# ABSTRACT


Title of Thesis: Assessing Evapotranspiration Rates of a Mid-Atlantic Red Maple Riparian Wetland Using Sap Flow Sensors.

Jennifer Renz, Master of Science, 2005

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Riparian forests are unique due to increased exposure of trees to winds and radiation and the subsequent effects on the quality and quantity of water discharge from the system. Since "edge effects" can enhance evapotranspiration (ET) of exposed trees, ET rates of a first-order red maple riparian wetland were assessed with thermal dissipation probes during the 2002 growing season to address: a) if edge trees transpire more water daily than interior trees, b) correlations among sap flow rates and energy balance-derived estimates, c) variations in ecosystem ET estimates based on 6 scaling variables, and d) diurnal correlations between maximum sap flow rates and streamflow losses. Results from this study indicate that: a) edge trees transpire more water daily than interior trees during early summer, b) choice of scaling variable affects estimation of ecosystem ET rates, and c) maximum sap flow rates correlate with streamflow losses diurnally under specific environmental conditions.

# ASSESSING EVAPOTRANSPIRATION RATES OF A MID-ATLANTIC RED MAPLE RIPARIAN WETLAND USING SAP FLOW SENSORS.

By

Jennifer Theresa Renz

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Advisory Committee:
Dr. Bahram Momen, Chair
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# Dedication

To Tim, my unshakable husband.  Come rain, snow, or teary downfall, your support and friendship make life beautiful.

# Acknowledgements

First and foremost, I'd like to thank the God above that gave me the eyes with which to read and wonder, the ears with which to listen, and the sense with which to know that I should never stop learning.

Second, I'd like to thank my husband Tim. Without him, I would never have stayed sane throughout the overwhelming beginning, the monotonous middle, or the flurrying end of this project. Indeed, life and the data processing in between would have been a torture instead of a joy without him.

I will never have the proper words with which to thank Dr. Bahram Momen. However, I can say that I am a better person for having met him, having worked beside him, and having learned from him. My wish for all eager students is to have at least one teacher and mentor as experienced and selfless as he. My wish for all mentors like him is that they realize the difference they make and sleep confidently and peacefully as a result. His many kindnesses will never be forgotten.

Thanks should go to the good folks at BARC who work hard for the greater good of the earth: Greg, Jonathan, Rachel, Swati, Leticia, and Katey. Three cheers for OPE3!

Thanks should also go to Dr. Marla McIntosh for her support, both monetary and inspirational, throughout my graduate career. Without her enthusiasm, this never would have been.

Lastly, I would like to thank my ever supportive family: Mumsy, Pop, Dan, Angela, Paul, Julia, David, Sue, Keith, Claire, Maddie, Ed, and John. And, of course, Joanne and Ed. I owe all I am in part, or in full, to each of you in turn.

Thank you. So much.

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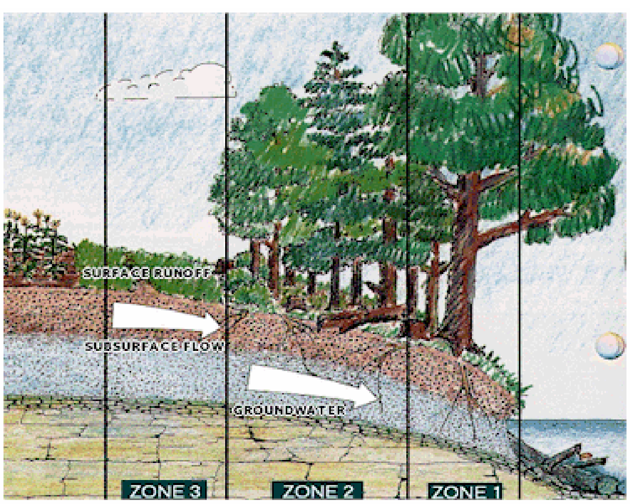
# 1 Introduction

## *1.1 Research Justification*

In the early 1600s, the 64,000 square mile Chesapeake Bay watershed was a forested wilderness, with over 500 prominent tree species. Land clearing continued through the 1800s in response to the need for wood and farmland, and by the early 1900s, only 30-40% of the watershed remained forested. In the mid 1900s, forests gradually reclaimed previously harvested areas, and by 1980 forested areas had reached 60%. Since then, suburban sprawl and development have again decreased forested areas (Alliance for the Chesapeake Bay 1996). This loss of forest land has adversely influenced water quality since forests decrease soil erosion and nutrient runoff. As a result, streamside (riparian) forests have slowly become the preferred management practice to mitigate the loss of forests in the surrounding landscape. Currently, nearly 50% of the Chesapeake Bay Watershed's 100,000 miles of river and stream remain unbuffered, despite rising interest in improving water quality (Alliance for the Chesapeake Bay 1996). These circumstances have placed more interest in defining the optimum riparian zone planting and maintenance strategies to help protect the Chesapeake Bay Watershed.

To help offset the impact of suburban sprawl on the water quality of the Chesapeake Bay, a three-zone riparian buffer model was developed by the USDA Forest Service in cooperation with the Chesapeake Bay Program (see Figure 1). Zone 1 of the riparian buffer model is a permanent tree buffer adjacent to the stream bank. This zone should prevent stream bank erosion, shade stream waters, and provide wildlife habitat. Zone 2 is a managed forest immediately upslope of zone 1, and should primarily remove pollutants carried by surface runoff and shallow groundwater. Root zone hydrology and the effects of vegetation on subsurface waters in this zone have been widely studied. Despite inconsistent results, his zone can be effective if preferential flow pathways are minimized. Zone 3 is an herbaceous or grass filter strip upslope from zone 2 which should protect the forested buffer, slow runoff, and improve the sediment trapping ability of zone 2 (Alliance for the Chesapeake Bay 1996; Palone and Todd 1998). The Chesapeake 2000 Agreement set the goal of implementing 2,010 miles of forested riparian buffers by the year 2010. The goal was achieved 8 years in advance and a new goal was established in 2003 to implement 10,000 miles of buffers by 2010 (Chesapeake Bay Program, 2005). More research is needed to develop optimum vegetation planting and maintenance strategies for these ecologically and economically important areas.

**Figure 1 Three-zone approach to forested riparian buffer corridor management (Alliance for the Chesapeake Bay 1996).**



Evapotranspiration (ET), or the water that vaporizes from the water or soil (evaporation) together with moisture that passes through plants to the atmosphere (transpiration), plays an important role in riparian and wetland hydrology (Dunne and Leopold 1978). As a result, concerned natural resource managers and hydrologists have developed a variety of ways to estimate riparian and wetland ET. One recently developed method used to estimate forest ET rates is the usage of Thermal Dissipation Probes. By quantifying the sap flow velocity of a tree using heated and reference thermocouples, whole-tree transpiration rates can be estimated. Scaling up transpiration estimates from a single tree to a forest stand, however, is complicated due to species, topographic, and environmental heterogeneities throughout the stand.

Riparian forest buffers and forested riparian wetlands pose additional sap flow scaling error due to the presence of "edge effects". That is, trees on the edge of a forested area are exposed to higher levels of radiation and winds relative to interior trees. As riparian corridors consist of a high proportion of trees exposed to these effects, an accurate ET estimation method for riparian areas has not yet been developed since energy balances (commonly used to estimate forest stand ET) are inaccurate when applied to these small-fetched areas.

## *1.2 Research Objectives*

The primary goal of this study is to determine if there are significant differences in ET levels between red maple trees exposed to edge effects, interior trees along the stream, and those located in intermediate areas. In order to test the validity of the sap flow-derived ET estimates of the riparian wetland near Laurel, MD, this I compare the sap flow-derived estimates to those calculated from a simple energy balance. Ecosystem-level ET estimates based on the ET estimates of six red maples will be calculated according to a vegetation survey of the wetland while comparing six sapwood-based scaling parameters. Finally, I test if daily maximum sap flow rates and daily streamflow losses are correlated. In addition, these tests will allow me to a) develop a series of representative daily hydrographs depicting the impact ET has on the riparian wetland water balance under baseflow conditions, and b) aid in the understanding of the effect ET and the subsequent stream flow trends have on daily nutrient cycles within the riparian wetland.

