus virginiana* soil water storage displayed a different trend by remaining mostly unchanged for the entire study period. This was the only evergreen tree which may explain why the soil water did not fluctuate very much, the tree was transpiring year round. It was also the largest tree based on height, trunk diameter and canopy volume and may have extracted water from a greater distance outside of the basin, thereby maintaining a greater level of soil moisture depletion.

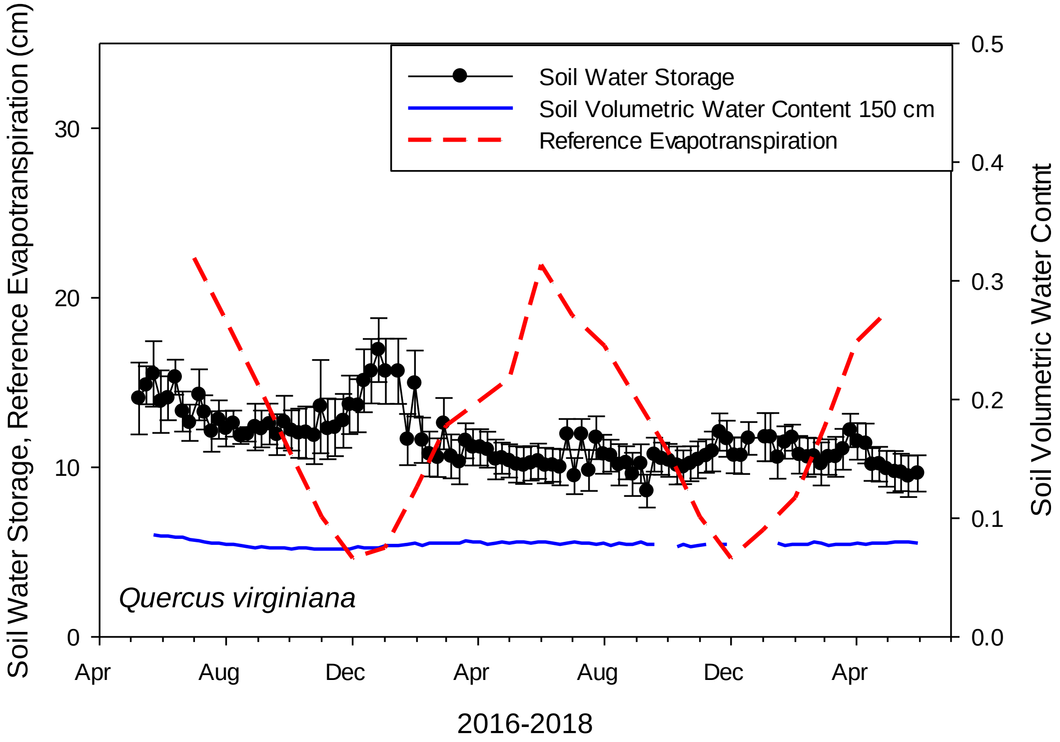

Figure 1. Soil water storage, reference evapotranspiration (ETref) and soil moisture at 150 cm. All points are means with error bars.

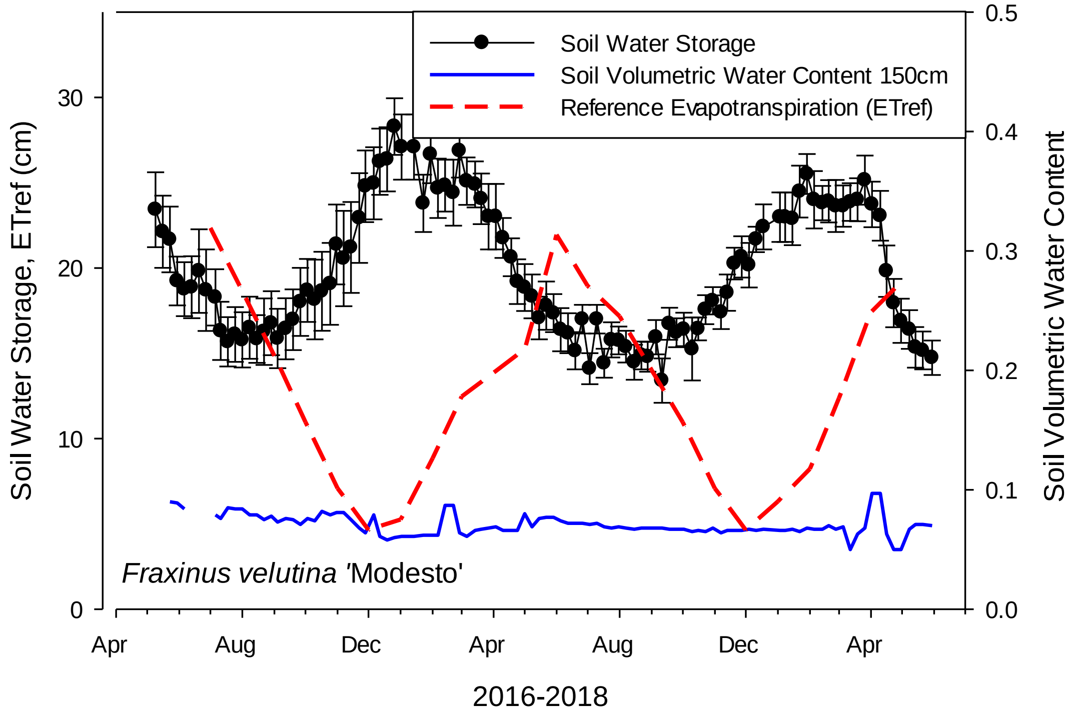

Figure 2. Soil water storage graphed with reference evapotranspiration (ETref) and soil moisture at 150 cm. All points are means with error bars.

## V. Evapotranspiration

Evapotranspiration (ET. liters) was measured by the hydrologic balance technique on each tree. In order to compare the ET for the 10 different tree species, the ET (L) was normalized with the basal canopy area to generate ET in centimeters (cm). This also allowed for direct comparison with turfgrass species ET in cm. The majority of tree species used less water than reference ET. The exceptions were *G. tricanthos* which used water at a similar rate as reference ET and *Lagerstroemia indica* which stood out as the highest water user, despite the short height of the tree, using more water than reference ET throughout most of the year. ET in cm is shown for *C. linearis* and *L. indica* in Figure 3, which reveals contrasting water use relative to reference ET. The water use varied in a sinusoidal fashion throughout the year with higher water use in summer months (June/July) and lower water use during winter months (January-March). In the case of the high water using *L. indica* ET rates in June and July were over 10 fold higher than during the inactive winter early spring period. All ten trees' graphs are displayed in the appendix.

Different ways of adjusting and comparing the amount of water used by each tree were assessed. ET was estimated in liters but also based on the basin area where water was supplied and also based on the basal canopy area. It was more straightforward to compare trees to grass based on the area from the drip line of a tree projected onto the ground (basal canopy area). Using the irrigation basin area to compare the plants was misleading since the trees would actually replace the amount of grass covered by the total expanse of the tree branches and leaves and not just the basin area.

Interestingly the ET of all the trees showed a one or two-month lag behind the $ET_{ref}$. This was particularly noticeable during peak ET for the trees around July and August 2017, whereas the $ET_{ref}$, based on tall fescue, peaked around June. Perhaps the trees were placing some physiological control over water loss and it required a decline in environmental demand for maximum water usage to occur. ET vs. $ET_{ref}$ linear regressions were done by adjusting for this one month offset aligning the ET with July $ET_{ref}$. All trees had a positive relationship between ET and $ET_{ref}$ with a $R^2$ ranging from 0.20-0.74 as seen in Table 4.  Results for the trees indicated that 73% of the variation in the amount of liters applied to *G. tricanthos* could be accounted for based on ETref ($p<0.001$) seen in Figure 4. *P. alba* relationship was a weaker relationship with an $R^2=0.196$, $p=0.022$.

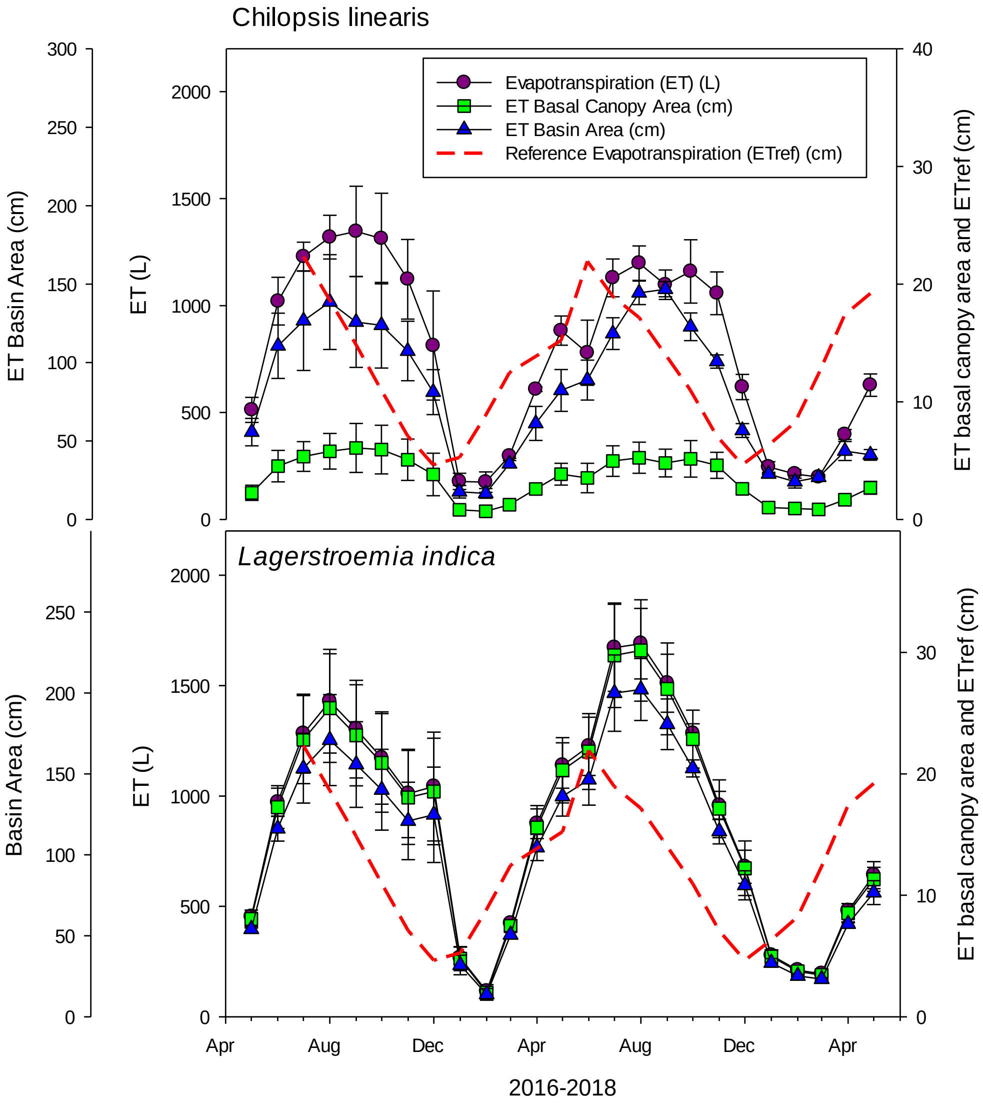

Figure 3. Evapotranspiration (ET) of two trees with different ways of reporting the ET compared to reference ET ($ET_{ref}$).

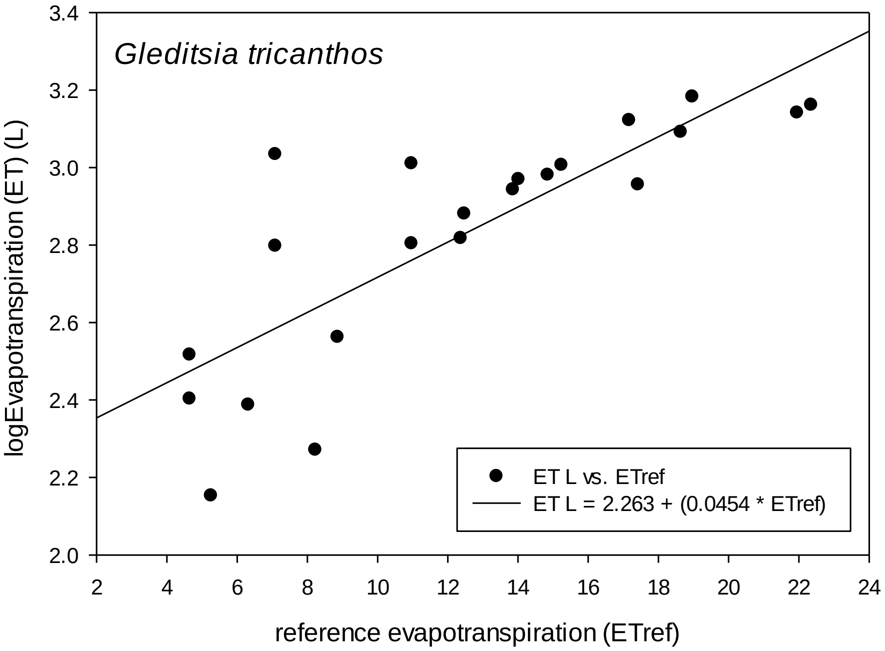

Figure 4. Linear regression of *Gleditsia tricanthos* log evapotranspiration (ET) in liters (L) relationship with reference evapotranspiration ($ET_{ref}$) ($p<0.001$, $R^2=0.731$)

Table 4. Evapotranspiration in cm versus reference evapotranspiration ($ET_{ref}$) for all ten species of trees in North Las Vegas with one $ET_{ref}$ offset, except for *Quercus virginiana, Parkinsonia florida,* and *Prosopis alba* which had $ET_{ref}$ set two months later.

| Tree Species | $R^2$ | p-value | F |
|---|---|---|---|
| *Chilopsis linearis* | 0.570 | <0.001 | 28.889 |
| *Fraxinus velutina* 'Arizona' | 0.596 | <0.001 | 26.525 |
| *Fraxinus velutina* 'Modesto' | 0.602 | <0.001 | 32.815 |
| *Gleditsia tricanthos* | 0.731 | <0.001 | 58.070 |
| *Lagerstroemia indica* | 0.759 | <0.001 | 67.183 |
| *Prosopis alba* | 0.474 | <0.001 | 19.906 |
| *Parkinsonia florida* | 0.638 | <0.001 | 36.192 |
| *Quercus virginana* | 0.519 | <0.001 | 22.560 |
| *Ulmus parvifolia* | 0.474 | <0.001 | 19.906 |
| *Vitex agnus-castus* | 0.582 | <0.001 | 30.292 |

Table 5. Hydrological balance (Hydro) evapotranspiration in centimeters (cm) for trees and grass in North Las Vegas.

| Plant Species | Hydro Year 1 cm | Hydro Year 2 cm | Hydro 2 Year Total cm |
|---|---|---|---|
| *Chilopsis linearis* | 45.76±23.42 | 38.03±15.88 | 83.79±39.29 |
| *Fraxinus velutina* 'Arizona' | 42.90±8.97 | 49.53±5.84 | 92.43±14.81 |
| *Fraxinus velutina* 'Modesto' | 88.41±25.30 | 66.59±13.25 | 155.00±37.90 |
| *Gleditsia tricanthos* | 61.70±15.72 | 60.21±21.03 | 121.90±33.25 |
| *Lagerstroemia indica* | 196.32±19.89 | 196.61±37.32 | 392.93±89.74 |
| *Prosopis alba* | 44.05±7.07 | 32.29±3.99 | 76.34±11.57 |
| *Parkinsonia florida* | 38.56±19.89 | 23.92±6.69 | 10.52±5.05 |
| *Quercus virginana* | 51.70±20.09 | 32.64±8.91 | 84.34±28.59 |
| *Ulmus parvifolia* | 49.55±2.30 | 33.69±6.38 | 83.23±5.43 |
| *Vitex agnus-castus* | 44.66±15.57 | 41.33±7.56 | 62.47±22.67 |
| *Cynodon dactylon* Low Fertility | 106.28±8.77 | -- | -- |
| *Festuca arundinacea* | 186.35±14.31 | 197.35±15.56 | 383.71±12.62 |
| *Cynodon dactylon* | 262.95±9.97 | 162.46±8.24 | 394.17±2.332 |

Table 6. Hydrological balance (Hydro) and sapflow evapotranspiration in liters (L) and centimeters (cm) for trees and grass in North Las Vegas.

| Tree Species | Hydro cm | Hydro L | Sapflow cm | Sapflow L |
|---|---|---|---|---|
| *Chilopsis linearis* | 42±18$_{ab}$ | 9513±1603 | 10±6 | 2330±1566 |
| *Fraxinus velutina* 'Arizona' | 46±7$_{ab}$ | 8768±1110 | 24±24 | 4722±4734 |
| *F. velutina* 'Modesto' | 78±22$_{a}$ | 12371±2157 | 26±20 | 4431±3621 |
| *Gleditsia tricanthos* | 61±17$_{ab}$ | 10217±2401 | 25±4 | 4277±994 |
| *Lagerstroemia indica* | 197±42$_{c}$ | 11039±1893 | 50±38 | 2692±1839 |
| *Prosopis alba* | 38±9$_{ab}$ | 9036±1718 | 32±7 | 7042±1281 |
| *Parkinsonia florida* | 31±16$_{b}$ | 5989±3317 | 27±2 | 7807±707 |
| *Quercus virginana* | 42±17$_{ab}$ | 8203±2 | 12* | 2982 |
| *Ulmus parvifolia* | 42±10$_{ab}$ | 9437±2746 | 23±3 | 5246±1270 |
| *Vitex agnus-castus* | 43±11$_{ab}$ | 8239±1792 | 50±29 | 9344±4649 |
| *Cynodon dactylon* Low Fert. | 106±9† | -- | -- | -- |
| *Festuca arundinacea* | 192±15$_{c}$ | 389±30 | -- | -- |
| *Cynodon dactylon* | 213±56$_{c}$ | 431±46 | -- | -- |

Different small letters denote significant differences within each column, α=0.05. * signifies one tree. † signifies a historical value.

ET for all four grass species followed reference ET as seen in Figure 5. *Lolium perenne* var. Palmer Prelude ET was not statistically different than reference ET most of the two year period ($p<0.05$). *Agrostis stolonifera* actually showed significantly more water usage in 2016 and began to follow ET$_{ref}$ in 2017. However, both *L. perenne* and *A. stolonifera* died back during summer months. *Cynodon dactylon* used more water than reference ET. The *C. dactylon* in our experiment was high fertility grass (0.22kg per 92.9 m$^2$ per month, April and October), so it used more water than the historical low fertility *C. dactylon* (Devitt 1992). *Festuca arundinacea* was similar to $ET_{ref}$ in winter months but exceeded $ET_{ref}$ during summer months.

The grass ET for all four species significantly correlated with $ET_{ref}$. In the case of *C. dactylon*, a clear relationship was found ($R^2=0.58$, $p<0.001$). *Festuca arundinacea* and *A. stolonifera* ET had a weaker positive correlation with $ET_{ref}$, still significant ($R^2=0.193$, $p=0.02$) ($R^2=0.35$, $p=0.006$) respectively. The last grass, *L.* perenne ET L also had a positive relationship ($R^2=0.41$, $p=0.002$).