### *1.3 Literature Review*

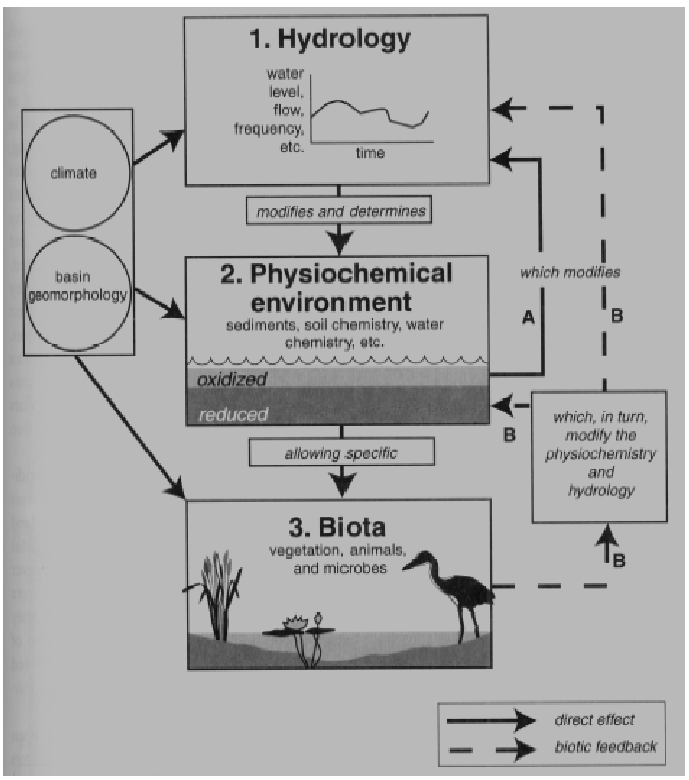
Evapotranspiration (ET) and its effect on riparian system hydrology, while frequently assessed in arid systems, is less often modeled in temperate systems. Forested riparian wetlands in particular are beginning to receive increased attention due to the awareness of the role riparian buffers can play in helping to "buffer" waterways from watershed pollutants such as N, P, K, and pesticides. Since understanding and evaluating the impact ET has on stream flow is critical when interpreting nutrient cycling, many methods of ET estimation have been developed. Descriptions of some of these methods are outlined in this review. However, assessment of riparian forest ET is difficult due to the presence of "edge effects". Since edge trees are exposed to increased radiation intensities and wind speeds relative to interior trees, edge trees experience elevated transpiration rates. It is unknown the extent to which edge effects impact sap flow within riparian forests, though differences in available energy between forest edge and streamside sites do exist (Giambelluca, Ziegler et al. 2003).

Riparian forests differ from other forests because they: a) generally have a serpentine form as a consequence of their proximity to rivers and streams, b) are open systems that receive frequent energy inputs and have the ability to regulate nutrient cycles of waters entering a stream network, and c) connect upstream and downstream as well as aquatic and terrestrial ecosystems, and thus they share ecological characteristics of these systems (Mitsch and Gosselink 2000). Riparian buffers and riparian wetland ecosystems in particular have positive impacts on water quality because:

1) Deep-rooting woody vegetation act as a nutrient sink and buffers the non-point source pollution from surrounding agroecosystems (Peterjohn and Correll 1984).
2) Woody vegetation, shrubs, and grasses can slow saturated overland flow (runoff) and increases sedimentation rates, effectively "buffering" the surface water from sediment and its associated pollutants (i.e. phosphorous, pesticides, herbicides) (Lowrance, Vellidis et al. 1997).
3) Wetland oxidation/reduction potentials can enhance soil and water quality if organic matter is present in adequate quantity and specie due to the potential for denitrification, decomposition, and other nutrient transformations associated with wetland soils (Mitsch and Gosselink 2000).

Due to the prevalence of interconnected cycles within riparian systems, these areas have opportunities to influence water quality. Riparian wetland ecosystems, above and beyond riparian ecosystems, can typically further influence water quality by having increased species richness, increased primary productivity, increased organic matter accumulation rates, increased nutrient cycling capability, and greater nutrient availability (Zhang and Mitsch 2004). A conceptual model outlining the fundamental role of hydrology in wetland ecosystems can be seen in Figure 2.

**Figure 2 Conceptual diagram illustrating the effects of hydrology on wetland function and the biotic feedbacks that affect wetland hydrology. Pathways A and B are feedbacks to the hydrology and physiochemistry of the wetland (Mitsch and Gosselink 2000).**




Riparian wetland ET is important because of its role in wetland hydrology, and is a function of factors such as stand density, nutrient availability, soil water availability, wind speed, radiation intensity, etc.. Vegetation density, vegetation location, and vegetation composition all influence and are, in turn, influenced by hydrology. Wetland vegetation plays a unique role in influencing nutrient dynamics within any wetland, but in riparian wetlands in particular.

Since ET plays such an important role in impacting ecosystems, a variety of ET estimation methods have been developed. According to Wilson et al 2001, ET measurement techniques 1) are only representative within a certain spatial and temporal scale, 2) differ in which components they measure, and 3) require unique assumptions and associated errors. ET estimation methods can be grouped into three categories: 1) water balance methods, 2) energy balance methods, and 3) thermometric methods. Brief descriptions of the most common methods within these categories follow.

Water balance calculations are based on the concept that what enters a system must also exit that system. An example of a standard water balance equation for a riparian stream system is:

$$Q_{in} + GW_{net} + Ppt_{ws} = Q_{out} + ET_{ripcanopy} + E_{ws} + \Delta Storage$$

**Equation 1**

where:

$Q_{in}$ = volume of water flowing into the zone as streamflow
$GW_{net}$ = net volume of water flowing into the zone as groundwater
$Ppt_{ws}$ = volume of water falling onto the stream surface as precipitation
$Q_{out}$ = volume of water flowing out of the zone as streamflow
$ET_{ripcanopy}$ = volume of water transpired by riparian canopy of each zone
$E_{ws}$ = volume of water evaporating from the stream surface
$\Delta$Storage = net change in soil water storage during time period in each zone.

Water balance studies of forest transpiration involve calculating ET as the residual term while utilizing direct measurements of rainfall interception, soil water storage changes, and surface runoff. Errors in calculated ET are considerable because of the error associated with each of the other measured terms, and depend on time scales (Dunne and Leopold 1978; Shuttleworth 1993; Wullschleger, Meinzer et al. 1998). Despite their known inaccuracies, local water balance analyses (including lysimeter studies and baseflow recession curve studies) are still recommended for time scales greater than one day unless water uptake is high and/or drainage is relatively low in comparison to moisture extraction through ET. Local water balances have proven to be particularly useful when estimating ET for small plots, but are not recommended for areas with vegetation supporting deep roots ( >2m) (Oren and Pataki 2001). Local water balances have been widely used for measuring forest stand ET (Shuttleworth 1993), (Mitsch and Gosselink 2000) and often other methods are checked for accuracy in comparison to water balance-derived ET estimates.

Energy balance calculations utilize aerodynamic and energy measurements from above and below a forest canopy to quantify the amount of latent energy used for ET (Dunne and Leopold 1978). By calculating the ratio of latent heat (used by the plants to transform water into vapor) to sensible heat (heat lost to the atmosphere) within the system, ET can be estimated. Though useful for calculating ET for homogeneous agronomic species, energy balance methods are usually not applicable to small forest systems due to varying canopy albedo and topographic heterogeneity. Energy balance calculations are especially not appropriate for estimating riparian ET, as fetch conditions and forest canopy boundary layer heterogeneities are the norm.

The Penman and Penman-Monteith models are commonly referenced combination equations (simplified energy balances) which take into account local energy balances and aerodynamic principles (Stannard 1993). More accurate in water limited situations, the Penman-Monteith model also incorporates an index of canopy resistance (stomatal resistance). Both models are assumed accurate if fetch conditions are met and if the canopy is closed (Kustas, Stannard et al. 1996). However, both conditions are rarely met in riparian systems. Overall, the empirical methods mentioned here are most commonly used for estimating ET over large areas and they are most effective when applied to agricultural crops where the plant canopy is homogenous both in composition and in height, and where the fetch conditions are relatively large.

Transpiration rates of whole plants or branches can also be determined through the use of three thermometric techniques that use heat to measure sap flow. These techniques are: the heat balance method, the heat-pulse method, and the thermal dissipation probe method. A thorough overview of these three methods as pertaining to whole-tree water can be found in Smith and Allen 1996. Heat balance methods measure sap velocity by applying heat to an entire woody or herbaceous stem and calculating the speed with which sap flow carries away the heat from the heater. Since insulation limits external influences, heat applied to the stem surface can be divided into the heat that is lost to vertical conduction within the stem, radial heat lost to conduction, and heat taken up by the moving sap. A variation of the heat balance method is the "trunk sector" heat balance method for stems greater than 120mm in diameter, in which steel plates divide sapwood into separate sectors for ease of radial sap flow velocity calculations.

The thermal dissipation probe method of sap flow velocity estimation was developed by A. Granier (Granier 1987) and is also referred to as the "Granier-type sensor" method. In this method, two cylindrical probes are inserted radially into the sapwood of a stem with the upper probe being roughly 40-100mm above the lower probe. The upper probe contains a heater element and a thermocouple junction that is referenced to the lower probe (Granier 1987; Smith and Allen 1996). Constant heat is applied to the sapwood surrounding the upper probe and the difference in the temperature between the two probes is dependent on the sap flux density around the probes. Increased sap flux density (sap flow per unit area active sapwood) allows heat to be dissipated more quickly, which lowers the temperature difference between the probes. Thus, transpiration can be calculated through gauging the temperature differences (Granier 1987, Smith and Allen 1996).

Some problems have been identified when monitoring sap flow using thermometric methods:

1) Sap velocities in woody stems vary with radial depth (Smith and Allen 1996), (Phillips, Oren et al. 1996). To combat this variability, sensors must be located at varying depths below the cambium in order to determine the radial

profile of sap flux density across the sapwood. Radial variation in sap flow is remedied by the thermal dissipation probe method, as measurements of sap flow are integrated and averaged along the length of the probe (Dynamax 1997; Simpson 2003).

2) The heat-pulse methods work best in softwood species and in ring-porous species or diffuse-porous species with closely-spaced xylem vessels (Smith and Allen 1996).
3) Distances between the thermocouple probes in all of the thermometric methods must be measured precisely in order to ensure accurate results (Cermak and Nadezhdina 1998).
4) Inaccuracies can result from wound reactions within the woody tissue of the stem following probe installation. Wound reactions caused by the accumulation of resin within the xylem vessels cause sap flow diversions which can only be averted by monitoring sap flow sensitivities closely and moving probes to another location within the stem when appropriate (Smith and Allen 1996).

Despite these inaccuracies, thermometric methods are the preferred method if stand heterogeneity is high and if site-specific, species-specific, and time-specific ET estimations are needed.

Scaling up sap flow measurements to a homogeneous stand is relatively easy: extrapolation from a single plant could be done based on plant density and stand area. However, accurate scaling becomes more of a challenge when vegetation is heterogeneous in species, size, and age, or when canopy gaps are present. The most obvious approach for these stands is to measure sap flow of all plants within a representative portion of land and scale up based on land area. This, however, presents error due to differing soil water moisture and microclimatic conditions throughout the stand. To resolve this, scaling methods have been developed based on determining relationships between sap flow rates and stem diameter, sapwood area, or leaf area and scaling up based on a full stand survey of these parameters. Error can then only be introduced two times during the scaling up process: when scaling from probe to tree and from tree to stand (Hatton and Wu 1995b; Cermak and Nadezhdina 1998; Wullschleger, Meinzer et al. 1998; Clearwater, Meinzer et al. 1999). These errors can and should be dealt with on a local scale by informed resource managers.

In general:

1) Proportional sampling and scaling procedures should be used when scaling short-term and long-term sap flow measurements (Granier, Biron et al. 1996); Granier et al 1996). By allocating trees into categories based on diameter class or some other measure of tree size, scaling up becomes repeatable and reliable, despite the fact that transpiration rates are known to be more related to exposure to evaporative conditions and within-stand competition (Oren and Pataki 2001); (Hatton, Moore et al. 1995a).
2) At least 3 or more (and ideally 6-15) trees should be monitored within any fully grown stand (Cermak and Kucera 1990). Though the number of trees needed is dependent on the accuracy of the required results, it is important to

choose trees based on a field survey of species, crown position, DBH, tree height, etc. in order to adequately represent any area.

3) Sap flow rates are more variable between trees within the same stand under drought stress conditions and relatively low when water supply is adequate (Cermak, Cienciala et al. 1995). This suggests that forested wetland trees should be less prone to within-stand variability.

According to Wullschleger et al 1998, "The best way to determine the transpiration rate of a stand is to measure the water use of every tree in a plot large enough to be unaffected by edge effects." However, in logistically-limited situations or in situations where almost the entire stand is influenced by edge effects (as is the case for most riparian wetlands and corridors), this approach is not plausible. Only one known study to date has focused on this issue using a thermometric method. Giambelluca et al, 2003 tested the significance of edge effects using micrometeorologic calculations of energy flows and sap flow analyses. They found that while a microclimatic gradient existed between edge and interior forested areas, mean transpiration rates of the edge and interior areas did not differ significantly. It was suggested that this was likely due to the high variability both between trees and within a species. It was also noted that the difference between evaporation at the edge and interior sites decreased as conditions became wetter.

Numerous studies have assessed edge effects based on altered energy flows, though they bear little relevance to studies based on sap flow measurements and require an understanding of thermodynamics beyond the scope of this review. In addition, most riparian zones are too small to affect the properties of their surrounding regional atmospheres. As a result, riparian zones are supplied with unlimited saturation deficit which enhances evaporation above normal levels expected from available energy (Hipps, Cooper et al. 1998; Giambelluca, Ziegler et al. 2003). For these reasons, discussions of energy flow as they pertain to riparian ET will not be included here. It has been well established by these studies, however, that edge effects do play an important role in influencing areas with high occurrence of trees exposed to edge effects; hence the justification of this study.

# 2 General Materials and Methods

## *2.1 Experimental Site Description*

The study site is located in a first-order agricultural watershed in the Mid-Atlantic coastal plain in Laurel, MD, and is part of the Optimizing Production Inputs for Economic and Environmental Enhancement (OPE3) research projects conducted at USDA/ARS Beltsville Agricultural Research Center (BARC). The OPE3 projects are part of an international research program involving several U.S. Federal agencies and universities. The four major research areas of this project are: remote sensing, atmospheric monitoring, water and chemical behavior, and riparian buffer research. This study will provide insight into the impact the red maples have on riparian wetland hydrological function and nutrient cycling on site.

A first-order stream ~1200 m in length runs Northeast to Southwest through the riparian wetland. At the southern end, the stream joins a higher-order stream. Five permanent sampling and measuring stations divide the stream into four zones varying in length and characteristics (see Figure 3). The zone located between stations 1 and 2 has variable groundwater depth ranging from near surface in winter to much lower in summer (Angier, McCarty et al. 2001). The zone between stations 2 and 3 is a groundwater-fed wetland with perennially saturated surface conditions. The zone located between stations 3 and 4 contains the lower half of the riparian forest and is wider than the upstream portion. The zone located between stations 4 and 5 is driven by a highly variable water table. No surface water inputs contribute to any of the riparian wetland areas.

The soils have been identified in a previous study by Angier et al, 2002, as Typic Haplosaprist (Johnston silt-loam series) and are about 2 m deep. The entire study site is underlain by an oxic sand and gravel aquifer. The riparian soils have been estimated to be nearly 10,000 years old. Little is known about activity on the site prior to the 20$^{th}$ century. Up until the 1980s, a pig farm was located on the adjacent agricultural fields, which undoubtedly played a role in site geochemistry.