Total evapotranspiration for trees and grass were compared for the two-year period, revealing a very clear separation between the two groups (Figure 6). The trees used significantly less water than the grasses, even low fertility *C. dactylon*, with one exception: *L. indica*. So 9 out of the 10 species of trees commonly planted in Southern Nevada used less water than the grasses. Only *F. arundinacea* and *C. dactylon* total ET were compared to the trees due to the *L. perenne* and *A. stolonifera* death during both summers and therefore having incomplete yearly data. The one-way ANOVA results based on log transformed two year total ET (cm) standardized on basal canopy area showed *F. arundinacea* and *C. dactylon* used significantly more water than all the trees except *L. indica*. ($p<0.03$). Low fertility *C. dactylon* ET was significantly higher than *P. alba, U. parvifolia, P. florida, V. agnus-castus, Q. virginiana,* and *C. linearis.* Also, *L. indica* used significantly more water than all other tree species ($p<0.03$) on a basal canopy area basis. Interestingly, *Fraxinus velutina* ‘Modesto’ used more water than *P. florida* ($p<0.003$) even though it was a significantly smaller tree (Table 2).

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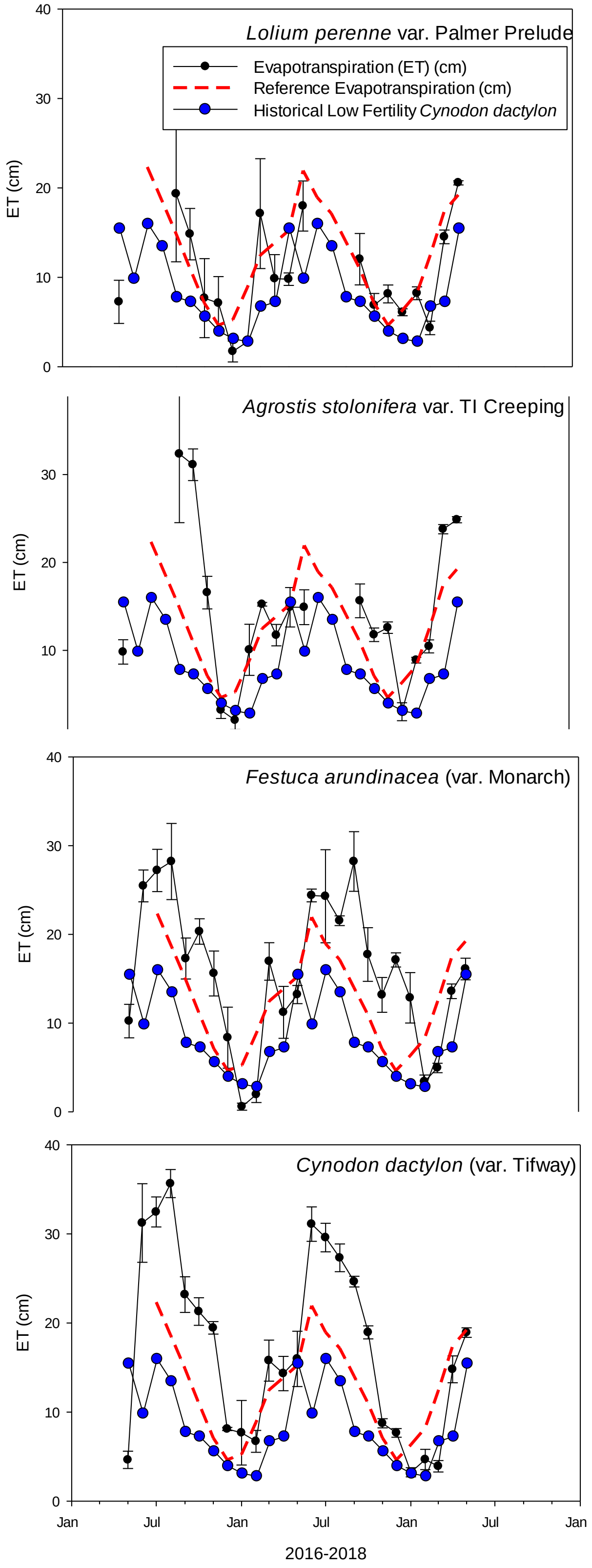
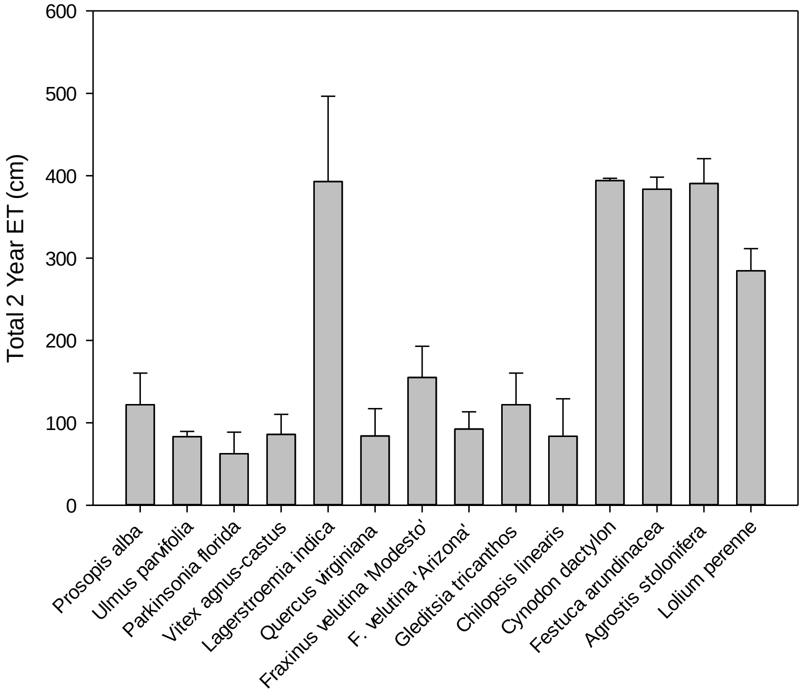
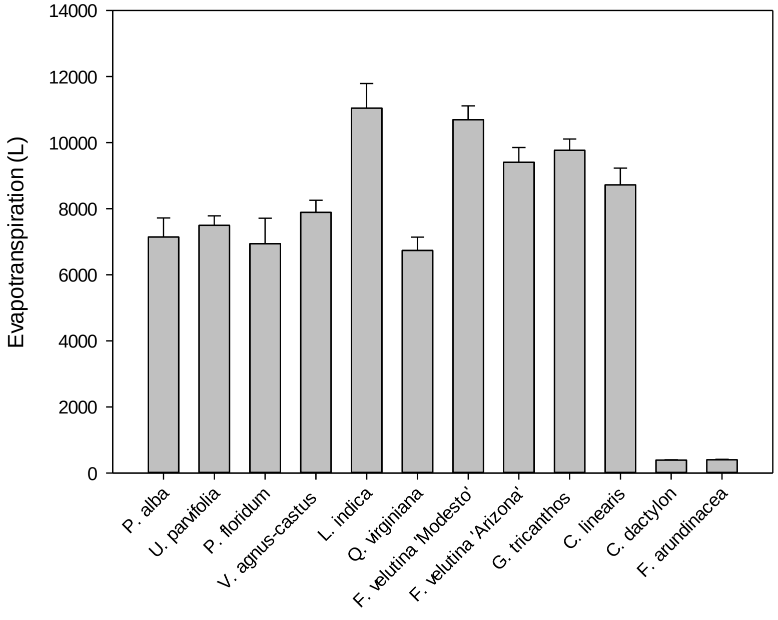


Figure 5. Grass evapotranspiration for all four species compared to reference evapotranspiration ($ET_{ref}$) and low fertility *Cynodon dactylon*. Points are means with 1 standard error.



Grasses Generally Uses More Water Than Trees per Basal Canopy Area



2nd Year Water use Per Plant or Lysimeter, Not Scaled to Water per Area

Figure 6.
Evapotranspiration (ET) standardized by area for both trees and grass. *Lolium perenne* and *Agrostis stolonifera* were excluded due to the lack of summer time values. (Means with one standard error). ET in liters is not normalized to area, and simply refers to the area of the lysimeter for the grass, and per tree.

## VI. ET vs. Transpiration

Sap flow data showed transpiration was significantly less during summer months than evapotranspiration occurring with the hydrological balance revealing a clear seasonal oscillation pattern (Figure 7 and 8). The eight other additional graphs for each tree species are in the appendix. During the winter months, the sap flow and the hydrological balance had very similar values. During the summer months the values were very different and this was probably due to the higher irrigations and larger evaporation component. The effect was more pronounced in the *L. indica*, probably because more water was supplied to those trees and they had the smallest canopy volume leading to greater percentage of the basin area exposed for greater evaporation. During winter months, irrigation volumes were significantly less as was $ET_{ref}$ leading to a lower evaporation component which led to a closer relationship between transpiration and ET. During the winter all plants reduced their water intake and subsequently their transpiration.

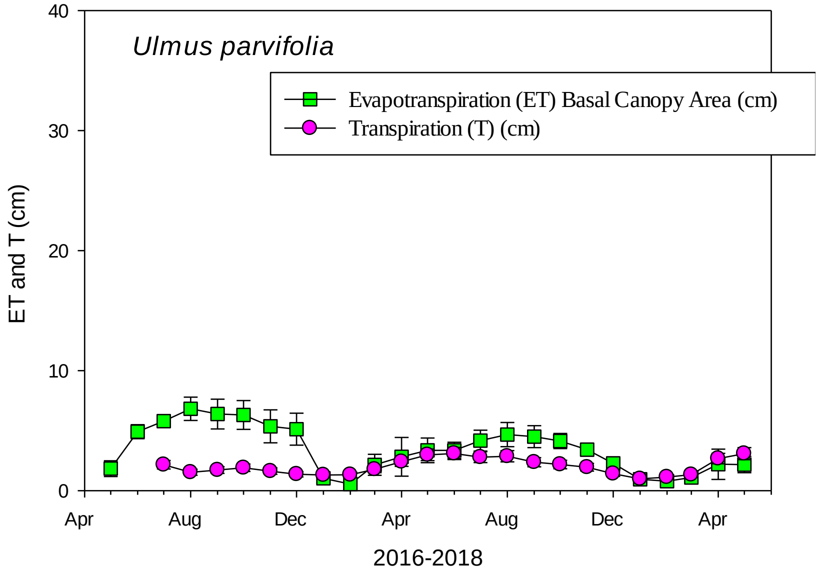


Figure 7. Sapflow transpiration and evapotranspiration (ET) determined by hydrological balance. Points are the mean (n=3), error bars show 1 standard error, single trunk tree.

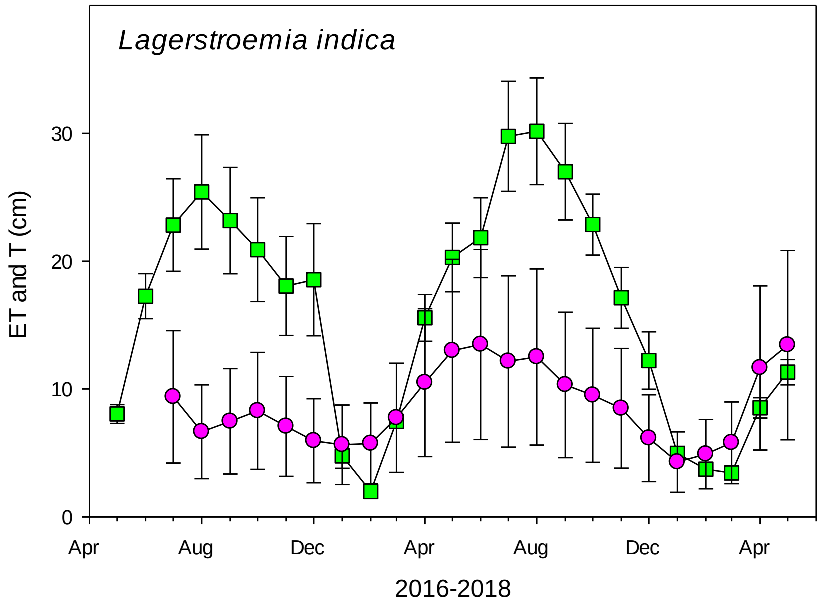


Figure 8. Sapflow transpiration and evapotranspiration (ET) determined by hydrological balance. Points are the mean (n=3), error bars show 1 standard error, trees have 1-4 trunks. (sapflow was adjusted by multiplying sapflow by trunk number).

## VII. Tree to grass Water Use Ratios

The tree to grass ratios typically fell below the 1:1 ratio line except for a few instances. *Lagerstroemia indica* had the highest ET (cm) of all trees, leading to tree to grass ratios > 1:1 during most months (Figure 9). Low Fertility *C. dactylon* (Bermuda) grass used less water than the other four experimental turf grasses, leading to tree grass ratios closer to one. *Lagerstroemia indica* used significantly more water than low fertility *C. dactylon* (n=3, p<0.008). When comparing Low Fertility *C. dactylon* to *Q. virginiana,* the tree used significantly less water than the grass based on one year totals (n=3, p<0.001). The spike in December and January of 2016 resulted from reduced water on the grasses to bring storage values down. Irrigation to the trees was also reduced to avoid deep drainage during the low ET period. The winter irrigation adjustment was not needed during the second year.

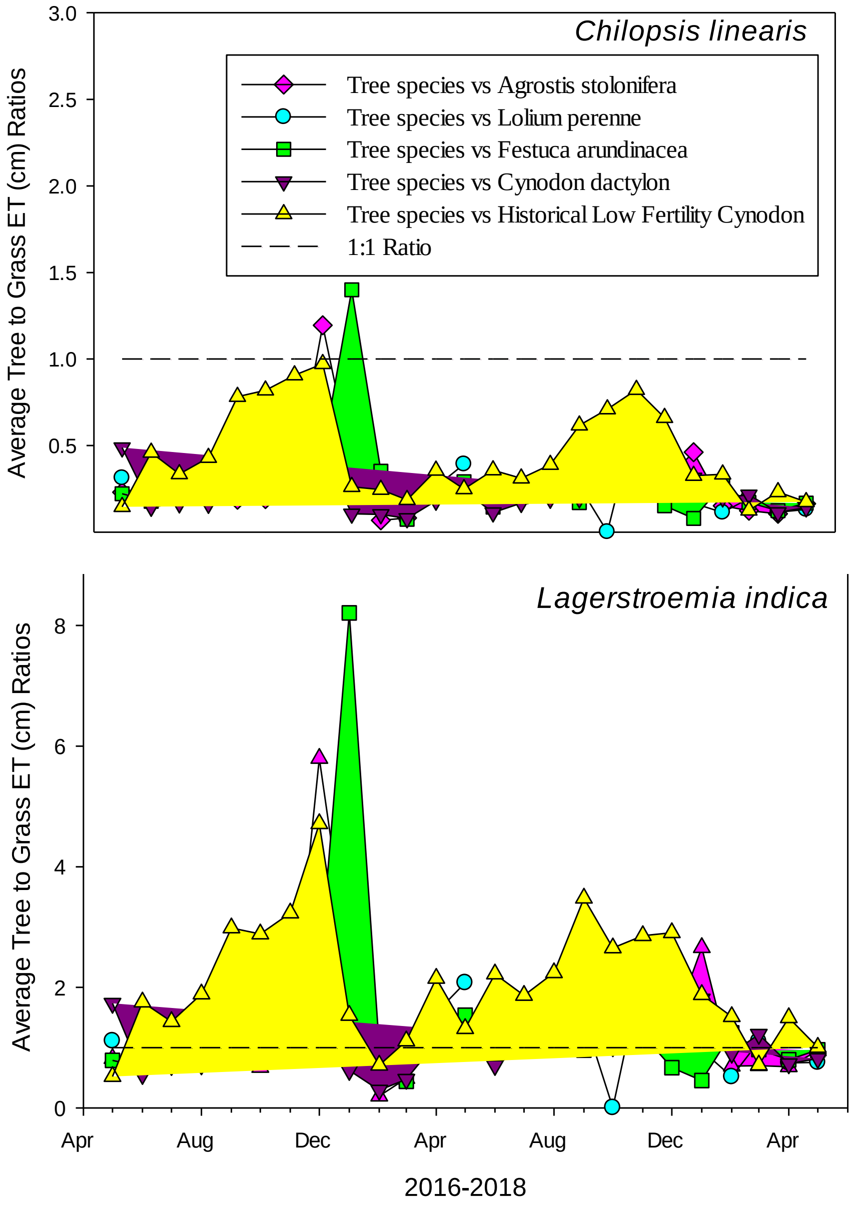


Figure 9. Tree to grass evapotranspiration (ET) ratios for one desert adapted tree (*Chilopsis linearis*) and one tropical tree (*Lagerstroemia indica*).

## VIII. ET vs. distance from the middle of the experimental plot.

We measured the distances trees were located from the middle of the experimental plot were measured to see if plants on the outside of the plot used more water than plants inside the grid. This excluded the crepe myrtle which used more water than any other tree per area basis. All three *L. indica* were close to the middle of the stand of trees. Because the trees on the outside were more prone to wind and sun exposure, those trees may have transpired more water than inner trees. However, the results did not show this phenomena occurring. Results of the spearman rank correlation showed that trees on the outside of the stand did not use more water than trees on the inside (p=0.762, correlation coefficient= -0.0601). It must be noted that the trees in this experiment were in a grove setting with multiple trees close together which may have influenced evaporation and transpiration. Urban trees usually stand alone at larger distances from one another, and due to increased wind and sun exposure may use more water than the trees in this experiment. All plants also received water based on their respective evapotranspiration. Plants receiving more than the necessary water for growth and survival tend to subsequently use more water (Devitt, et al., 1994).

## IX. ET relationship with morphological parameters

Backward stepwise regressions indicated the total year two ET (L) could be determined by trunk diameter, basal canopy area, and the area of the sun leaves (ET(L)=12070.34-150.82*Trunk Diameter-84.64*Basal Canopy Area+37.09*Area of Sun Leaf, $R^2=0.58$, $p<0.001$). Also, ET in centimeters in year one which was adjusted for basal canopy area could be determined by canopy volume and PAR (ET cm Year 1=1.89-0.005*Canopy Volume+0.04*1/PAR, $R^2=0.477$, $p<0.001$). Year two backward regression of ET in cm which was adjusted for basal canopy area resulted in only canopy volume being accepted into the regression equation (ET cm Year 2=2.033-0.008*canopy volume, $R^2=0.642$, $p<0.001$). ET in centimeters for the two year total revealed canopy volume and 1/PAR as the accepted parameters in the backward regression analysis (ET cm 2 Year Total=2.204-0.006* Canopy Volume+0.034*1/PAR, $R^2=0.585$, $p<0.001$). VIF's were all less than two and the sum total of VIF's were all less than 10 for all backward regression equations indicating no co-correlations of accepted parameters.

Depending on the data set (year, ET cm vs. ET L) different morphological parameters were accepted in the backward regression analysis. The choice of equations will be linked to the end user. Landscapers would probably select ET L as they could relate liters/gallons to the rate of water discharged by bubblers or drip systems. Accounting for approximately 60 % of the variation in ET is excellent but on-site adjustments would need to be made based on different growing conditions compared to the experimental conditions imposed in this experiment.

## Discussion

Several factors associated with the study site and experimental design could have influenced results. For example, the research site was situated on the urban/desert fringe with the northern and eastern boundaries associated with an undisturbed creosote bursage plant community, whereas the western and southern boundaries had extensive residential development. Wind was predominately from the south during the summer and from the north during the winter. Trees grew in the ground with irrigation basins that were spaced 4.9 m apart. The trees were planted over 20 years ago and canopies were often separated by only 1-2 m. Irrigation treatments were applied weekly to meet the previous weeks ET rate. Xylem water potential and leaf temperature suggested the trees were not under stress. However, during spring to summer, each weeks ET was typically greater than the previous weeks ET. While during fall and winter just the reverse situation occurred based on irrigating using the equation: Irrigation=ET/(1-Leaching Fraction) where Leaching Fraction was set equal to zero. We don’t know how much water the trees might have used if they were located in a more open setting with irrigations above and beyond ET to achieve leaching.

Our results indicate that nine out of the ten landscape tree species used less water than the four grass species. This coincides with work done by Litvak (2017a) with mature landscape trees and landscape grasses. *Lagerstroemia indica* stood out as the one tree that used as much water as the turfgrasses based on basal canopy area. *Lagerstroemia indica* has a very small stature and therefore was exposed to more sunlight and wind within the experimental plot, which led to higher transpiration and evaporation rates. It also has tropical origins and its evolutionary origin also may have played a role in its water use.

Young trees may use more water than grass as displayed in the study by Devitt et al. (1995). The smaller trees in the 1995 study reached a canopy volume ranging from 0.08 to 1.88 $m^3$ and had the ET of 435.1 L, 748.7 L, and 461.8 L per year for *Q. virginiana, P. alba, and C. linearis* respectively. As the size of the tree increased, the water usage went up for each tree under a zero leaching fraction: 791.6 L, 865.8 L, and 630.1 L per year for *Q. virginiana, P. alba, and C. linearis* respectively. The ratio of ET from the Devitt et al. (1995) study trees compared to the current study trees of the same species ranged between 5-10%, yet the young trees trunk size was 10-30% of the mature trees, the height 15-45% of the mature trees, and the canopy volume of 0.1-2% of the mature trees. The basal canopy area of the young trees from the study in 1995 was 1-2% of the size of the mature trees in the current study. Such data suggests scaling up from small to large trees would be difficult and more extensive data would be needed. The scaling of ET to compare young trees to mature trees did not accurately take into account the water efficiency of mature trees. The trees in the project in 1995 were not only young trees that may not be as water efficient (Cavender-Bares et al. 2000), but they also were placed in lysimeters with a lot of space between canopies. The extra space between the trees may have contributed to increased water usage (Hagashima et al. 2007). Interestingly, this first study by Devitt et al. (1995) used three trees that used the least amount of water in the current study and still found them to use more water than *F. arundinacea.*

Balogen et al. (2009) in Kansas City, MO set up a weather station in a new suburban housing development and measured Bowen ratio estimates of ET of the young trees with irrigated grass lawns. The Kansas City observations had a higher ET than other more established suburbs of other North American cities with mature trees. Offerle (2006) also found that urban vegetation in the form of both mature trees and turfgrass transpired at a higher rate than a completely vegetated grass surface. However, what grass and tree species grew in the rural area is unknown and given that our results varied based on the species of the tree and grass, that detail is important. Another project studying trees and grass found that a grass field used 467 mm $yr^{-1}$ of water compared to a suburban area with mature tall trees that used 324 mm $yr^{-1}$ (Peters et al. 2011). These numbers look low compared to our study most likely because the project took place in Minneapolis/St. Paul, Minnesota with a different climate. The differences between how much water the trees used in various studies may also be attributed to the fact that some trees were grown close together and others were further apart (Hagashima et al. 2007). Other studies have also shown that grass uses more water than trees, such as Kotani and Sugita (2005) that used Bowen ratio estimates of ET in Japan, validating our findings.

In our study, the transpiration was routinely less than the evapotranspiration of the trees. The transpiration did not account for the evaporation that occurred in the irrigation basins of the trees, which would have been high during the hot summer days. Sap flow sensors may underestimate transpiration during periods of high radiation (Peters et al. 2011). When the transpiration was subtracted from the evapotranspiration for each tree and then averaged the evaporation was on average 41.33 cm with a standard deviation of 38.71 cm. The average ET was 61.92 cm with a standard deviation of 49.06, so the evaporation on average was greater than 50% of the evapotranspiration, although there was a large standard deviation. Ideally the study would have included 2-3 sap flow sensors on each tree increasing the accuracy of the measurements, but due to cost only one per tree was used. The novel dye injection system clearly labeled the sap wood of our trees making the measurement more exact. Some trees, like the oak had very nonuniform sapwood, therefore a percentage of the wood was used in the estimations. Usually visual inspection of the wet tree core is used to estimate conductive sapwood (Litvak et al. 2017a). Staining the tree sapwood revealed a much more exact way to measure the area of wood conducting water.

Table 7. Number of trees that compare to a 185 $m^2$ patch of grass. The first column lists the number of trees that fit in the space using the tree basal canopy area. The second and third column show how many trees would use the same amount of water to equal to the water use of grass in 185 $m^2$.

| Tree Species | # of trees that fit in the space | # of trees to water use of *Festuca arundinacea* | # of trees to water use of *Cynodon dactylon* |
|---|---|---|---|
| *Chilopsis linearis* | 7.5 | 34.4 | 19.0 |
| *Fraxinus velutina* 'Arizona' | 9.7 | 40.3 | 22.3 |
| *F. velutina* 'Modesto' | 11.1 | 27.5 | 15.2 |
| *Gleditsia tricanthos* | 10.4 | 32.7 | 18.1 |
| *Lagerstroemia indica* | 32.5 | 31.7 | 17.6 |
| *Prosopis alba* | 8.3 | 41.7 | 23.1 |
| *Parkinsonia florida* | 6.2 | 38.1 | 21.1 |
| *Qurecus virginana* | 9.0 | 41.0 | 22.7 |
| *Ulmus parvifolia* | 8.1 | 37.3 | 20.7 |
| *Vitex agnus-castus* | 9.4 | 42.0 | 23.2 |

Our research was done to assess the tradeoffs between landscape trees and turfgrass. To demonstrate the tradeoffs in a landscape we compared our trees and grasses to a plot size of 185 $m^2$. Table 7 reveals how few trees can fit into the 185 $m^2$ area, yet many more would be needed to equal the same amount of water lost as ET from the grasses in the same area. For example, 7.5 *C. linearis* trees would fit in the area of 185 $m^2$, however, it would take 34 *C. linearis* trees to use the amount of water used by *F. arundinacea* in the same 185 $m^2$ area. All but one of the trees fit more trees in the space compared to the number needed to use the same amount of water as the grasses. *Lagerstroemia indica*, the tropical tree, used a comparable amount of water as *F. arundinacea*, with 33 trees fitting into the 185 $m^2$ area based on basal canopy area, while 31 trees used the same amount of water as the *F. arundinacea* in the same area. *Lagerstroemia indica* would not result in water savings by removing *F. arundinacea* and planting this tropical tree. It is important to choose species wisely as the low fertility *C. dactylon* did have a comparable water use to *F. velutina* 'Modesto', meaning that removing one and planting another may not result in any water savings at all. However, if *F. velutina* 'Modesto' was compared to *F. arundinacea* significant savings would occur. In most cases it would be beneficial to remove the grass and plant trees based on the basal canopy size of the trees in our study. Such as with *Q. virginiana*, although nine trees would fit in the 185 $m^2$ area it would take 41 trees to use the same amount of water as a lawn of *F. arundinacea*.

Looking at plants in natural settings, without irrigation, similar ET values were found in Southern Nevada for *Tamarix ramosissima,* which used between 75 cm and 145 cm growing along the Virgin River (Devitt et al. 1998). This was comparable to the native trees that grew alongside the invasive *Tamarix* (Sala et al. 1996). These plants were in a riparian setting surrounded by large arid regions that swamped the system with additional sensible heat via advection. Still the lower amount of water lost as ET (75 cm) was comparable to some of the trees used in our experiment.

Future directions for the research include identifying the cause of the two-month lag in the data comparing $ET_{ref}$ and ET of the trees and grass. When regressions were done between $ET_{ref}$ and ET there was no correlation until the tree data was moved backward two months, then all the data was strongly correlated. Perhaps the trees had a lag due to the late winter here and harsh summertime weather since the trees are at peak growth a couple months later (August-September) than the peak reference ET. Although it may be due to Las Vegas weather, Peters et al. (2011) found that mature deciduous trees had peak ET during August and September in Minnesota. Possible satellite observations of canopy development over time could be compared to changes in ET and $ET_{ref}$ to help identify the mechanism behind this lag.

Many golf courses in the southwest U.S.A have reduced water consumption by removing turf along the roughs and the fairways. This has led to trees becoming isolated in the landscape areas. Golf course managers have little information to help guide the irrigation of trees. Results from this study would suggest that environmental demand ($ET_{ref}$) and tree morphology can provide an excellent starting point to determine the irrigation amount.

## I. Conclusion

Depending on the species, mature landscape trees generally used less water than turfgrass species. Generally trading grass for trees saves the amount of water used per year, except in the case of *L. indica.* You can fit nine *Q. virginiana* trees in aspace of 185 $m^2$ yet it would take 41 trees to compare to the water use of *F. arundinacea* in the same area. Such information can allow landscape managers and even homeowners to make wise decisions regarding plant choices and irrigation strategies to conserve water in our desert. Future directions include identifying a time lag between $ET_{ref}$ and ET of the trees. With the area of study of water conservation, hopefully we can conserve the precious resource of water.

## **Appendix A:** Soil Water Storage

Soil water storage graphed with reference ET (ETref) and Soil moisture at 150 cm.

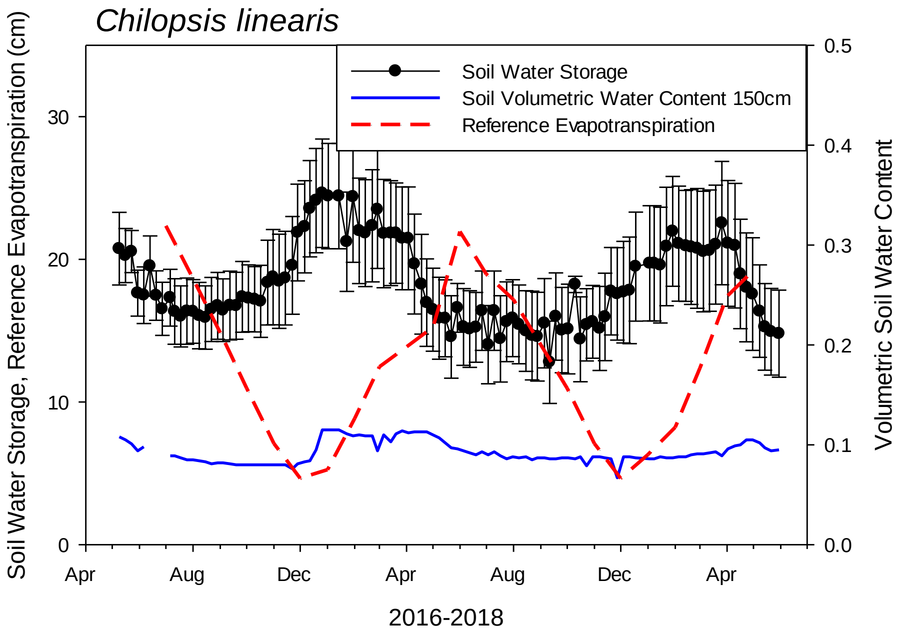


Figure 10. *Chilopsis linearis* soil water storage graphed with reference evapotranspiration ($ET_{ref}$) and soil moisture at 150 cm. All points are means with one standard error (SE).

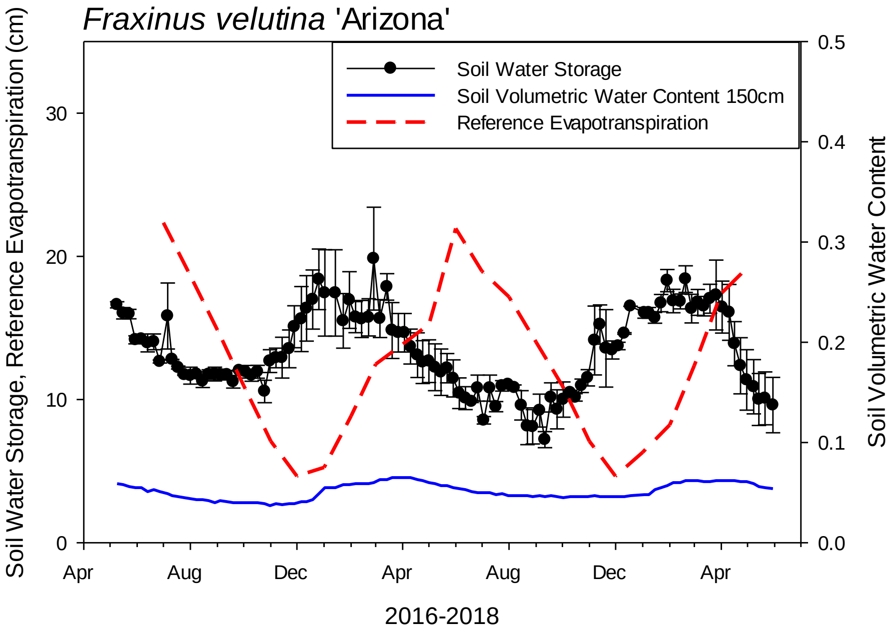


Figure 11. *Fraxinus. velutina* ‘Arizona’ soil water storage graphed with reference evapotranspiration ($ET_{ref}$) and soil moisture at 150 cm. All points are means with one standard error.

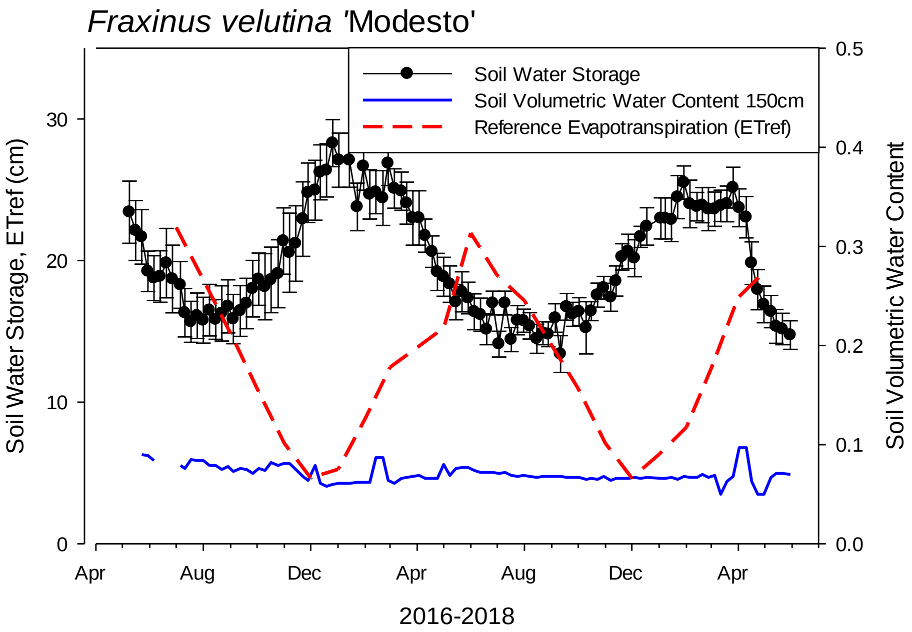


Figure 12. *Fraxinus velutina* ‘Modesto’ soil water storage graphed with reference evapotranspiration ($ET_{ref}$) and soil moisture at 150 cm. All points are means with one standard error.

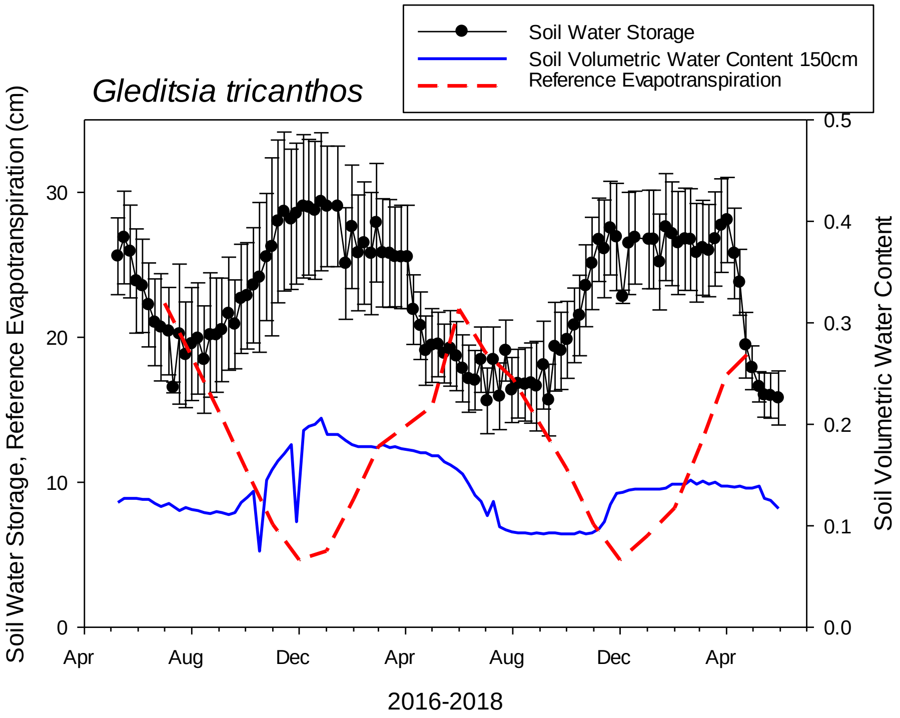


Figure 13. *Gleditsia tricanthos* soil water storage graphed with reference evapotranspiration ($ET_{ref}$) and soil moisture at 150 cm. All points are means with one standard error.