Throughout the zones, the following species are present in varying compositions (Herbert 2003): red maple (*Acer rubrum*), white oak (*Quercus alba*), northern red oak (*Quercus rubra*), southern red oak (*Quercus falcata*), black gum (*Nyssa sylvatica*), sweet gum (*Liquidambar styraciflua*), holly (*Ilex sp*.), river birch (*Betula nigra*), willow oak (*Quercus phellos*), beech (*Fagus grandifolia*), and tulip poplar (*Liriodendron tulipifera*). The area between stations 1 and 2 is dominated by red maple and white oak and the area between stations 2 and 3 is predominately red maple.

Skunk cabbage (*Symplocarpus foetidus*) is the most prevalent herbaceous species throughout the zones. Between stations 1 and 2, jewelweed (*Impatiens capensis*) and bladder sedge (*Carex intumescens*) are dominant herbaceous species. Further downstream between stations 2 and 3, cinnamon fern (*Osmundo cinnamonae*) accompanies skunk cabbage and jewelweed. Between stations 3 and 4, false nettle *(Boehemeria cylindrica*), rice cutgrass (*Leersia oryzoides*), wild strawberry

(*Fragraria sp*.) and Virginia creeper (*Polygonum arifolium*) cohabitate. Between stations 4 and 5, hastate tearthumb (*Polygonum arifolium*), Canadian clearweed (*Pilea pumelia*) and jewelweed increase in percent cover.

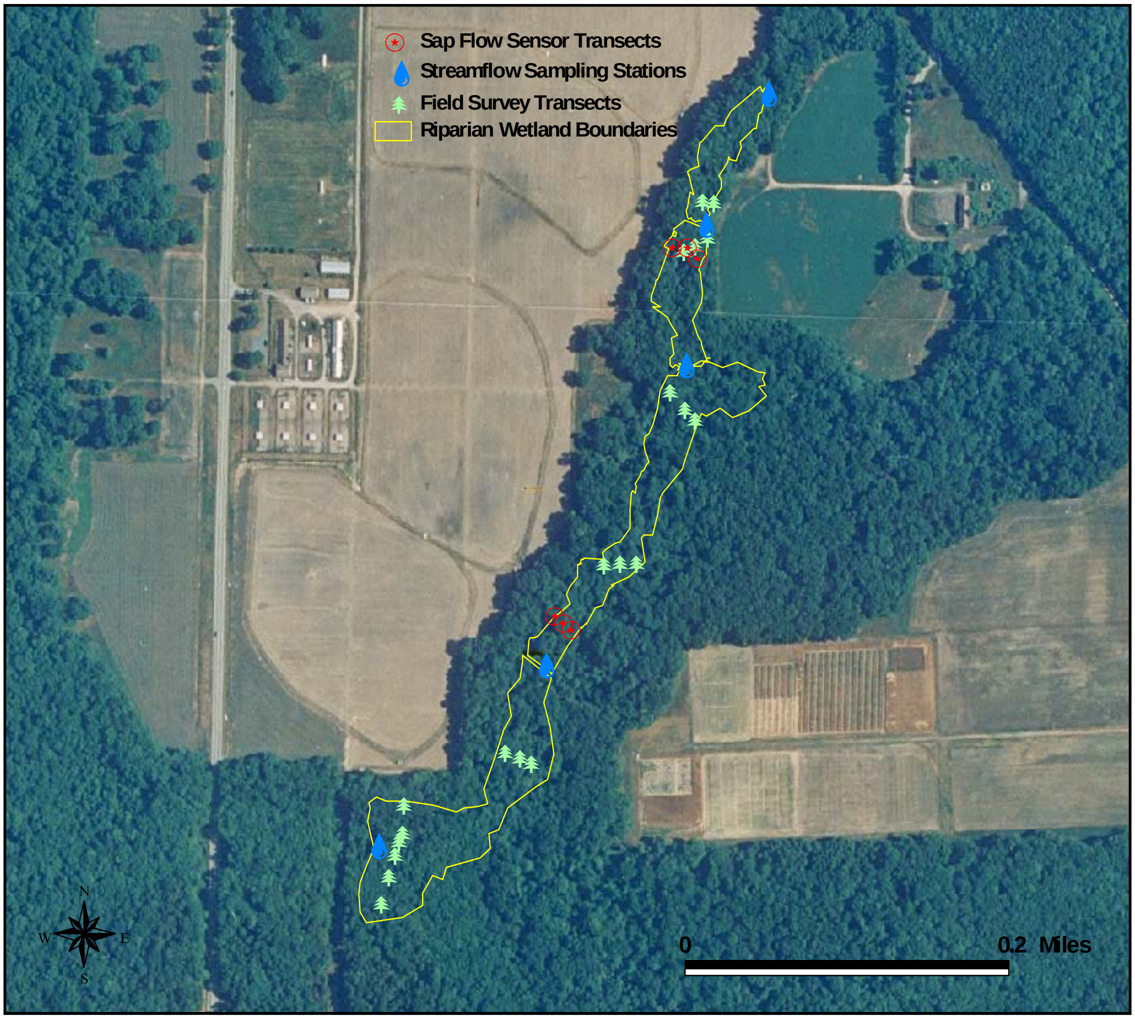



**Figure 3 Aerial photo of experimental site. Yellow shows boundary of riparian wetland, blue droplets represent streamflow sampling stations, green trees represent the vegetation survey transects.**

## *2.2 Vegetation Survey*

The first-order stream was divided into 4 zones by 5 streamflow sampling stations by previous Beltsville National Agricultural Research Center Environmental Quality Lab researchers. Six 25-m wide transects were randomly established to represent these zones for the vegetation survey. Zones 1 and 2 each have 1 transect and zones 3 and 4 contain 2 transects each, as can be seen in Figure 3. Transect locations were assigned by measuring the distances between the streamflow sampling stations and randomly choosing the number of meters to pace from each station while following the stream. Transect azimuths were assigned by exactly bisecting the stream at the measured point.

Transects were flagged along the azimuth which bisected the stream. Transect boundaries were flagged 12.5m from either side of the initial transect in order to create 25m-wide transects. Each tree located within the transect boundaries was then tagged with a unique number. Data collected from each tree included: species and diameter (cm) at breast height (1.3m from the ground). Relative importance values of each tree species found within the riparian wetland can be seen in Figure 4. Additional data collected for each red maple included: distance to riparian edge (m), distance to gap edge (m), canopy position (dominant, co-dominant, intermediate, or suppressed), % live crown, % crown density, bark depth, and sapwood depth (see tree core analysis section).

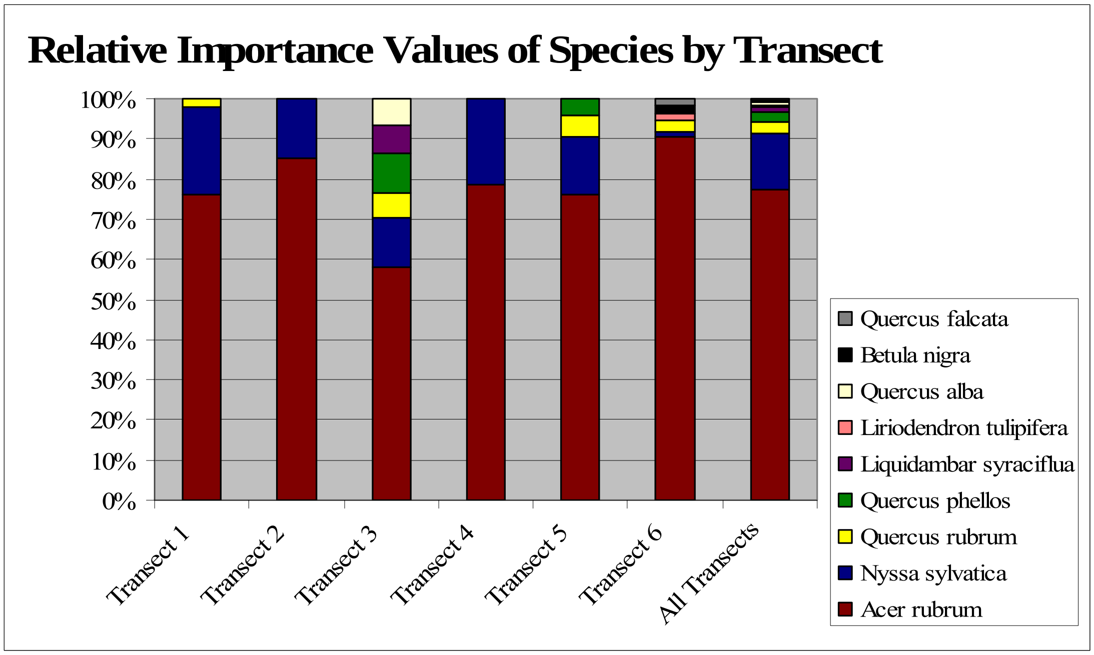



**Figure 4 Relative importance values of tree species on site. Importance value = relative frequency + relative density + relative dominance (Burns and Honkala 1990).**

## *2.3 Tree Core Analysis*

A tree core analysis of all red maple trees within the 6 transects was needed to provide information on sapwood area within the wetland. Three increment cores (5-mm thick) were taken from every red maple tree within the six transects (>10-cm DBH). Standard operating procedures for tree coring and interpretation outlined by EPA (EPA 1994) were used. A picture of the increment borer used is shown in Figure 5.