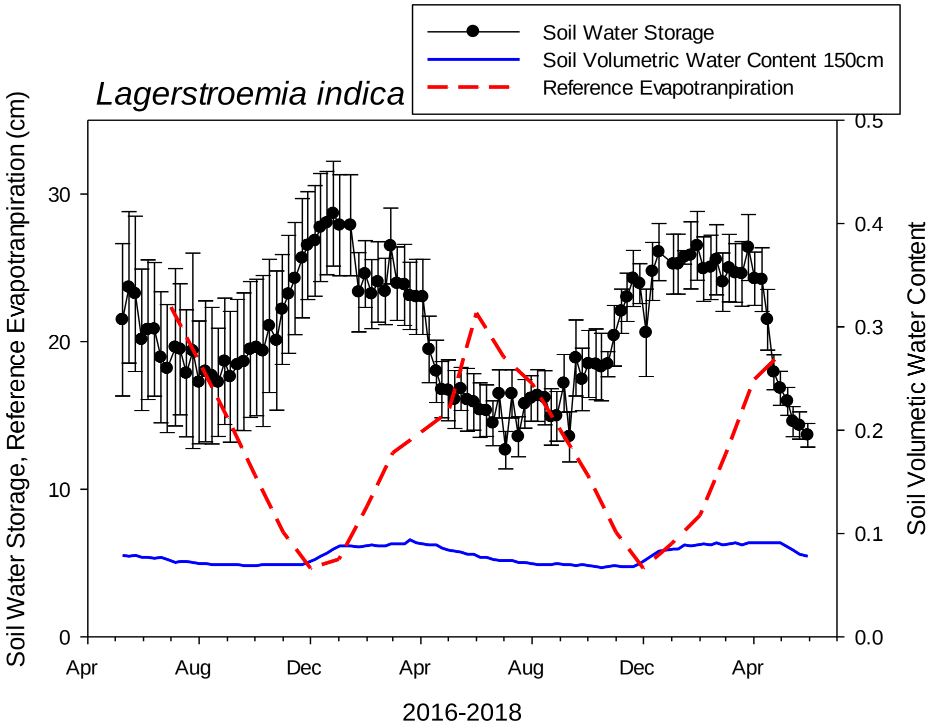


Figure 14. *Lagerstroemia indica* soil water storage graphed with reference evapotranspiration ($ET_{ref}$) and soil moisture at 150 cm. All points are means with one standard error.

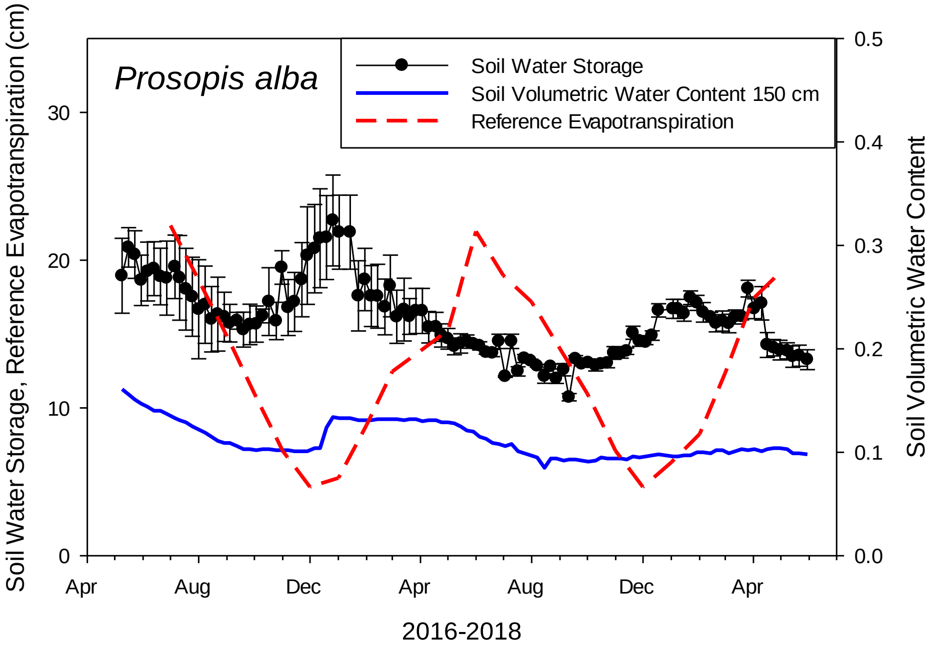


Figure 15. *Prosopis alba* soil water storage graphed with reference evapotranspiration ($ET_{ref}$) and soil moisture at 150 cm. All points are means with one standard error.

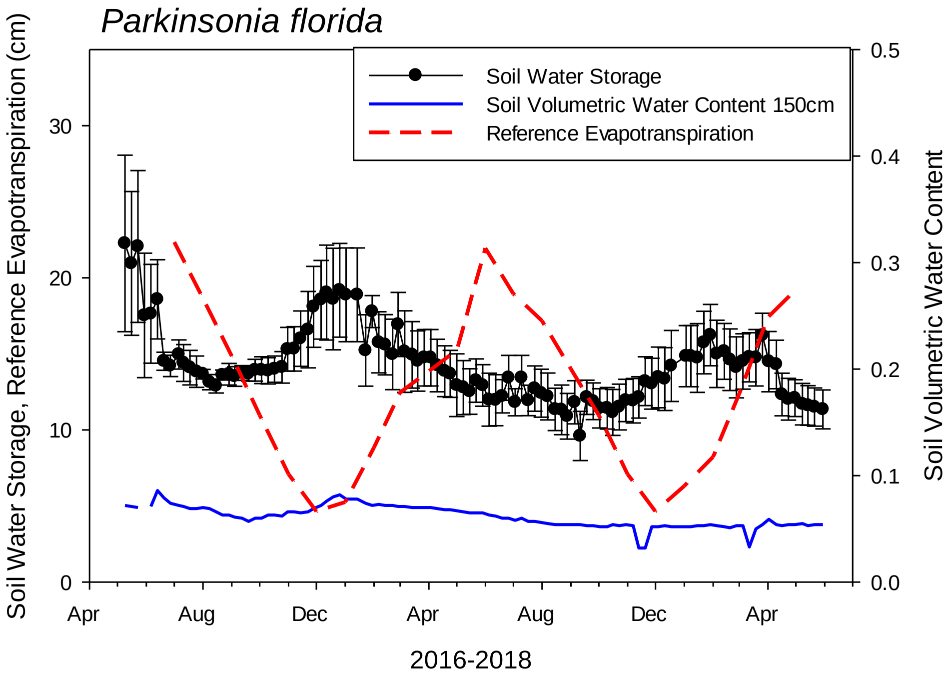


Figure 16. *Parkinsonia florida* soil water storage graphed with reference evapotranspiration ($ET_{ref}$) and soil moisture at 150 cm. All points are means with one standard error.

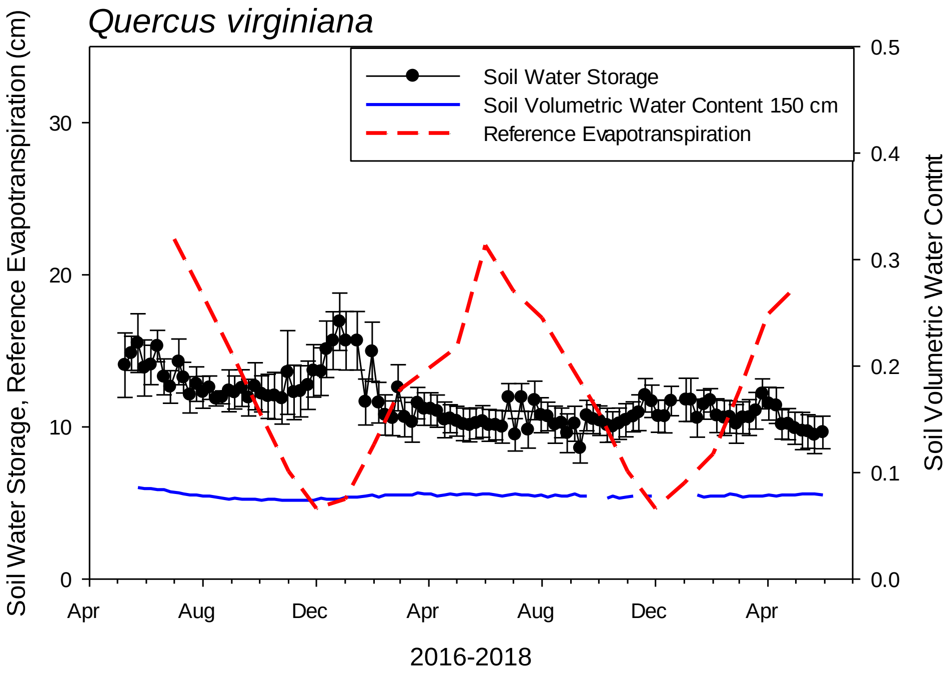


Figure 17. *Quercus virginiana* soil water storage graphed with reference evapotranspiration ($ET_{ref}$) and soil moisture at 150 cm. All points are means with one standard error.

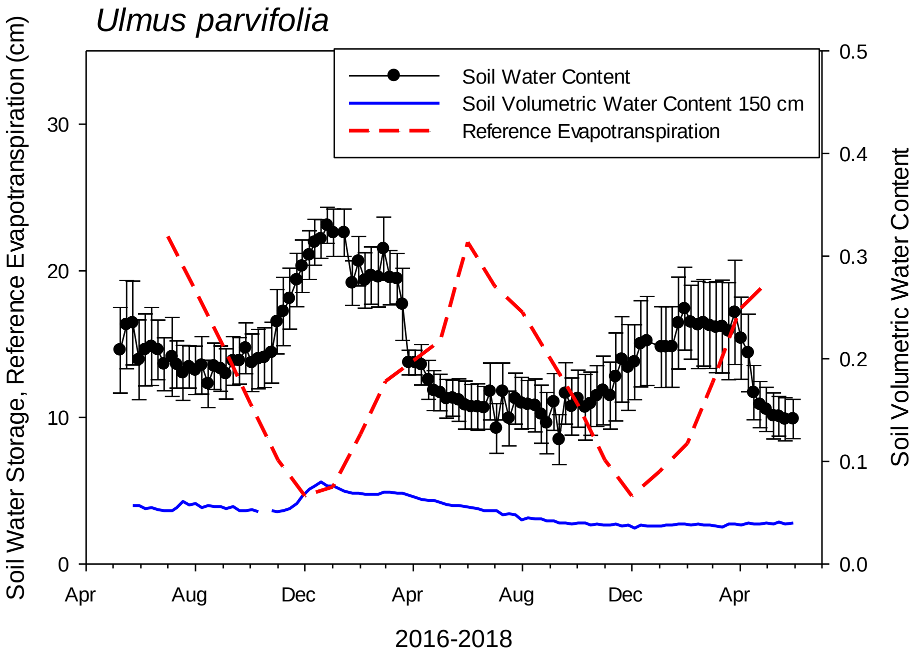


Figure 18. *Ulmus parvifolia* soil water storage graphed with reference evapotranspiration ($ET_{ref}$) and soil moisture at 150 cm. All points are means with one standard error.

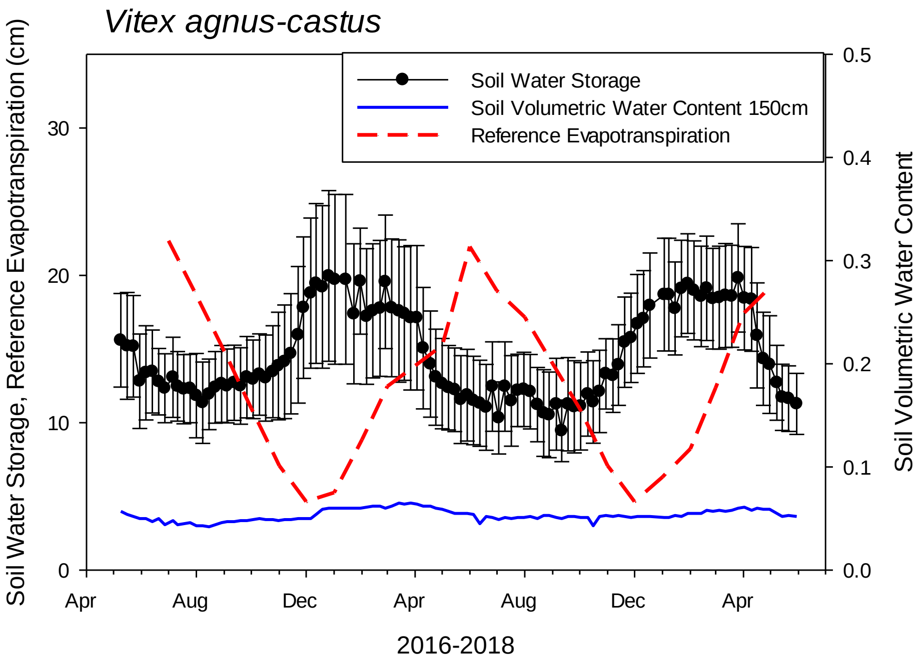


Figure 19. *Vitex agnus-castus* soil water storage graphed with reference evapotranspiration ($ET_{ref}$) and soil moisture at 150 cm. All points are means with one standard error.

## **Appendix B:** Evapotranspiration of 10 Trees

Evapotranspiration (ET) of 10 trees with different ways of reporting the ET compared to reference ET. All points are means with one standard error (SE).

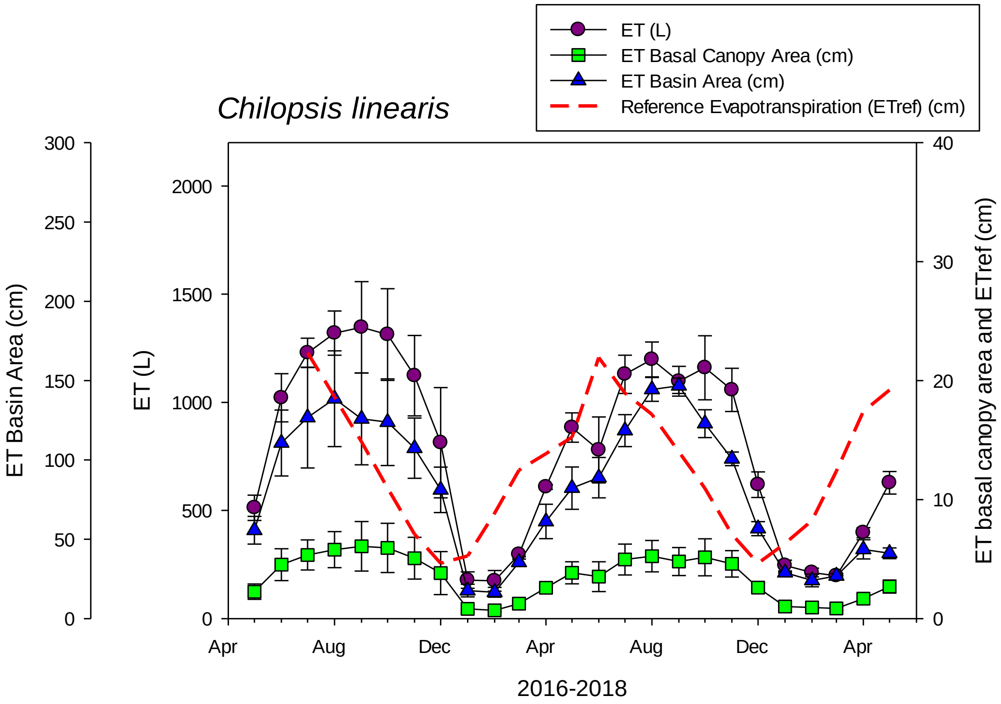


Figure 20. Evapotranspiration (ET) of *Chilopsis.linearis* with different ways of reporting the ET compared to reference ET. All points are means with one standard error.

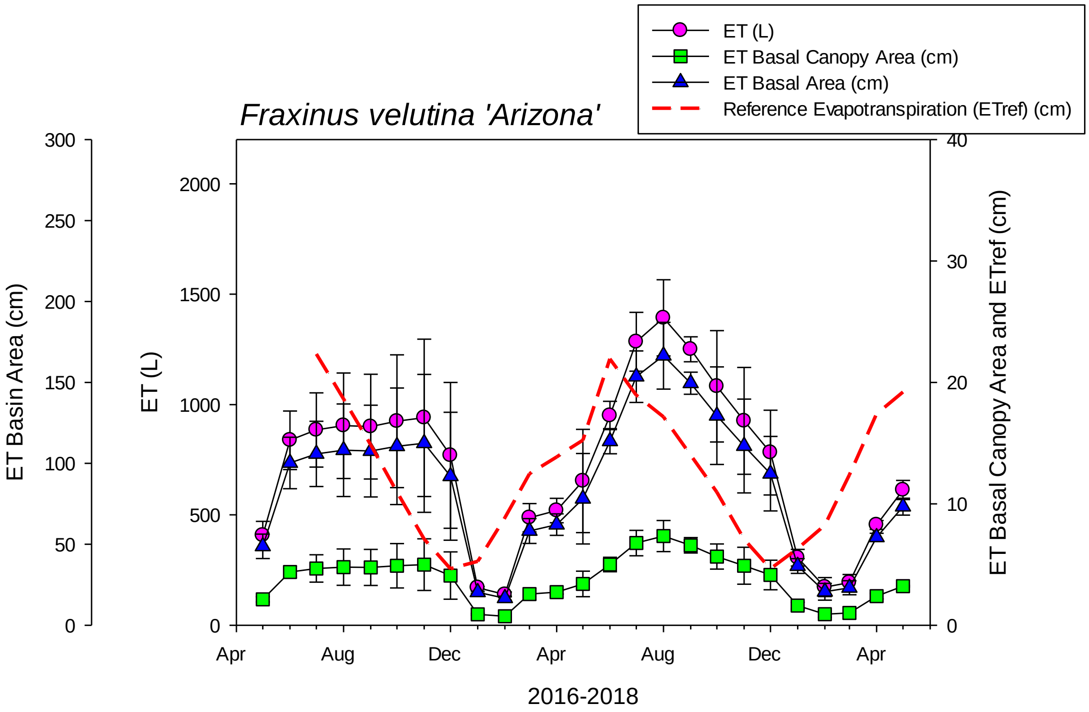


Figure 21. Evapotranspiration (ET) of *Fraxinus velutina* ‘Arizona’ with different ways of reporting the ET compared to reference ET. All points are means with one standard error.