**Figure 5 Tree increment borer. Upper drill bit is used to penetrate tree and lower extractor sleeve is used to retrieve a 5-mm diameter core.**

Sapwood depth was identified through techniques similar to (Dunn and Connor 1993), by holding the cores up to a bright light. Light has been shown to be blocked by tylose within the heartwood (and not in sapwood) and thus sapwood can be differentiated from the heartwood. Sapwood was measured to the nearest millimeter and the three values were averaged for each tree. Pictures of representative cores can be seen below in Figures 6 and 7.

**Figure 6 Tree core showing obvious heartwood/sapwood boundary. Color differences due to tylose blockage in inactive heartwood (to the right).**

**Figure 7 Tree core exhibiting severe decay.**

Calculations of sapwood area were completed as shown in Figure 8. Measurements of bark depth, sapwood depth and diameter at breast height (DBH) were taken from every surveyed red maple tree >10-cm DBH. In instances where the sapwood/heartwood boundary was unidentifiable due to decay (or if the trunk was not circular and the heartwood was "missed" by the borer), substituted values were calculated using information derived from the calculated relationship of sapwood area to DBH (see Figure 9) where $r^2$=0.9573.

**Figure 8 Idealized cross-section of red maple showing sapwood area calculation formula.**

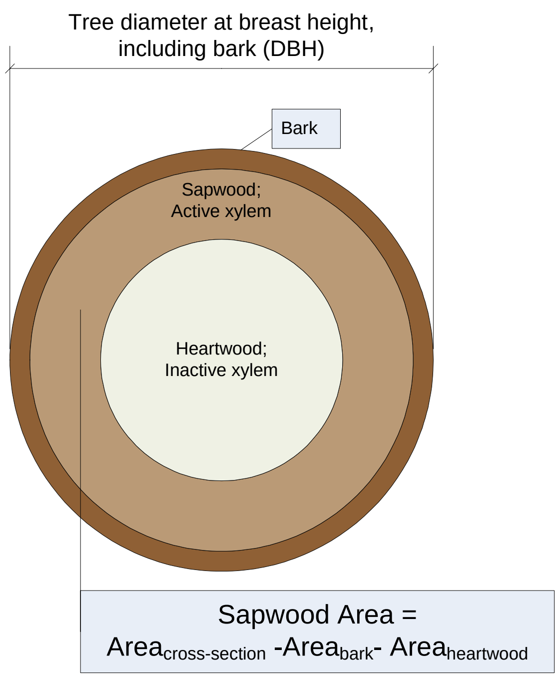
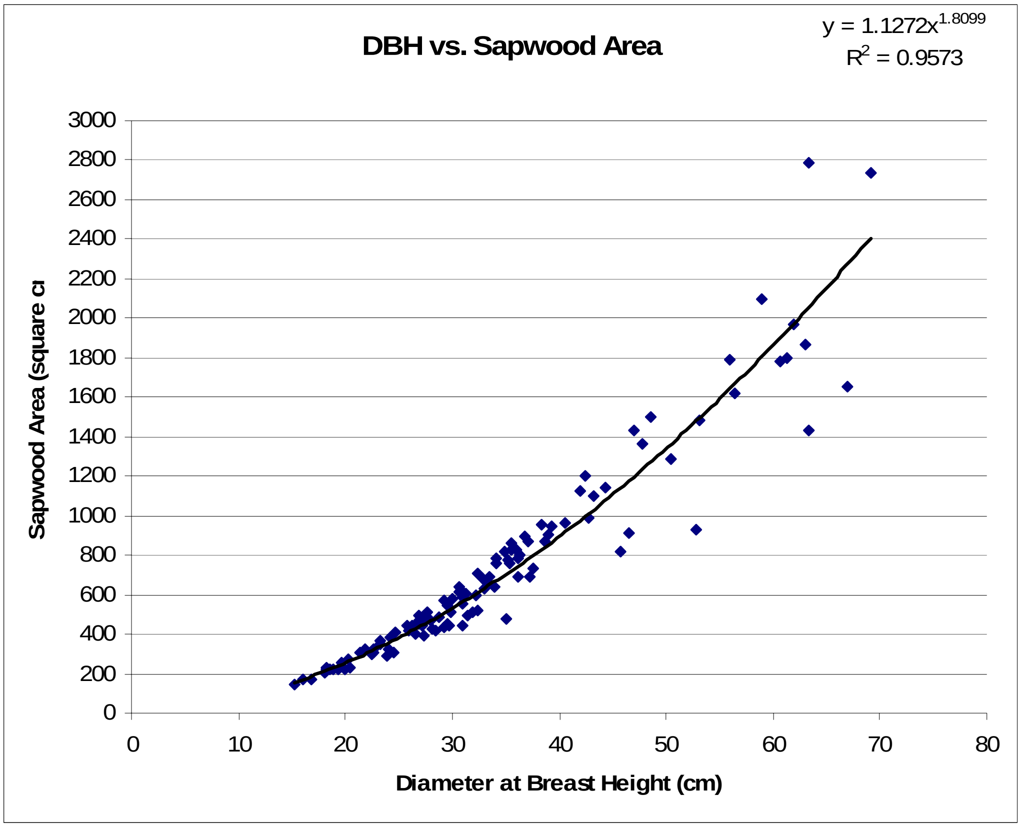


**Figure 9 Relationship developed between measured diameter at breast height and calculated sapwood area.**




## *2.4 Monitoring Meteorology*

Meteorological data were collected throughout the study in an agricultural field adjacent to study site (USDA-Beltsville ARS Station #3 at Old Beltsville Airport). All data were monitored every 15 seconds and logged at 15 minute intervals. Temperature and relative humidity data were gathered five feet from the ground surface in a 12-gill plate radiation shield. Wind speed, wind direction, and solar radiation (pyranometer) were all assessed at a ten foot elevation. A tipping rain gage was installed at three feet above the ground to collect precipitation data. Figures 10 and 11 show yearly meteorological trends for the 2002 and 2003 growing seasons.

**Figure 10 Meteorological trends of the 2002 growing season.**

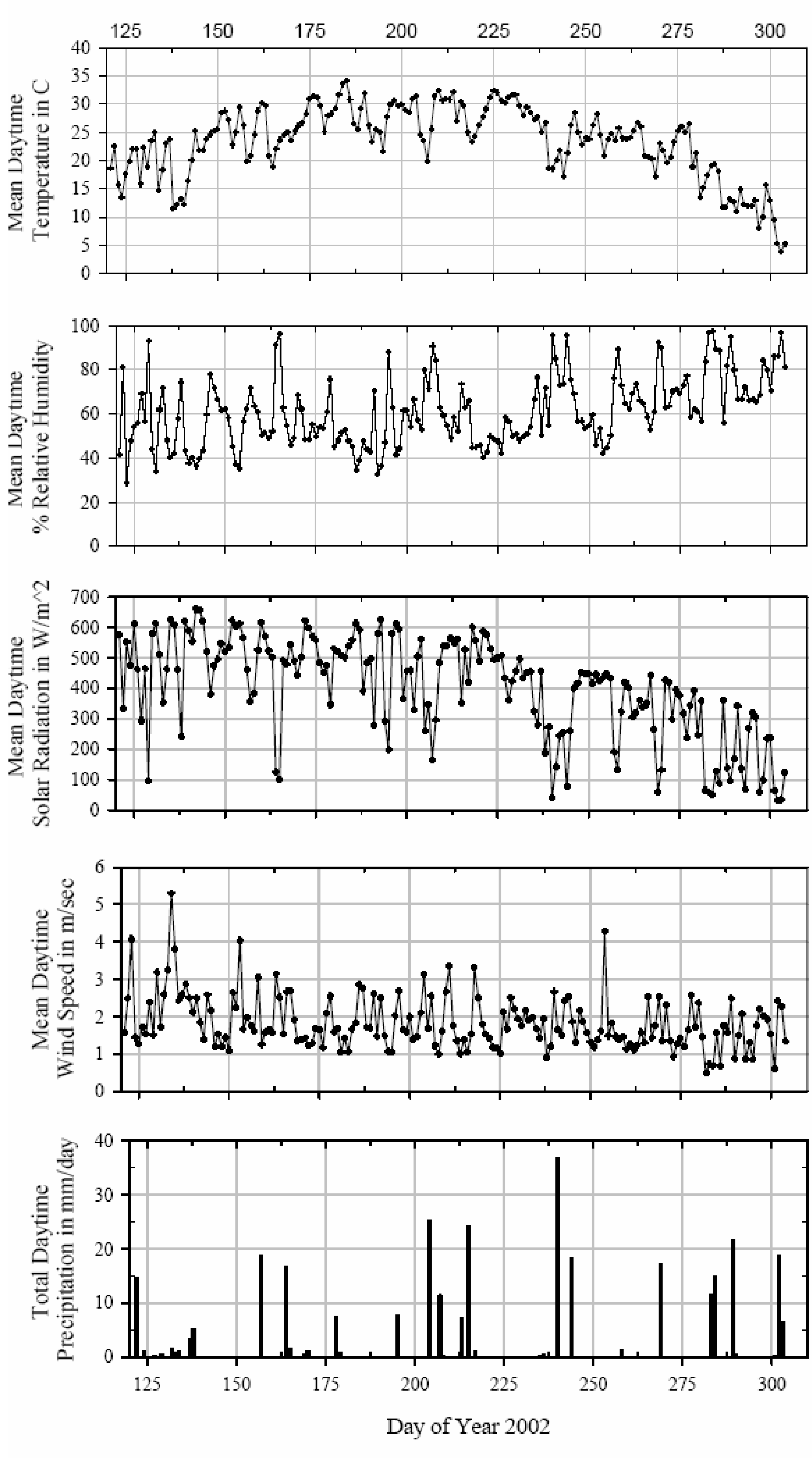
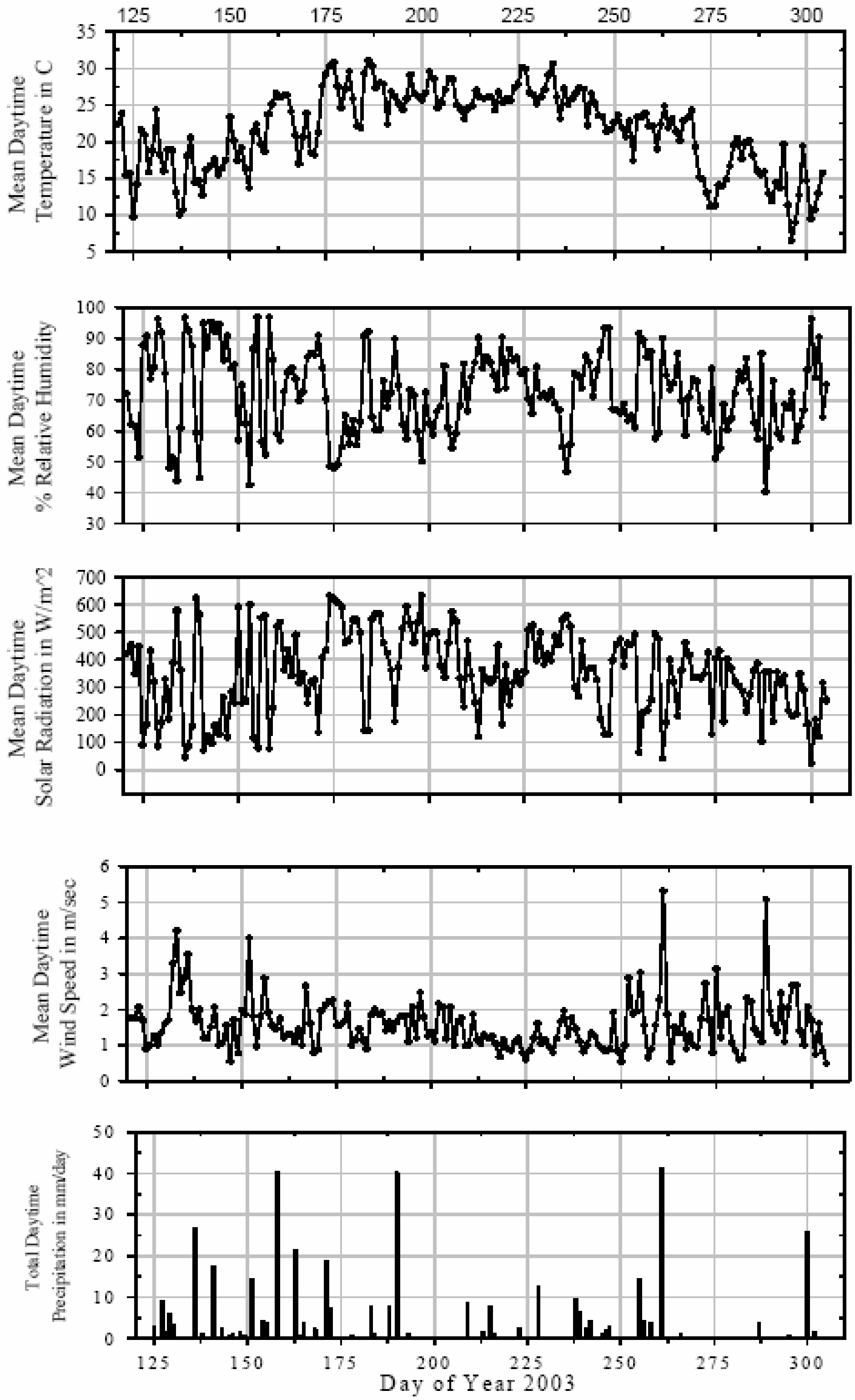


**Figure 11 Meteorological trends of the 2003 growing season.**



# 3 Edge Effect Study

## *3.1 Introduction*

Forested riparian areas and riparian wetlands surrounding first-order streams are being implemented as agricultural best management practices, though buffer effectiveness depends fully on hydrology and its associated processes. Riparian forest evapotranspiration (ET) therefore must be quantified for these areas in order to develop accurate hydrologic models. A variety of methods have been used to assess forest ET. However, energy balances require adequate fetch conditions which cannot be met in riparian forests and water balances do not provide instantaneous measurements of ET which would be useful, if not necessary, to gain an understanding of how ET affects stream flow (see Chapter 2).

Quantification of riparian forest ET is difficult due to the presence of "edge effects", since edge trees are exposed to increased radiation intensities and wind speeds relative to interior trees. This increase of available energy is assumed to increase transpiration levels of trees located on forest edges (Giambelluca, Ziegler et al. 2003). This phenomenon could be of special importance in riparian systems, though it is unknown if daily ET rates of edge trees are greater than those of non-edge trees. Riparian buffer planting strategies could be improved to maximize tree exposure and maximize buffer effectiveness if it is established that edge trees transpire greater volumes of water.