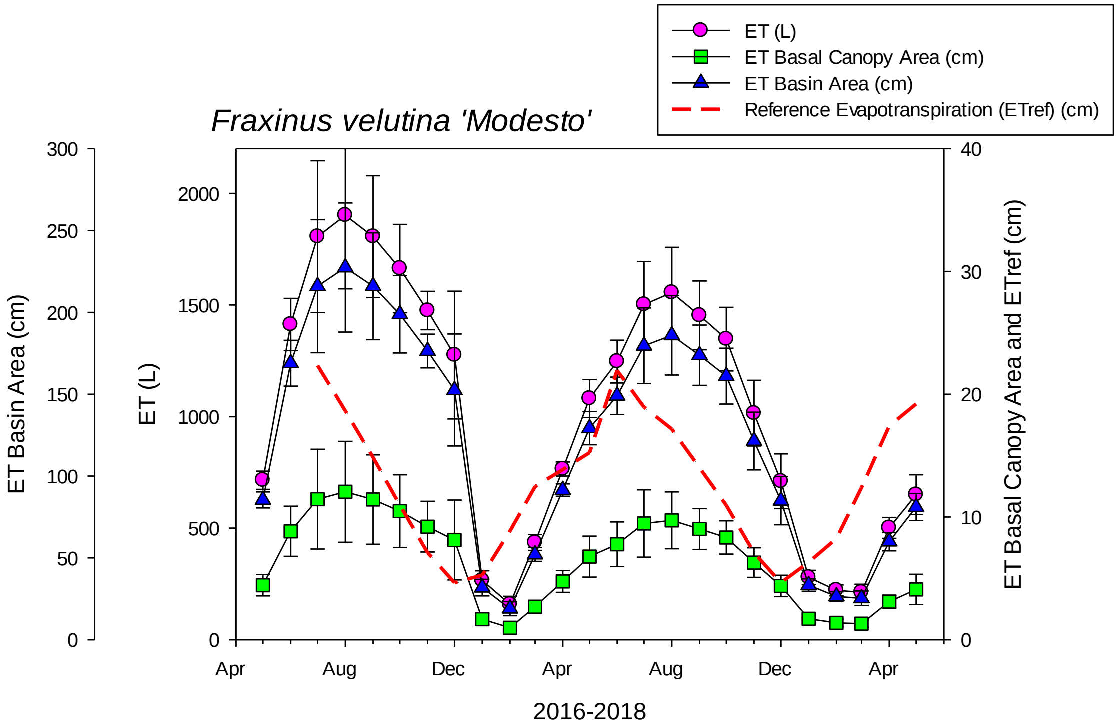


Figure 22. Evapotranspiration (ET) of *Fraxinus velutina* 'Modesto' with different ways of reporting the ET compared to reference ET. All points are means with one standard error.

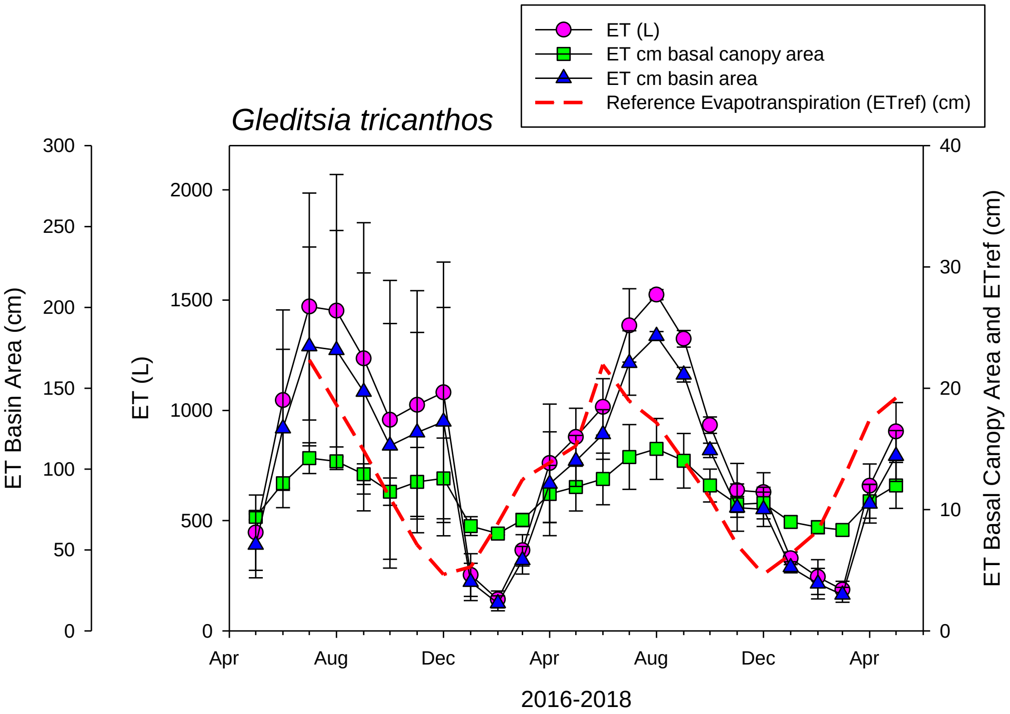


Figure 23. Evapotranspiration (ET) of *Gleditsia tricanthos* with different ways of reporting the ET compared to reference ET. All points are means with one standard error.

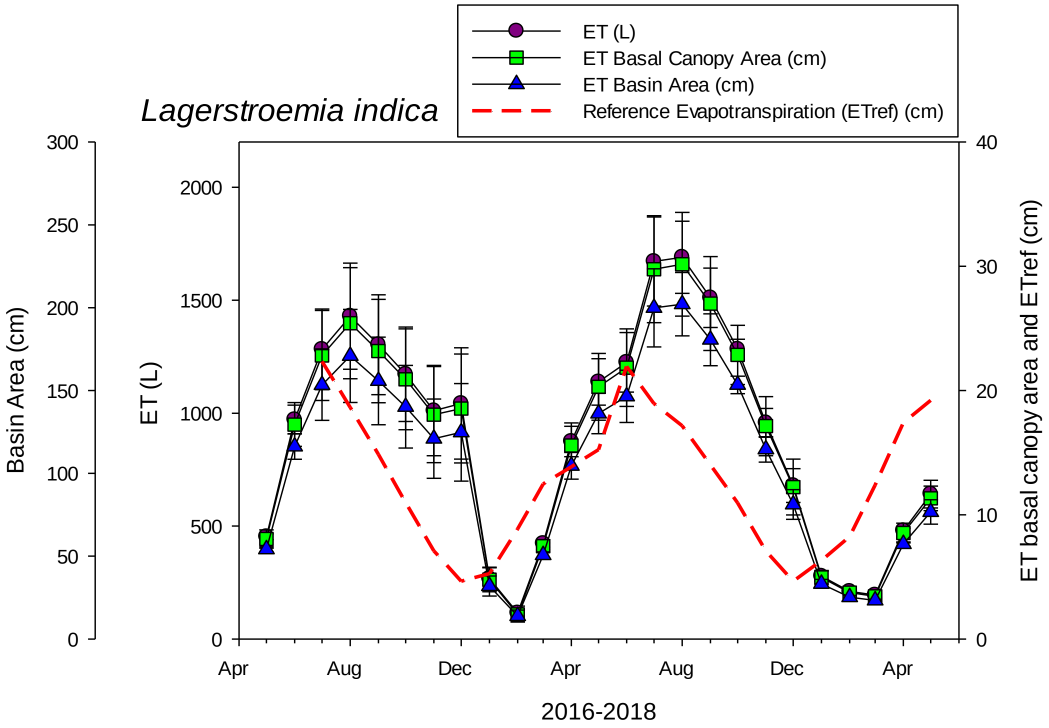


Figure 24. Evapotranspiration (ET) of *Lagerstroemia indica* with different ways of reporting the ET compared to reference ET. All points are means with one standard error.

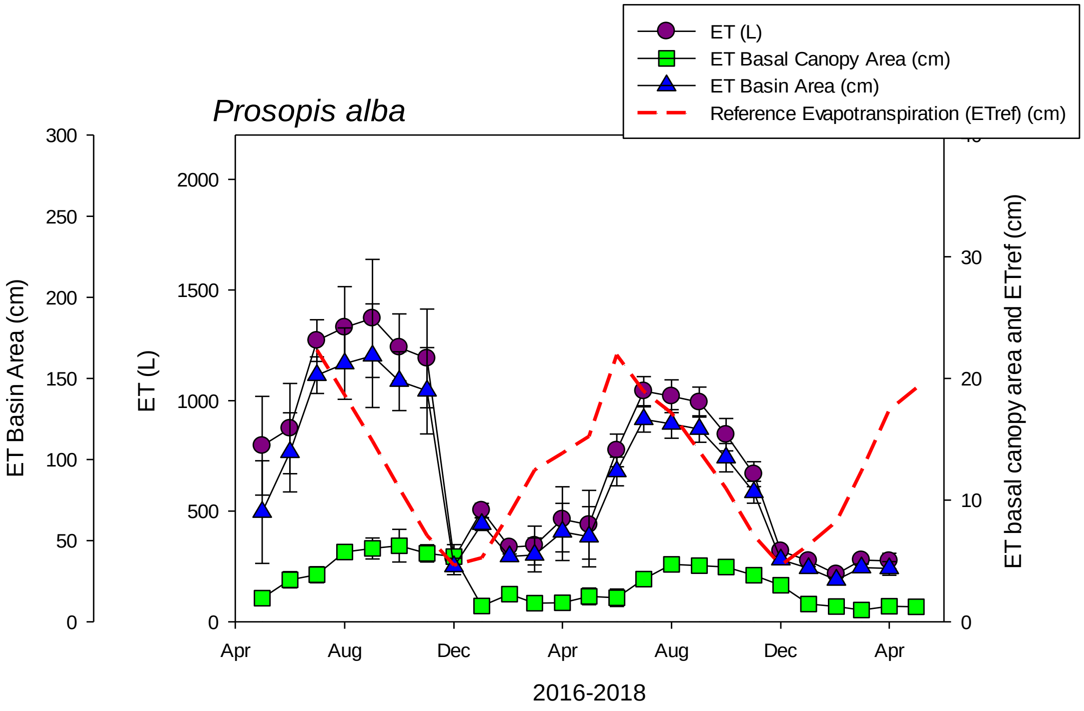


Figure 25. Evapotranspiration (ET) of *Prosopis alba* with different ways of reporting the ET compared to reference ET. All points are means with one standard error.

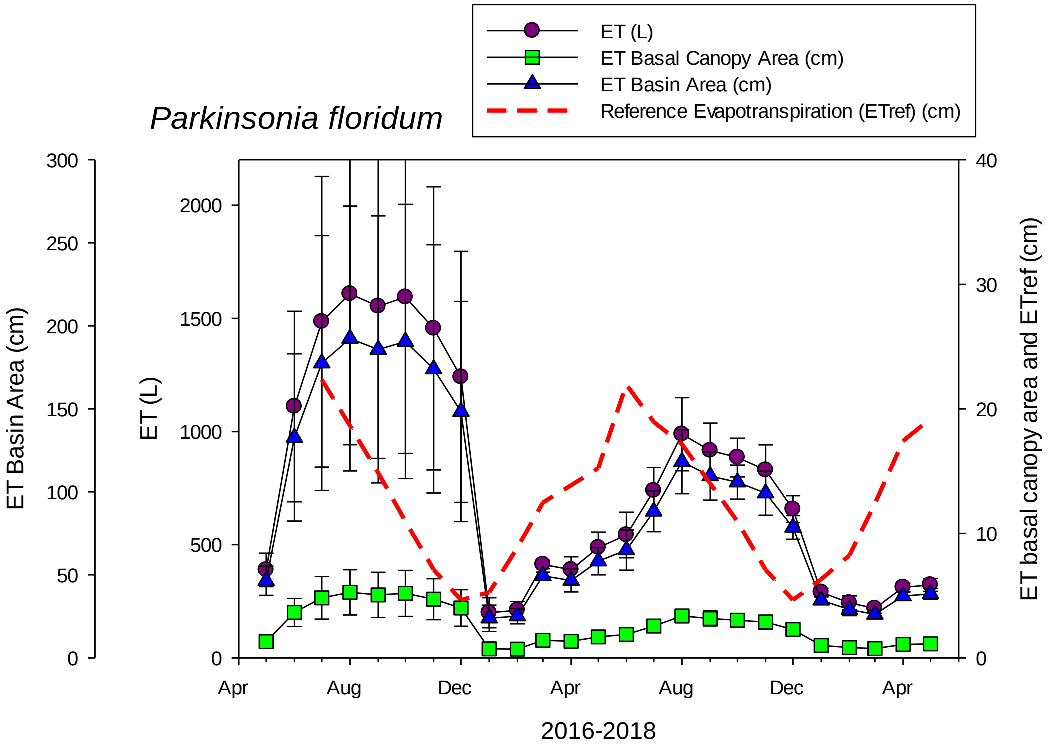


Figure 26. Evapotranspiration (ET) of *Parkinsonia florida* with different ways of reporting the ET compared to reference ET. All points are means with one standard error.

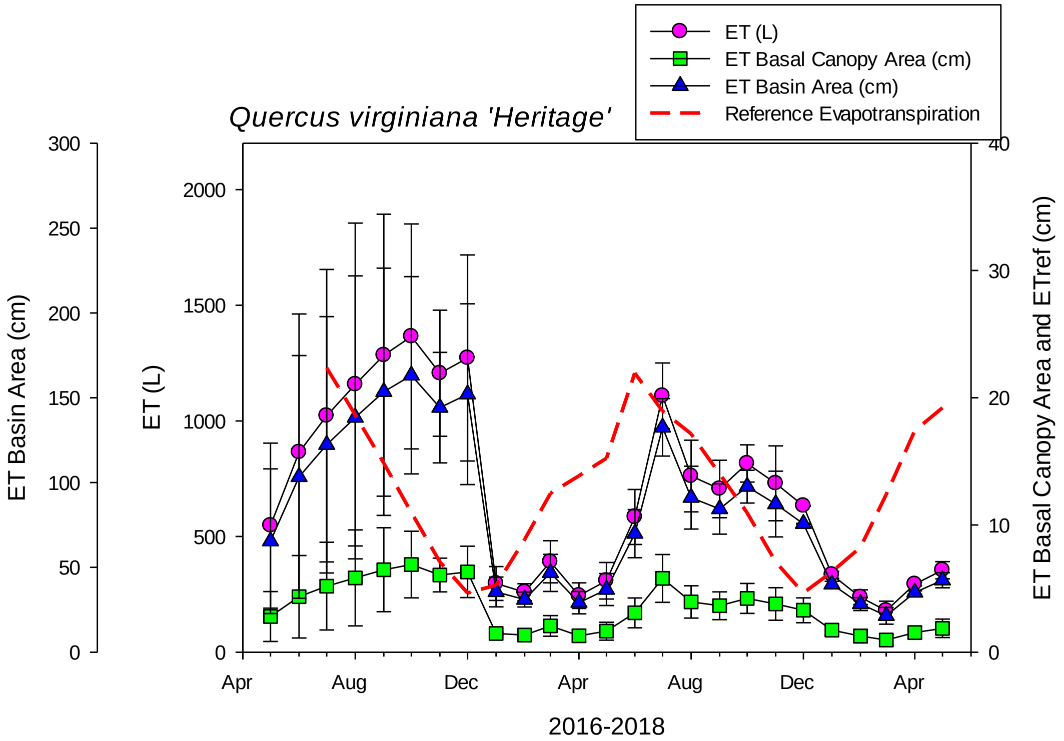


Figure 27. Evapotranspiration (ET) of *Quercus virginiana* ‘Heritage’ with different ways of reporting the ET compared to reference ET. All points are means with one standard error.

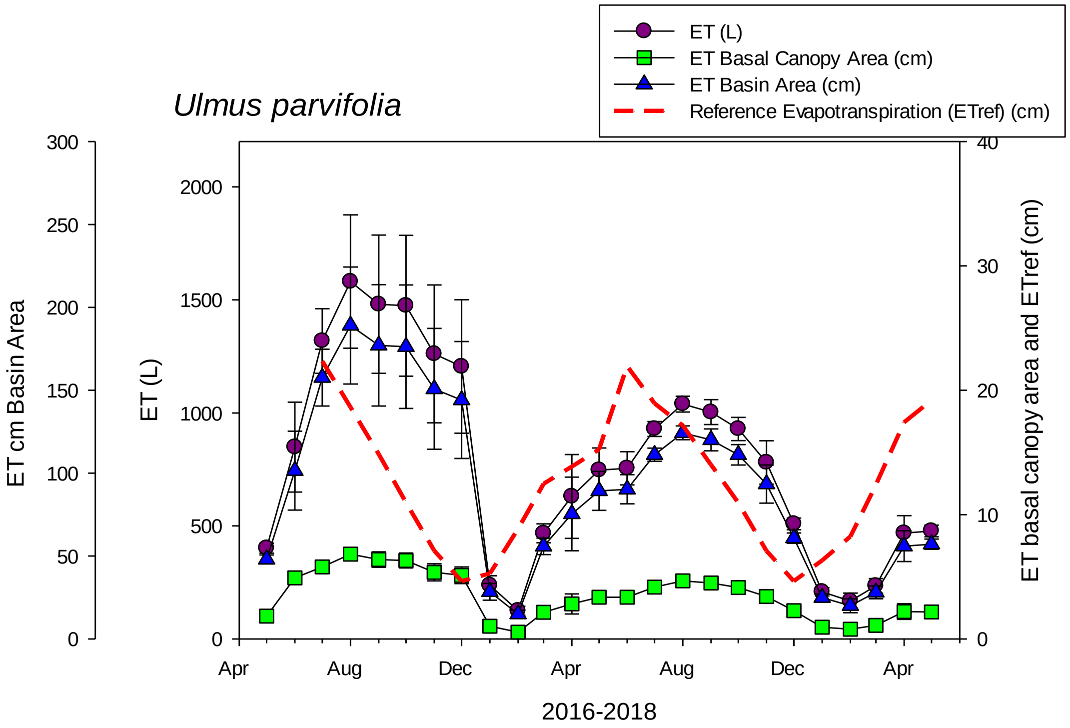


Figure 28. Evapotranspiration (ET) of *Ulmus parvifolia* with different ways of reporting the ET compared to reference ET. All points are means with one standard error.

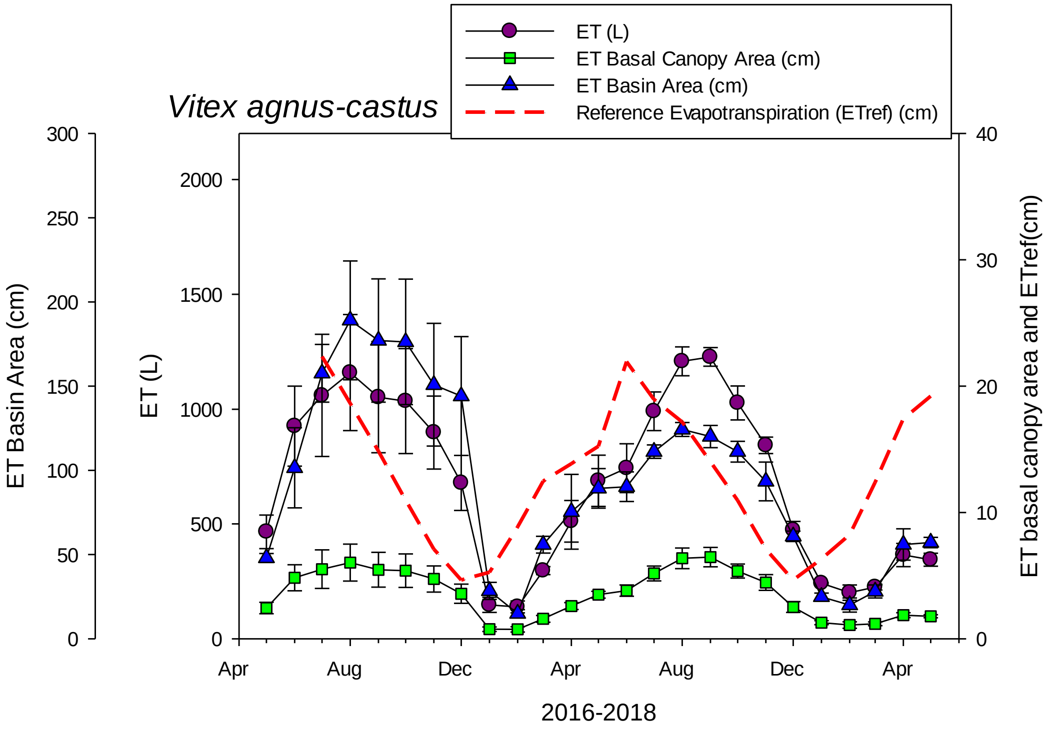


Figure 29. Evapotranspiration (ET) of *Vitex agnus-castus* with different ways of reporting the ET compared to reference ET. All points are means with one standard error.

## **Appendix C:** Sapflow Transpiration

Sap flow transpiration and evapotranspiration (ET) determined by hydrological balance. Points are the mean (n=3), error bars show 1 standard error.

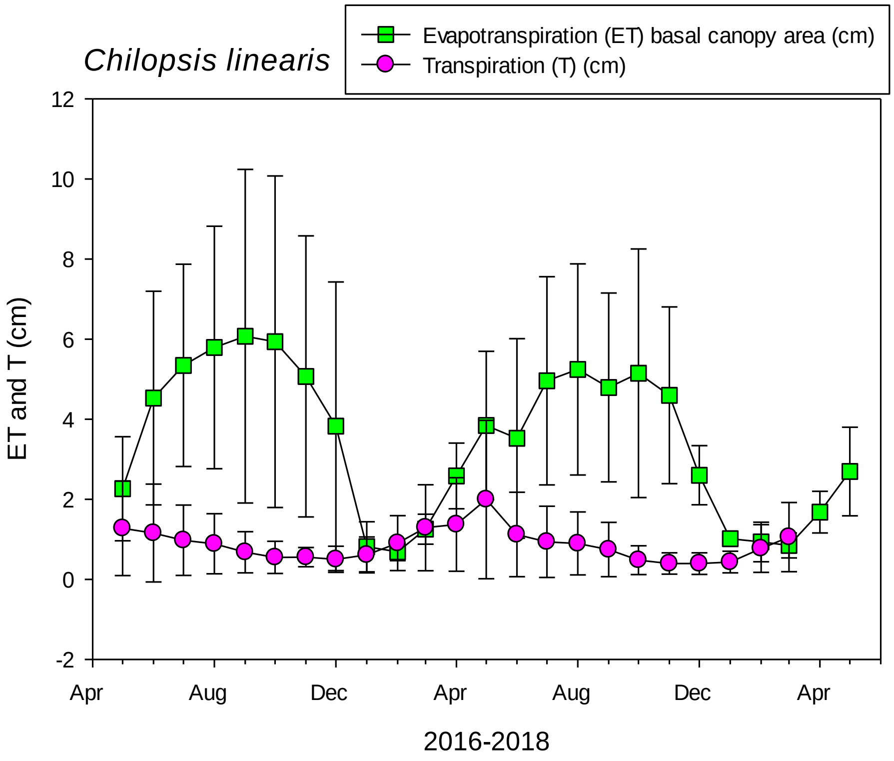


Figure 30. Sap flow transpiration and evapotranspiration (ET) determined by hydrological balance for *Chilopsis linearis*. Points are the mean (n=3), error bars show 1 standard error.

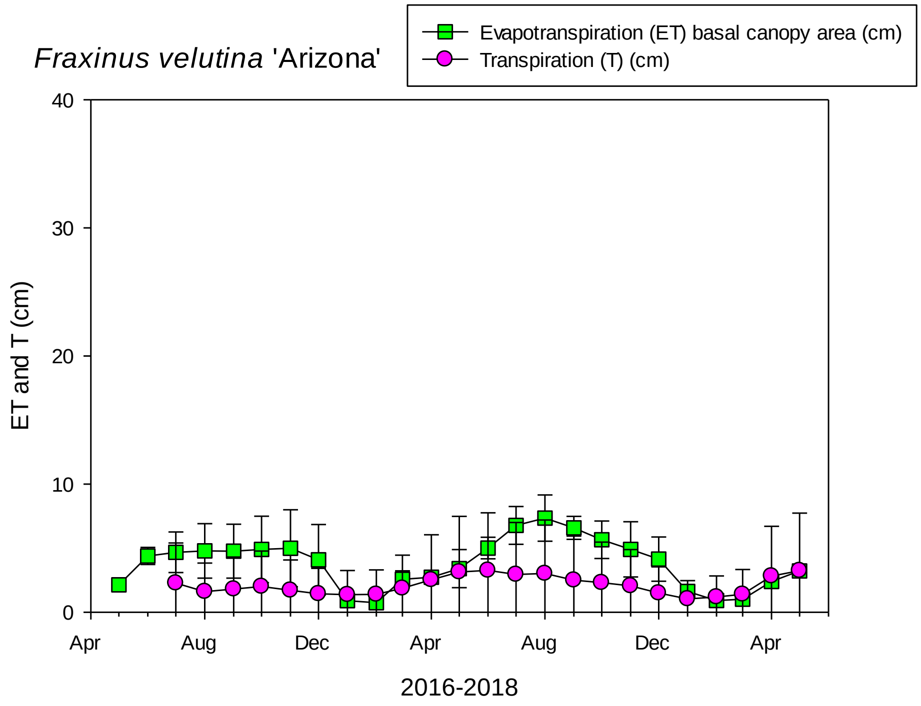


Figure 31. Sap flow transpiration and evapotranspiration (ET) determined by hydrological balance for *Fraxinus velutina* ‘Arizona’. Points are the mean (n=3), error bars show 1 standard error.

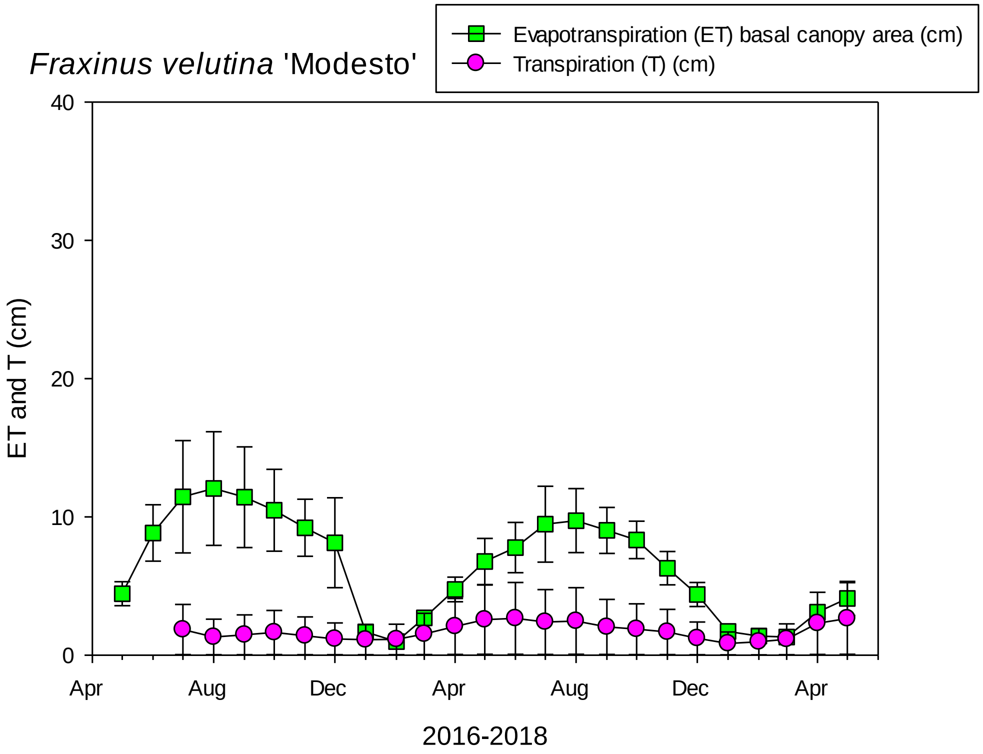


Figure 32. Sap flow transpiration and evapotranspiration (ET) determined by hydrological balance for *Fraxinus velutina* ‘Modesto’. Points are the mean (n=3), error bars show 1 standard error.

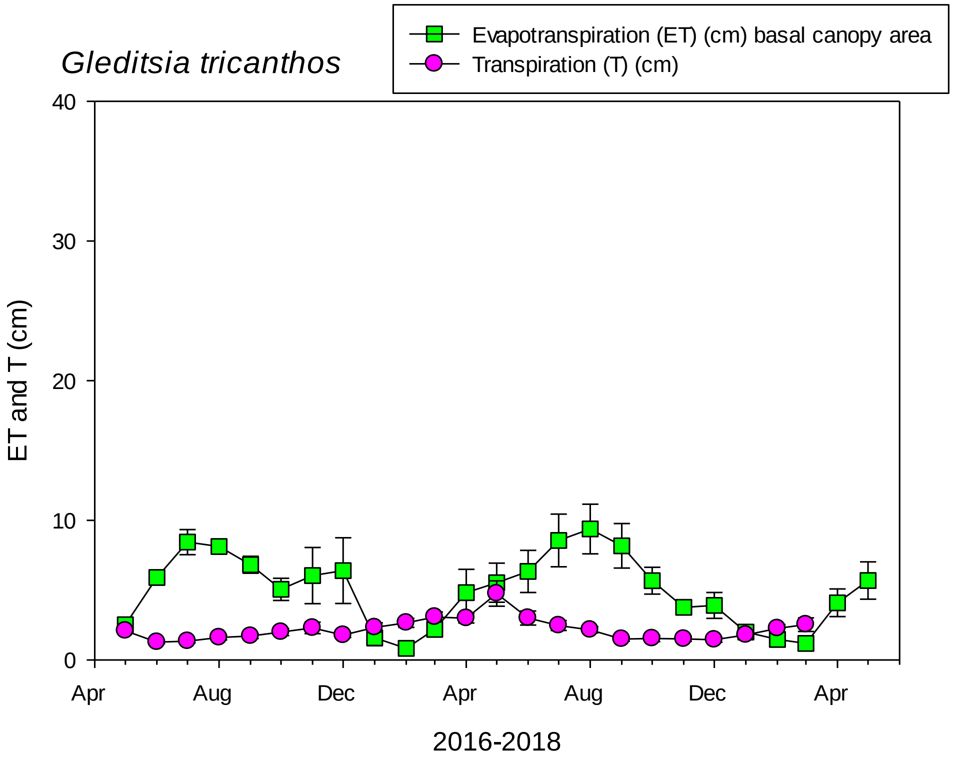


Figure 33. Sap flow transpiration and evapotranspiration (ET) determined by hydrological balance for *Gleditsia tricanthos*. Points are the mean (n=3), error bars show 1 standard error.

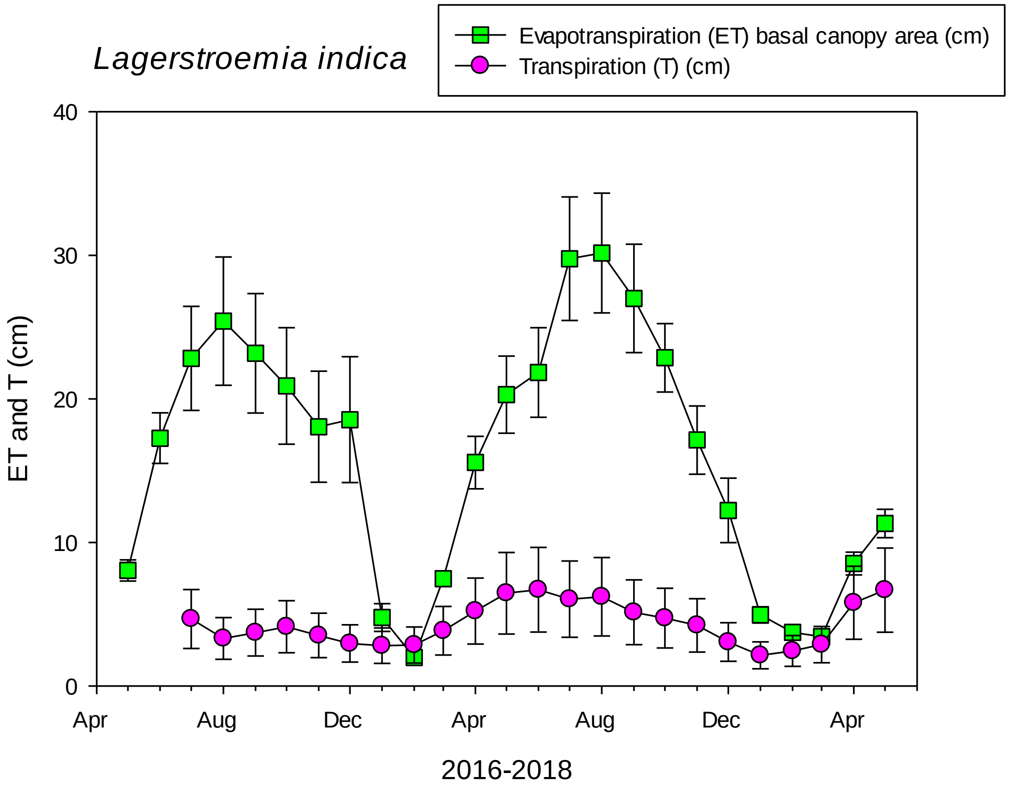


Figure 34. Sap flow transpiration and evapotranspiration (ET) determined by hydrological balance for *Lagerstroemia indica*. Points are the mean (n=3), error bars show 1 standard error.

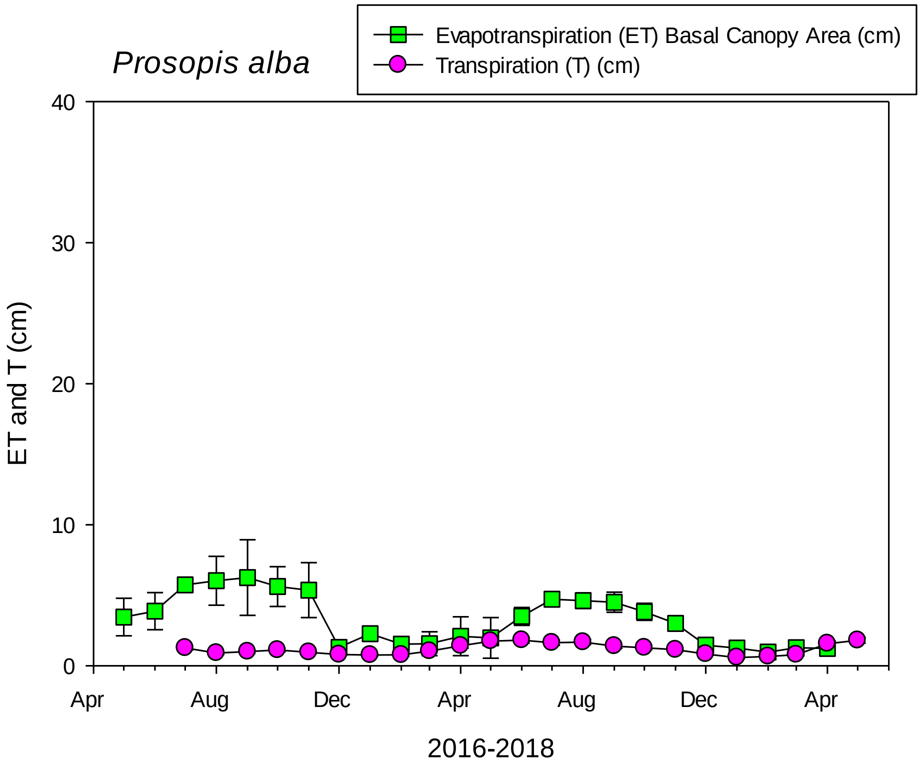


Figure 35. Sap flow transpiration and evapotranspiration (ET) determined by hydrological balance for *Prosopis alba*. Points are the mean (n=3), error bars show 1 standard error.

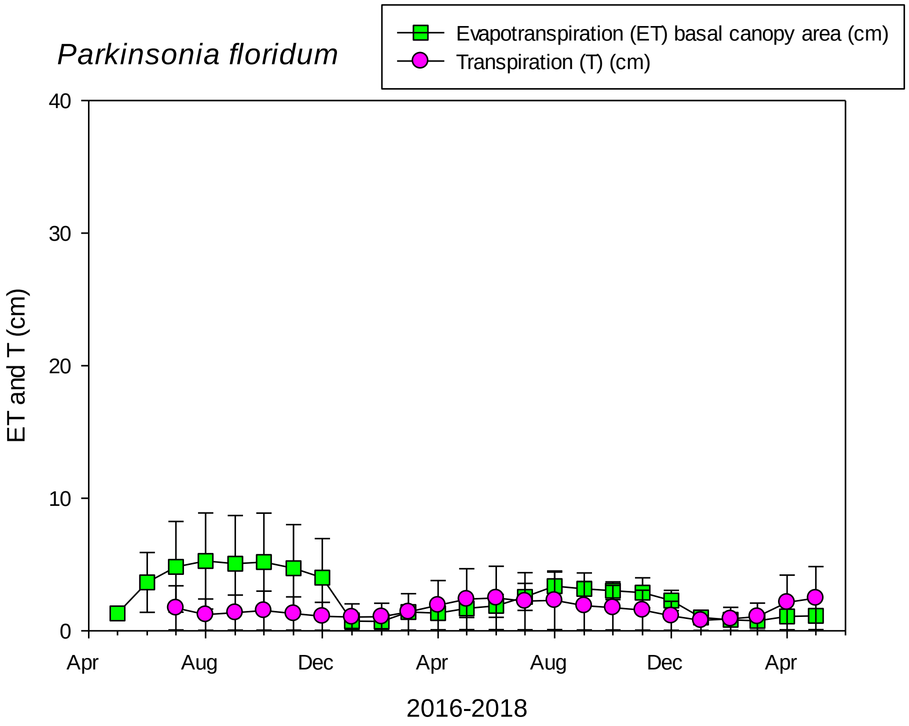


Figure 36. Sap flow transpiration and evapotranspiration (ET) determined by hydrological balance for *Parkinsonia floridum*. Points are the mean (n=3), error bars show 1 standard error.