In this study, thermal dissipation probes (a type of sap flow sensor) were used to quantify daily ET rates of six red maple trees. Sap flow sensors are the ideal method with which to determine if edge tree ET rates differ from interior tree ET rates, as they provide localized instantaneous measurements. In this chapter, I test whether edge effects significantly influenced sap flow rates of red maples in a Mid-Atlantic riparian wetland during the 2002 growing season and early portions of the 2003 growing season.

## *3.2 Materials and Methods*

### 3.2.1 Sap Flow Monitoring

Transpiration rates of woody plants are closely approximated by the volumetric sap flow rates in the main stem. Thermal dissipation probes measure sapwood heat dissipation and, in turn, sap flow velocity. This can be done since thermal conductance of sapwood increases with sap velocity (Dynamax 1997). Thermal dissipation probes were chosen to estimate ET for this study because they a) minimize error due to radial variation in sap flow rates by integrating sap flow velocity measurements along the length of the thermocouple probes, and b) require no daily calibration in order for accurate data to be collected for long periods of time, since calibration (needed due to meteorological differences between days) can occur after data collection.

A total of six red maples were monitored for sap flow throughout the riparian wetland. Installation of the upstream transect (see Figure 3) of sensors was completed by Dynamax representatives in July 2001 according to company standards of Dynamax, Inc., Houston, TX (Dynamax 1997). The second transect of sensors was installed by USDA researchers in May 2002, and is located downstream. Sensors were chosen to monitor red (swamp) maple trees since red maples dominate the area (see Figure 4). Physical and biological characteristics of the six monitored trees are outlined in Table 1.

**Figure 12 One set of thermal dissipation probes.**

Each monitored tree contained three equidistant Thermal Dissipation Probe Sets (TDP-30). Both probes in each probe set were 30mm long and 1.2mm in diameter. Probes were installed at ~25 cm depth at 1.3 m from the ground at 40mm apart (see Figure 10). Distances between the probe sets were based on tree diameter. To account for variation in sap flow throughout the depth of the sapwood profile, the measurements are integrated down the length of the probe. It was assumed that the probe length was similar enough to sapwood depth to provide an adequate estimate of sap flux density throughout the depth of the sapwood (Dynamax 1997), Simpson 2003).

**Table 1 Environmental and biological characteristics of six monitored Red maples.**

| Tree | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Location** | Upstream | Upstream | Upstream | Upstream | Downstream | Downstream |
| **DBH (cm)** | 32.9 | 43.2 | 63 | 31.2 | 36.7 | 42.5 |
| **Distance To Riparian Edge (m)** | 12 | 13 | 8 | 0 | 17 | 0 |
| **Distance To Gap Edge (m)** | 0 | not near gap | not near gap | not near gap | 0 | not near gap |
| **Edge Treatment** | Stream | Intermediate | Intermediate | Edge | Stream | Edge |
| **Relative Canopy Position** | Dominant | Dominant | Dominant | Intermediate | Intermediate | Intermediate |
| **% Live Crown** | 20 | 25 | 35 | 80 | 80 | 95 |
| **Crown Density** | 40 | 35 | 30 | 65 | 50 | 85 |
| **No Bark Tree Area ($cm^2$)** | 773.2 | 1308.2 | 2822.9 | 645.1 | 927.4 | 1260.5 |
| **Heartwood Area ($cm^2$)** | 89.0 | decay | 954.0 | 38.4 | 30.5 | 58.9 |
| **Sapwood Area ($cm^2$)** | 684.2 | decay | 1868.9 | 606.7 | 896.9 | 1201.6 |
| **Water Present at Soil Surface** | Yes | Yes | Half yes, half no | No | No | No |
| **Outstanding Bole Characteristics** | None | None | None | None | 4 vertical seams along length of lower bole | None |
| **Outstanding Canopy Characteristics** | None | Lowest large branch in crown missing | None | None | Many epicormic shoots present, 2 of 7 main branches dead | None |
| **Direction(s) of Canopy Exposure** | gap to N | NE to edge, E to gap | No exposure to gap or edge, nearest edge NW | All branches face SW toward W edge exposure | NNW to NNE | Gap NE, NW toward edge |
| **Picture(s)** | See Figure 31 in Appendix | See Figure 32 in Appendix | See Figure 33 in Appendix | See Figure 34 in Appendix | See Figure 35 in Appendix | See Figure 36 in Appendix |

Temperature differences between the two probes were measured every 15 seconds and the 30 minute averages were recorded by a Campbell Scientific CR10X datalogger (Campbell Scientific, Inc., Logan, UT). The sensors (Dynamax, Inc., Houston, TX) were powered on 12-volt deep cycle batteries. Temperature differences were automatically converted to sap velocity according to Granier's dimensionless "flow index" (Granier 1987), (Dynamax 1997) using the spreadsheet which accompanied the sensors. This "flow index" (K) was calculated from the measured temperature difference and the maximum temperature difference (which occurs at zero flow velocity). An exponential empirical relationship between sap flow velocity and K representative of several hardwood species (including red maple) was established by Granier: Velocity = 0.0119 * K^1.231. Sap flow rates can therefore be calculated using(Granier 1987; Dynamax 1997):

Sap flow rate = sapwood area * sap flow velocity

**Equation 2**

Where:

Sap flow rate = calculated rate of sap flow ($cm^3$ $hr^{-1}$)
Sapwood area = area of sapwood in monitored tree ($cm^2$)
Sap flow velocity = measured velocity of sap flow (cm $hr^{-1}$).

Gaps in the sap flow data resulted from differing installation dates, lightning strikes, high winds, battery failure and/or improperly functioning probes.

Comparisons between the sap flow rates of the six monitored trees (which differed in size/DBH) were possible because each of the probes represented only a 1 $cm^2$ area of active sapwood. Thus, the sap flow values measured did not need to be normalized on an area basis (Arneth, Kelliher et al. 1996) (O'Brien, Oberbauer et al. 2004).

### 3.2.2 Data Processing

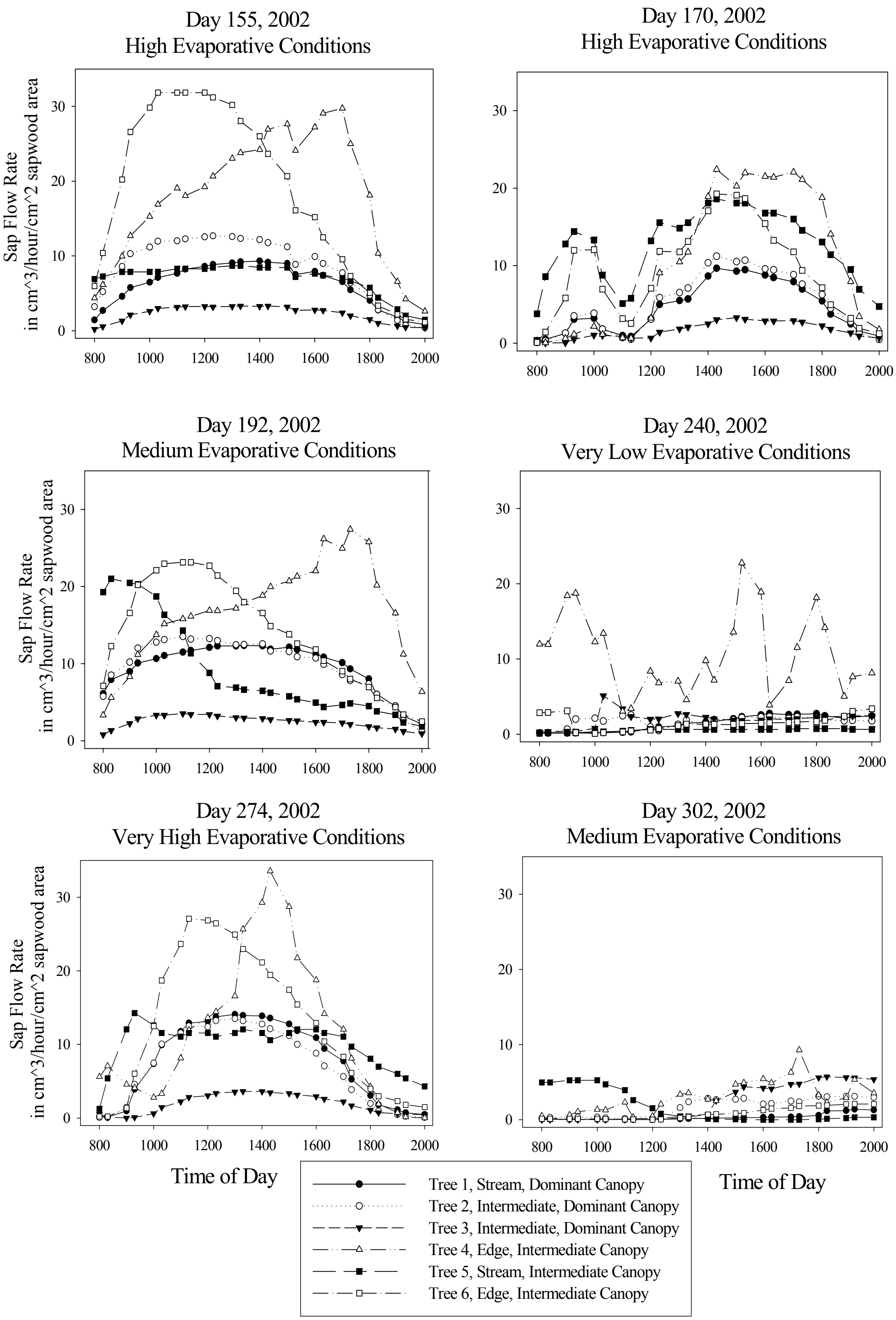
In order to remove obvious outliers due to lightning strikes, if the daily ET volume or if the maximum flow rate was zero for any probe, then days containing those values were deleted. Data losses were due to lightning strikes, battery maintenance issues, or equipment failure. Though this was expected for a study of this duration, this resulted in a significant loss of data. Data were used only if all six trees had at least two sets of functioning probes throughout the length of the day (08:00 through 20:00). The days used for the duration of this study are listed in Table 2.