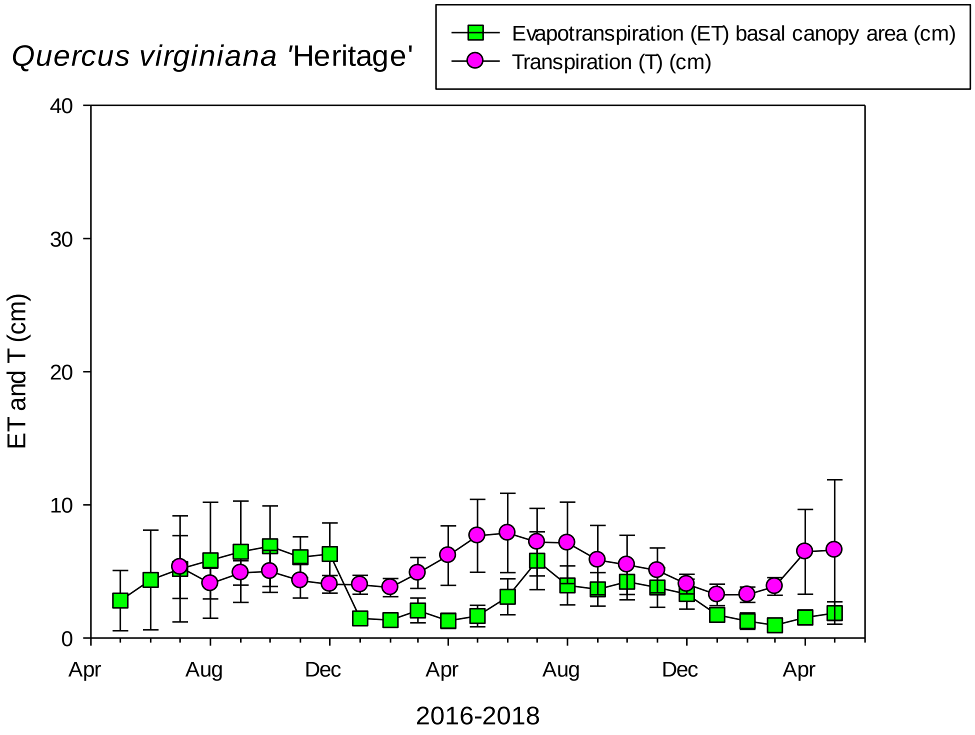


Figure 37. Sap flow transpiration and evapotranspiration (ET) determined by hydrological balance for *Quercus virginiana* ‘Heritage’. Points are the mean (n=3), error bars show 1 standard error.

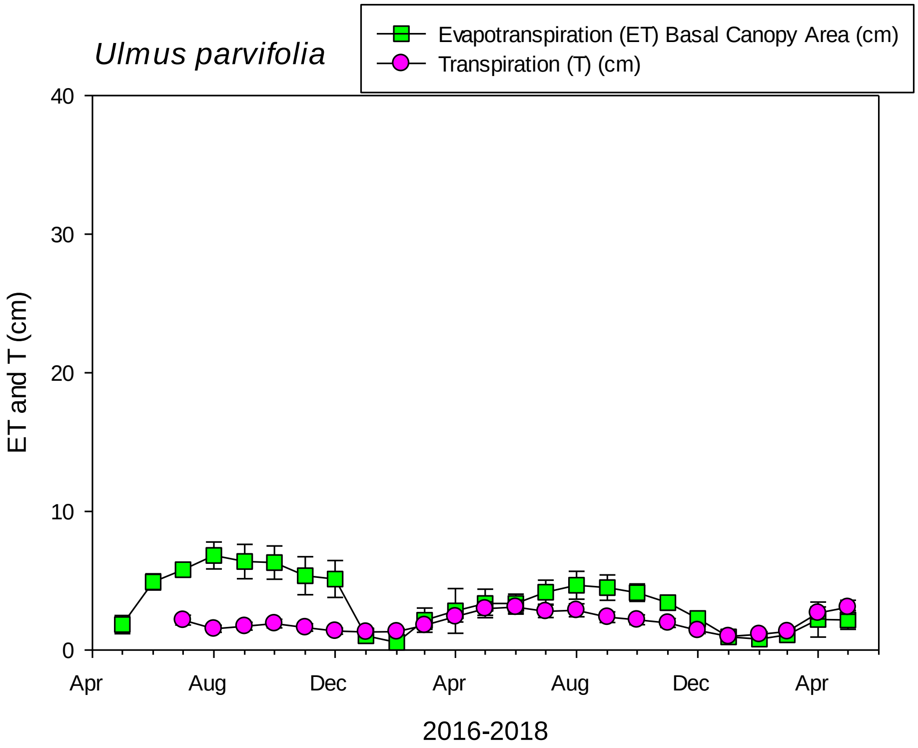


Figure 38. Sap flow transpiration and evapotranspiration (ET) determined by hydrological balance for *Ulmus parvifolia*. Points are the mean (n=3), error bars show 1 standard error.

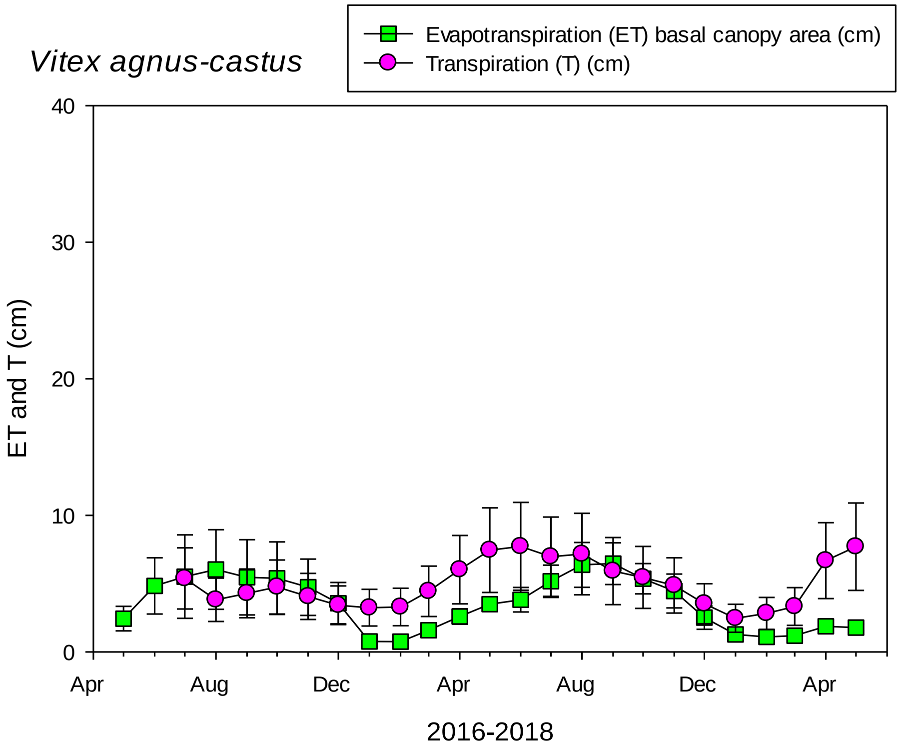


Figure 39. Sap flow transpiration and evapotranspiration (ET) determined by hydrological balance for *Vitex agnus-castus*. Points are the mean (n=3), error bars show 1 standard error.

## **Appendix D:** Tree to Grass Ratios

Tree to grass ratios for ten desert adapted trees.

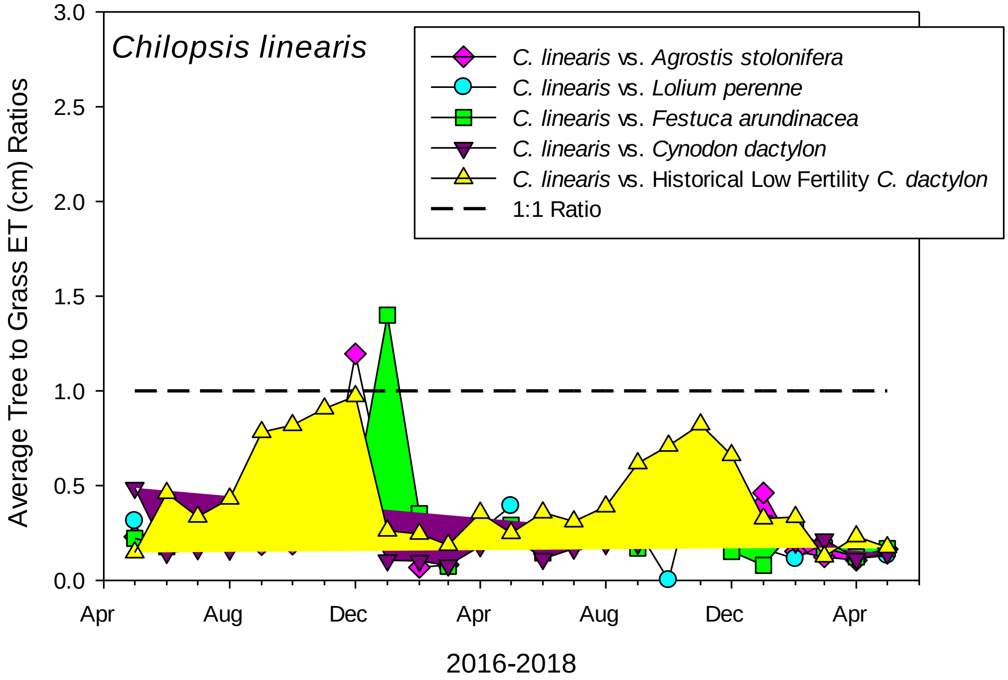


Figure 40. Tree to grass evapotranspiration (ET) ratios for *Chilopsis linearis*.

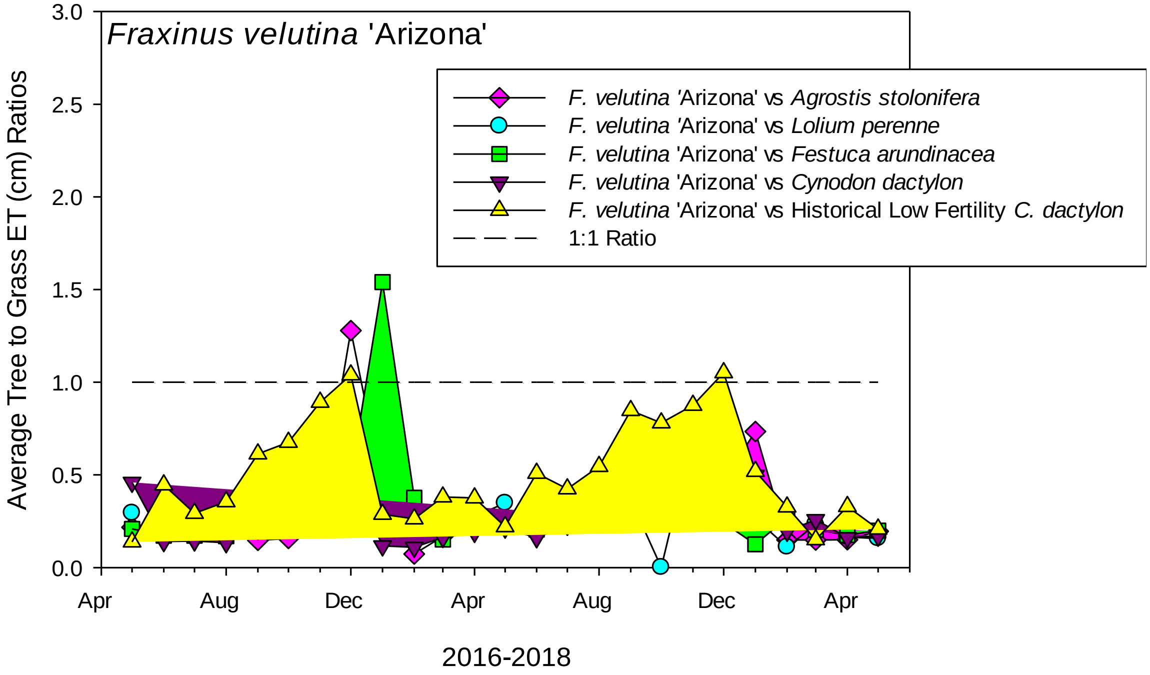


Figure 41. Tree to grass evapotranspiration (ET) ratios for *Fraxinus velutina* 'Arizona'.

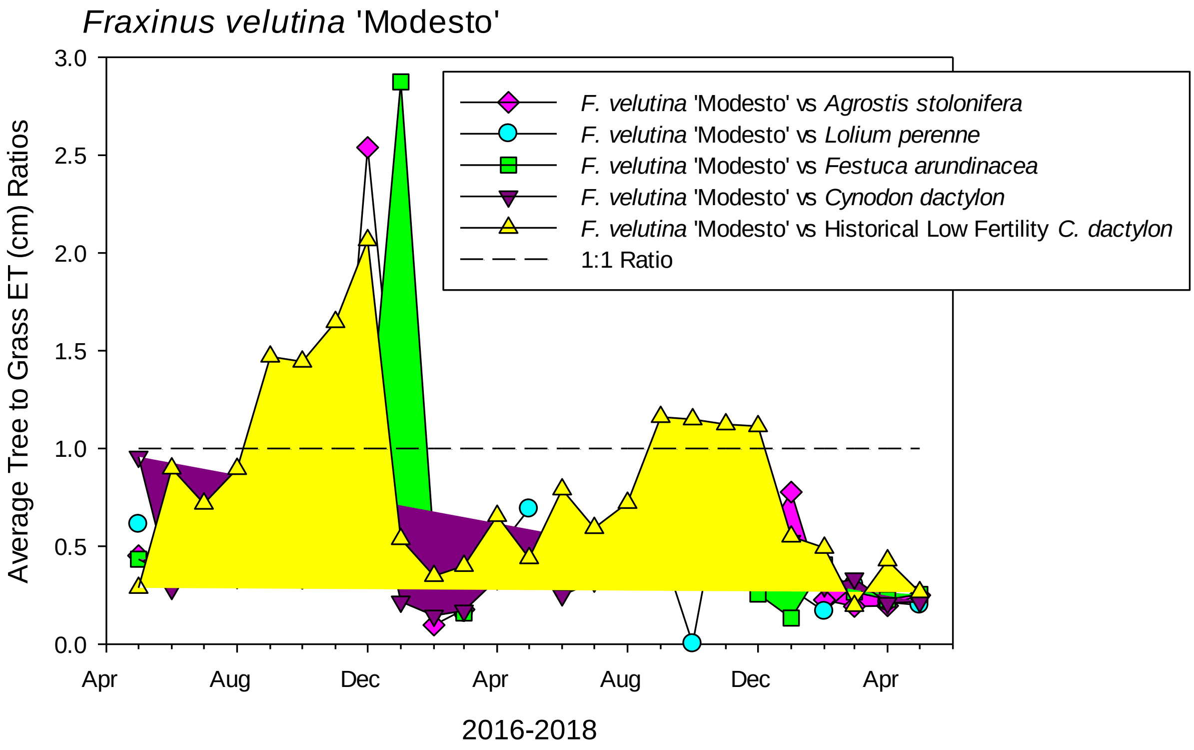


Figure 42. Tree to grass evapotranspiration (ET) ratios for *Fraxinus velutina* 'Modesto'.

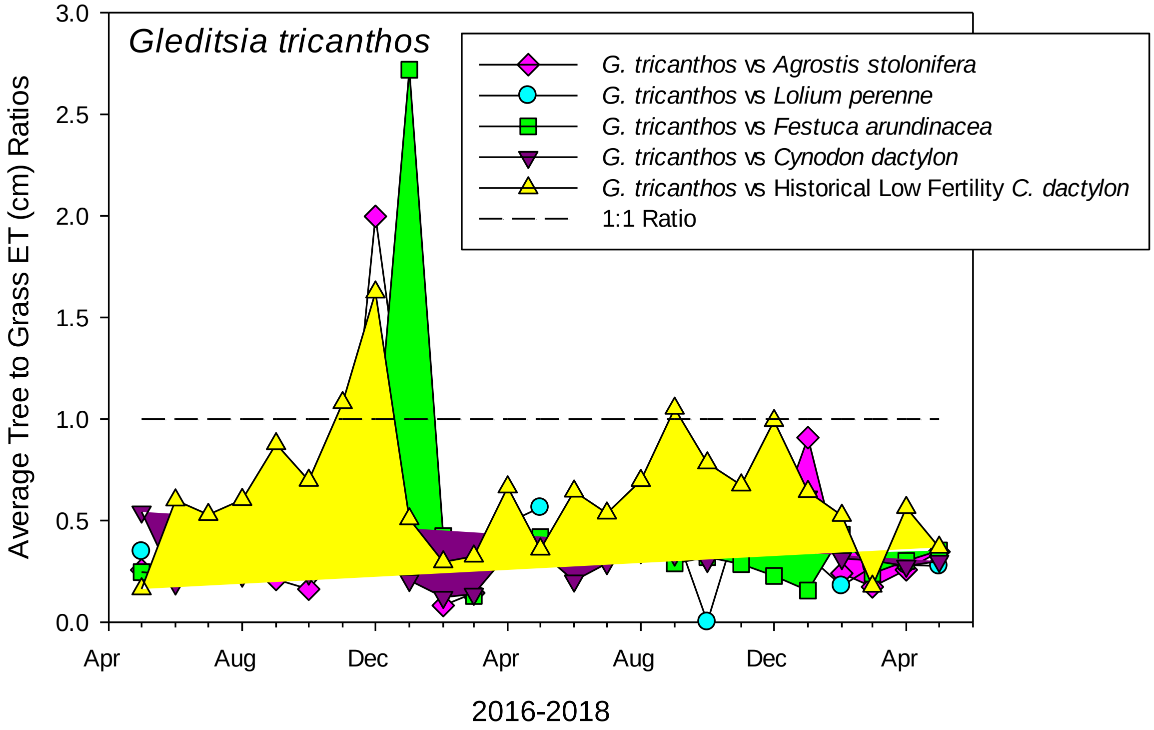


Figure 43. Tree to grass evapotranspiration (ET) ratios for *Gleditsia tricanthos*.

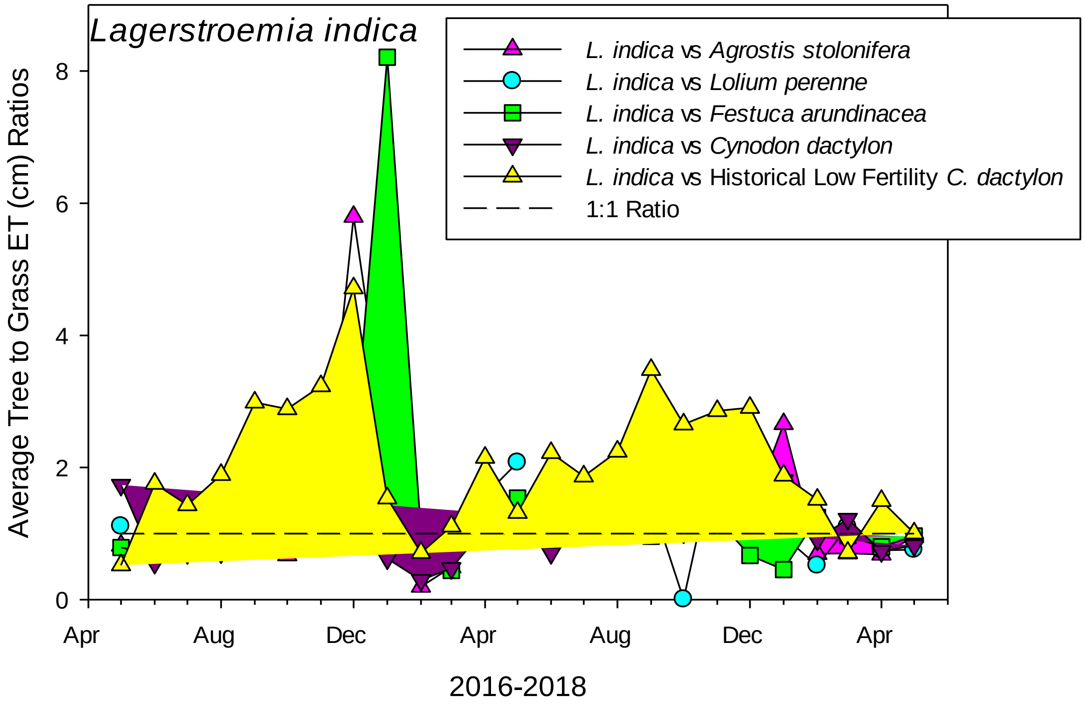


Figure 44. Tree to grass evapotranspiration (ET) ratios for *Lagerstroemia indica*.

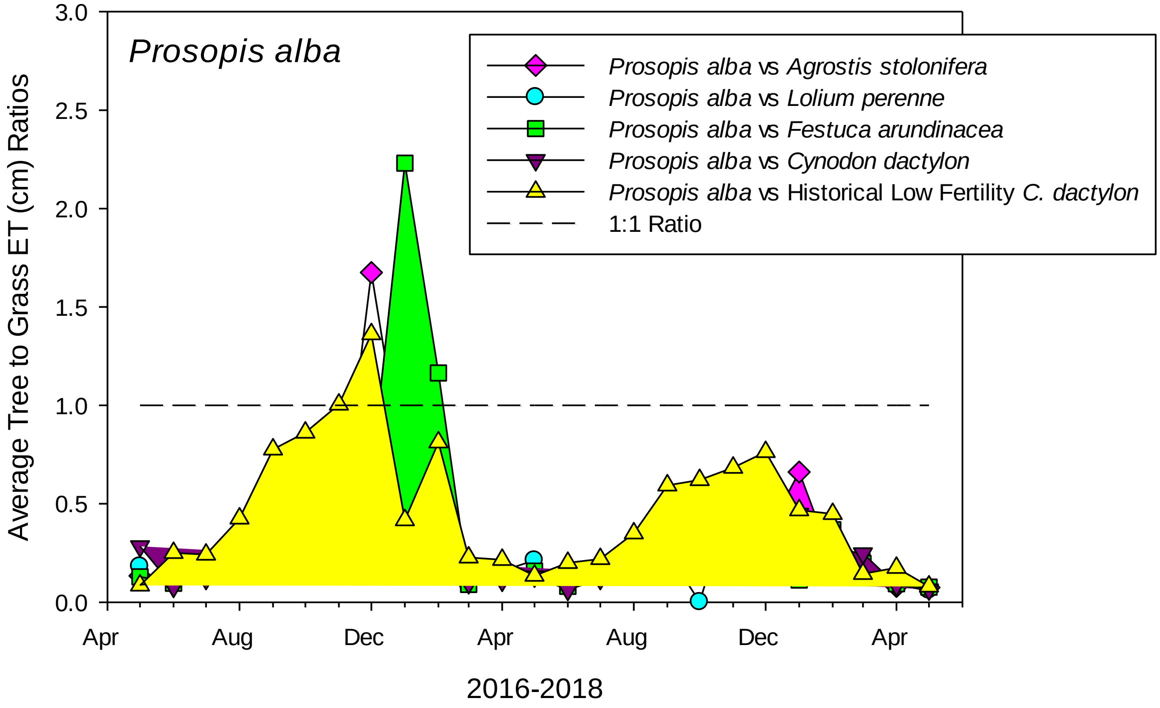


Figure 45. Tree to grass evapotranspiration (ET) ratios for *Prosopis alba*.

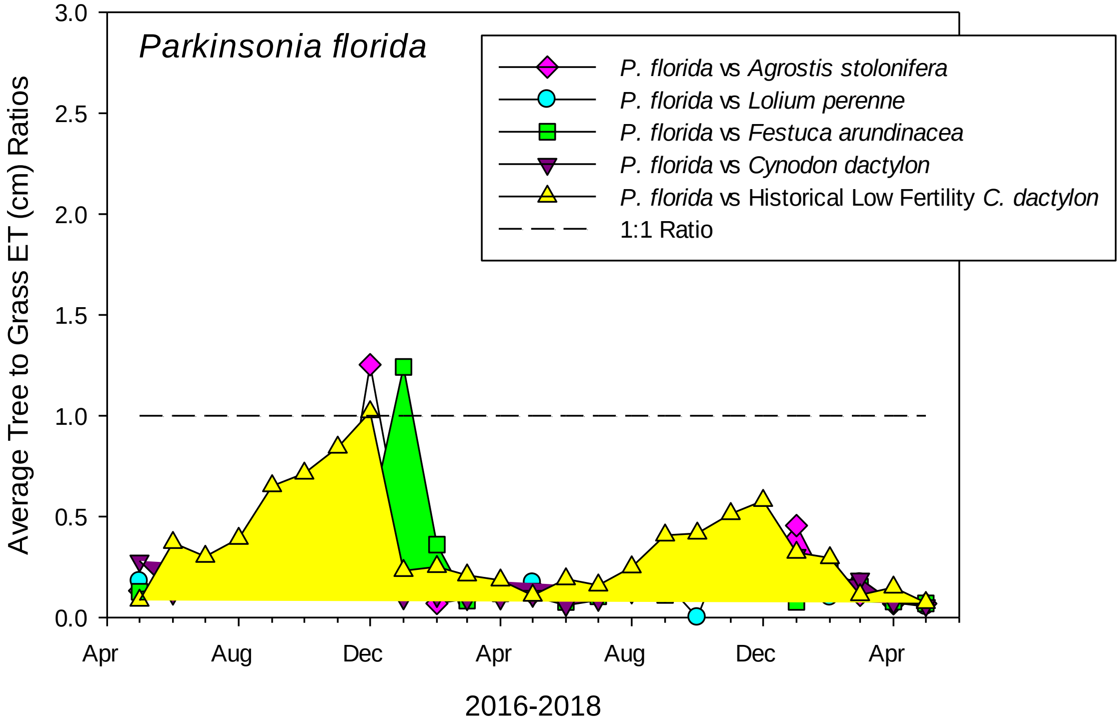


Figure 46. Tree to grass evapotranspiration (ET) ratios for *Parkinsonia florida*.

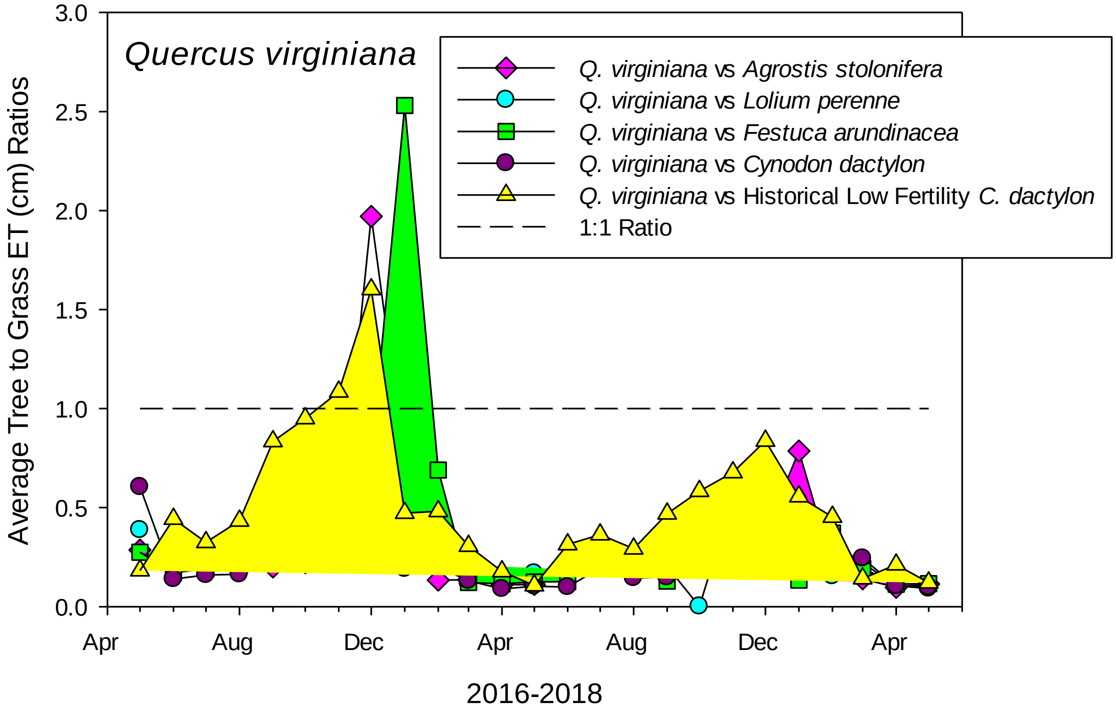


Figure 47. Tree to grass evapotranspiration (ET) ratios for *Quercus virginiana*.

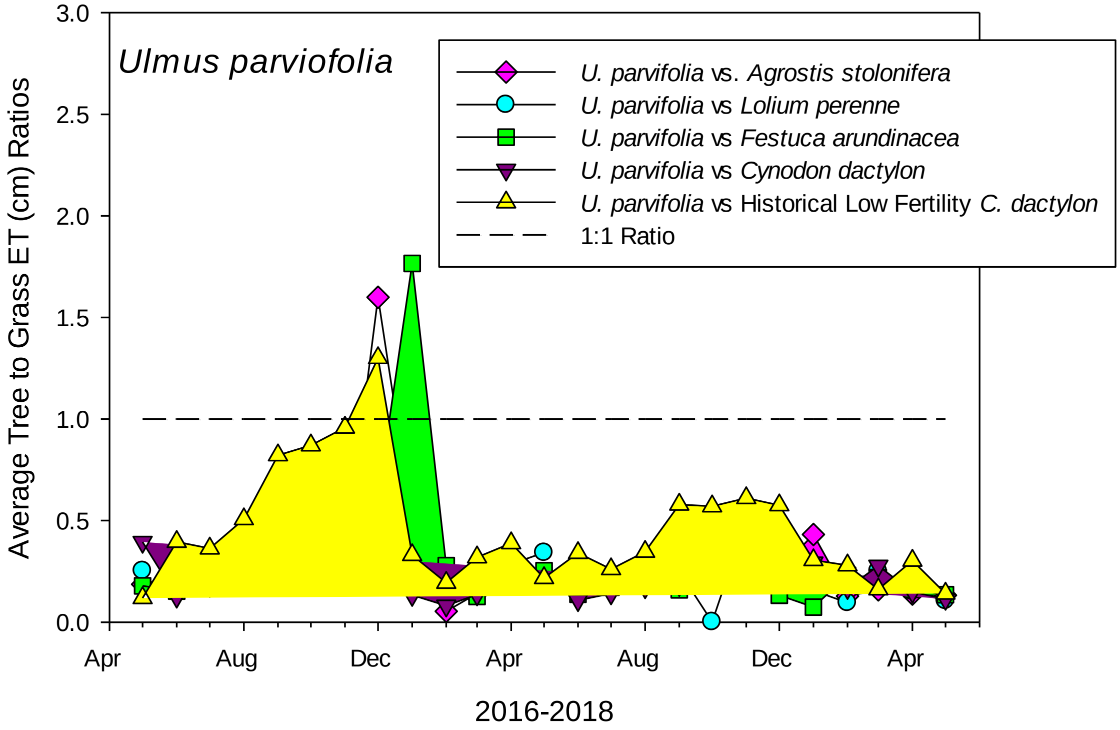


Figure 48. Tree to grass evapotranspiration (ET) ratios for *Ulmus parvifolia*.

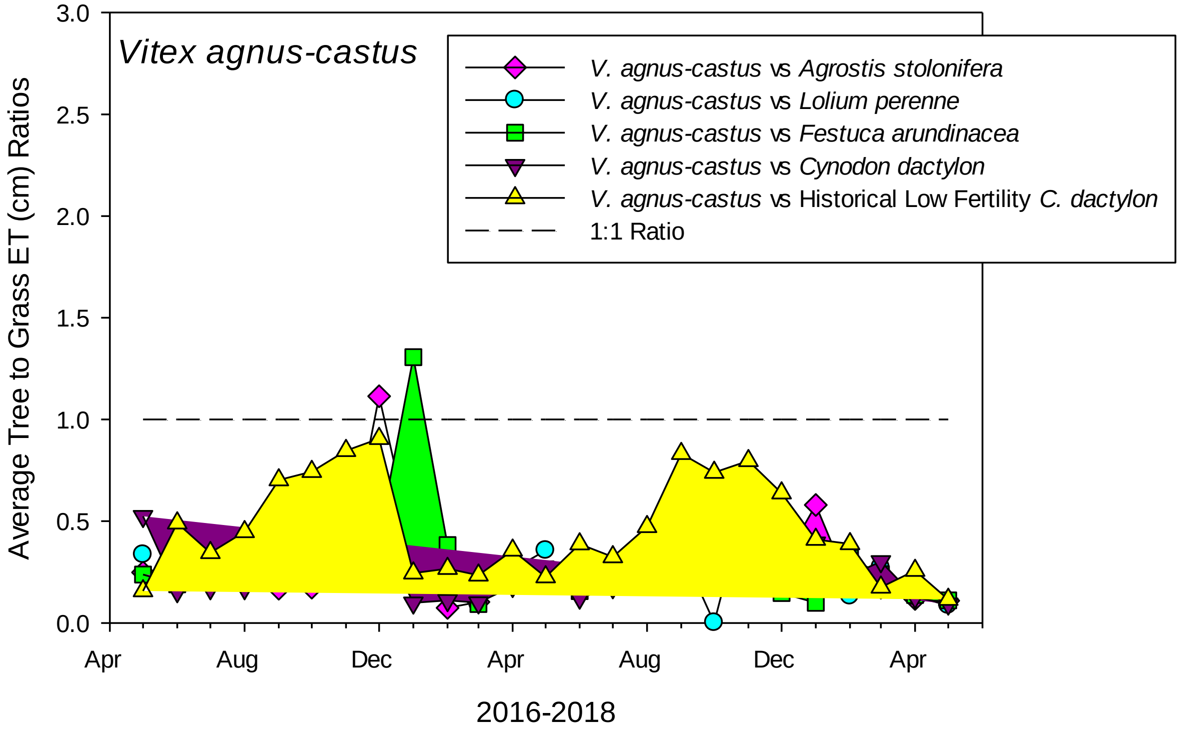


Figure 49. Tree to grass evapotranspiration (ET) ratios for *Vitex agnus-castus*.

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## Curriculum Vitae

Tamara Wynne

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Profile

Drawing by
Tamara Wynne

Talented University of Nevada Las Vegas graduate student with extensive botanical care and horticultural experience who is passionate about Earth's living components and eager to share that passion.

Work & Research Experience

2016-2018 *Graduate Student*, University of Nevada Las Vegas, Professor Dale Devitt

- Gathered data and compiled results for 30 trees and 12 grass lysimeters testing water consumption in Southern Nevada.
- Wrote thesis and generated 80 graphs in Sigmaplot and defended my thesis.
- began PhD program in fall 2018 studying native plants' response to solar facilities.

2017-2018: *Research Associate,* University of Nevada Cooperative Extension, Las Vegas, NV

- All the same duties as previous position.
- Design, implement, and analyze statistics of new research experiments.
- Write and publish research papers and fact sheets.

2015-2017: *Research Technician,* University of Nevada Cooperative Extension, Las Vegas, NV

- Organized and motivated thirty volunteers, including Master Gardeners, to learn and work in a 600 fruit tree orchard and 100 grapevines.
- Taught and organized small classes for public and volunteers regarding many plant and horticultural topics.
- Managed and cared for 600 fruit trees, 100 grapevines, and 12 vegetable beds, including fertilizing, pruning, planting, removing, applying pesticide/herbicide, and harvesting.
- Sell fruit to the public, teaching about fruit varieties that work in Southern Nevada.
- Wrote grant proposal for Western Sustainable Agriculture Research and Education, with the help of two faculty in University of Nevada Cooperative Extension, about growing new hops varieties and creating a Southern Nevada hops industry.

- Maintained and purchased equipment and materials needed for the Research Center and Demonstration Orchard by writing budget, state requisitions, and using the state purchasing card.
- Cared for honey bees and honey production.

2013-2014: *Manager's Assistant,* Gilcrease Orchard, Las Vegas, NV

- Helped people identify ripe fruit and vegetables and taught customers about fruit.
- Cashiered to sell fruit and vegetables to people.
- Actively participated in caring for the honey bees and honey production.
- Taught school children about pumpkins and apples during field trips in the orchard, giving tours around the trees and vegetable beds.

2010 – 2013: *Outside Salesperson*, Star Nursery, Las Vegas, NV

- Gained an advanced understanding of native plants and landscaping in southwest Nevada and California.
- Assisted people with a number of customer service needs including, but not limited to, determining the best plant selection for their landscape projects, special ordering, and diagnosing pests, diseases, and plant abuse.
- Responsible for care and maintenance of nursery plants including watering, adding fertilizer, and propagation.
- Successfully communicated with Spanish speaking coworkers.
- Earned a Restricted Use Pesticide Certificate: Greenhouse and Nursery

2009 – 2010: *Field Biologist*, URS Corporation, Santa Ana, CA

- Surveyed engineering sites for endangered and threatened animals and plants, many as large as 1,800 acres.
- Responsible for memorizing central and southern California native and introduced plants for survey projects.
- Identified obscure plants with the assistance of numerous references, including *The Jepson Manual*.
- Wrote detailed reports which described possible damage to habitat and projects concordance with federal and state environmental laws.
- Coordinated with senior director to approve reports prior to submission to appropriate government agencies.

2005 – 2009: *Undergraduate Assistant,* Cornell University, Ithaca, NY

*2007 – 2009: Undergraduate Researcher*, Natural Resource Department, Assistant Professor Bernd Blossey

- Built relationships with a variety of professors to learn and develop varying research methods and strategies.

- Designed and organized four experiments to test; 1) pathogenic/mutualistic fungi and allelopathic interactions with the invasive plant, *Phragmites australis*, advancement; 2) *P. australis* native and introduced seed and seedling survival affected by fungi and oomycetes.
- Developed reports to analyze and describe the results of each study.
- Responsible for propagating and care of 300+ plants for 4 months, including watering, fertilizing, removing of aphids.
- Successfully obtained all materials for an experiment, planted, and cared for 5000 seeds in growth chamber and 400 seedlings outside with the help of other undergraduate lab assistants.

## Education

2005 – 2009: Cornell University, Bachelor of Plant Science, College of Agriculture and Life Sciences, GPA: 3.2/4.0

- Relevant course work: Introductory Botany and Evolution, Taxonomy of Vascular Plants, Horticulture, Environmental Conservation, Plant Diseases and Disease Management, Soil Science, Symbiotic Relationships

## Awards

2011: Employee of the Month, Star Nursery

2009: Best Middle Distance Runner, Cornell University Varsity Track Team

2005 – 2009: Wilhelmine Lind Memorial Fund Award, Cornell University

2008 – 2009: Mrs. Francis King Scholarship, Cornell University

2008 – 2009: Melvin and Helen Hoffman Scholarship, Cornell University

## Other Activities

2005 – 2009: Cornell University Varsity Cross Country and Track Teams

2005-2009: Served for the Cornell Catholic Community as a lector, reading in front of the church Bible passages for the church service.