**Table 2 All days during the 2002 and 2003 growing seasons when all six trees had functioning probes. Each growing season was divided into early, mid-, and late summer time periods.**

| | Early Summer | Mid-Summer | Late Summer |
|---|---|---|---|
| **2002** | 155, 156, 157, 161, 169 through 203 | 229 through 240, 242 through 253 | 273, 274, 285 through 289, 300, 301, 302, 304 |
| **2003** | 152 through 156, 187 | 211, 212 | |

Sap flow rates from all functioning probes for each study tree were averaged per each day considered. Mean daily maximum flow rates were determined using plots of diurnal flow rates. Mean daily volumetric flow was determined for each probe by calculating the area under the diurnal flow rates (08:00-20:00). Figure 13 shows sap flow rates for each of the six trees on six representative days.

**Figure 13 Diurnal sap flow trends of the six monitored red maples on representative sample days.**



Each of the 2002 and 2003 growing seasons were broken down into 3 “seasons”: early Summer (days of year 155 to 205), mid-Summer (days of year 206 to 255) and late Summer (days of year 256 to 305). To further decrease confounding effects due to climatic differences, days within each “season” were separated into evaporative condition groups. Since “edge effects” can partially relate to differing radiation levels and wind speeds between edge and non-edge trees, days were separated according to average daily and maximum solar radiation, average daily wind speed, average daily and maximum % relative humidity, and average daily and maximum temperature. By graphing each of these parameters according to day of year, each day was assigned a rating of “+”, “-“, or “med” when conditions were highly evaporative, not evaporative, or neutral. For example, on day 170 of year 2002, solar radiation was ranked “+”, humidity was ranked “med”, wind speeds were ranked “-“ and temperature was ranked “med”. This was done because solar radiation conditions inspired evaporation, humidity conditions were average, wind speeds were slow, and temperature was average. After these conditions were assigned, all days within each time period (early, mid-, and late summer) were sorted according to solar radiation rank, relative humidity rank, wind speed rank, and temperature rank, in that order. This order was chosen, as solar radiation may be the most influential parameter and temperature was the least influential of the known parameters. Then, each day was assigned an evaporative condition group: “Very High”, “High”, “Mid”, or “Very Low”. Rules for group assignment were followed in this order:

1) If all conditions = + med, then: Very High
2) If all conditions = -, then: Very Low

3) If solar radiation and humidity = + and other conditions = + or med, then High

4) If solar radiation and humidity = + and other conditions = – or med, then Mid.

Grouping days according to evaporative conditions was effective, though as demonstrated in Figure 13, within-tree and between-tree variability is high regardless of evaporative conditions.

Tables 11, 12 and 13 in the appendix show the days of year under investigation and each day's group ranking based on meteorological conditions. Micrometeorological differences between the edge, intermediate, and stream canopy locations were not quantified, nor were eddy covariance or Bowen ratio techniques available for ET calculations above or below the canopy. Differences between the interior and edge tree crown conditions were assumed and meteorological data were collected from an adjacent agricultural field.

### 3.2.3 Experimental Design and Statistical Analysis

Average daily maximum sap flow rates and average total daily volume sap flow for each tree (based on the average of at least 2 sets of probes within each tree) were used to compare edge-influenced ("edge"), somewhat-influenced ("intermediate"), and trees along the stream receiving little or not edge effects ("stream"). The vegetation survey (see Chapter 2) provided information on tree crown proximity to the edge for each of the six trees. Accordingly, two trees were considered "edge" trees, as they were adjacent to the riparian edge, two trees were considered "stream" trees, as they were located along the stream in the interior of the riparian wetland, and two trees were considered "intermediate" trees, as they were situated between the stream and the riparian edge. Therefore, the edge effect factor had 3 levels, each having 2 replicates (2 trees).

Analysis of variance (ANOVA) of the edge effects were performed using the SAS system (SAS 2005). Tests were first performed based on the average of all days of the 2002 and 2003 growing seasons. Tests were then performed on 4 evaporative condition groups in 2002 (very high, high, medium, and very low) and on 2 (high and very low) in 2003. Lastly, tests were performed on data grouped by evaporative condition group and by season (Early, Mid-, and Late Summer). When a significant treatment effect was found (if treatment $P<.10$), then the Tukey's multiple mean comparison test was performed to determine pairwise treatment differences. All related SAS codes can be found in the Appendix (see entries 1 and 2).

P-values less than .10 were considered significant for this study because a) even minor differences between daily ET rates of edge and interior trees could be biologically important, b) so few replicates would make detection of even large differences between edge and interior trees difficult, c) no risk is involved if I determine that the edge treatment is significant at $P<.10$ rather than $<.05$; riparian forest management can only improve if scaling methods take into account more environmental conditions.

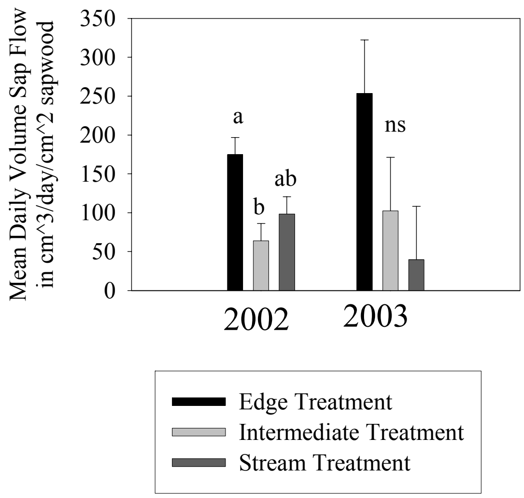
## *3.3 Results*

### 3.3.1 Test of Edge Effect Based on Mean Daily Volume Sap Flow

The edge treatment effect was significant on mean daily sap flow volumes during 2002 (P=.0805). Differences between the mean daily sap flow volumes for the three edge treatments can be seen in Figure 14. Tukey's multiple mean comparison test determined that the mean daily sap flow volume of edge trees differed significantly (P=.0703) from intermediate trees. Differences between edge and stream mean volumes and stream and intermediate mean volumes were not significant (P>.10). Detailed results of these tests of the differences between the edge, intermediate, and stream means are in the Appendix.

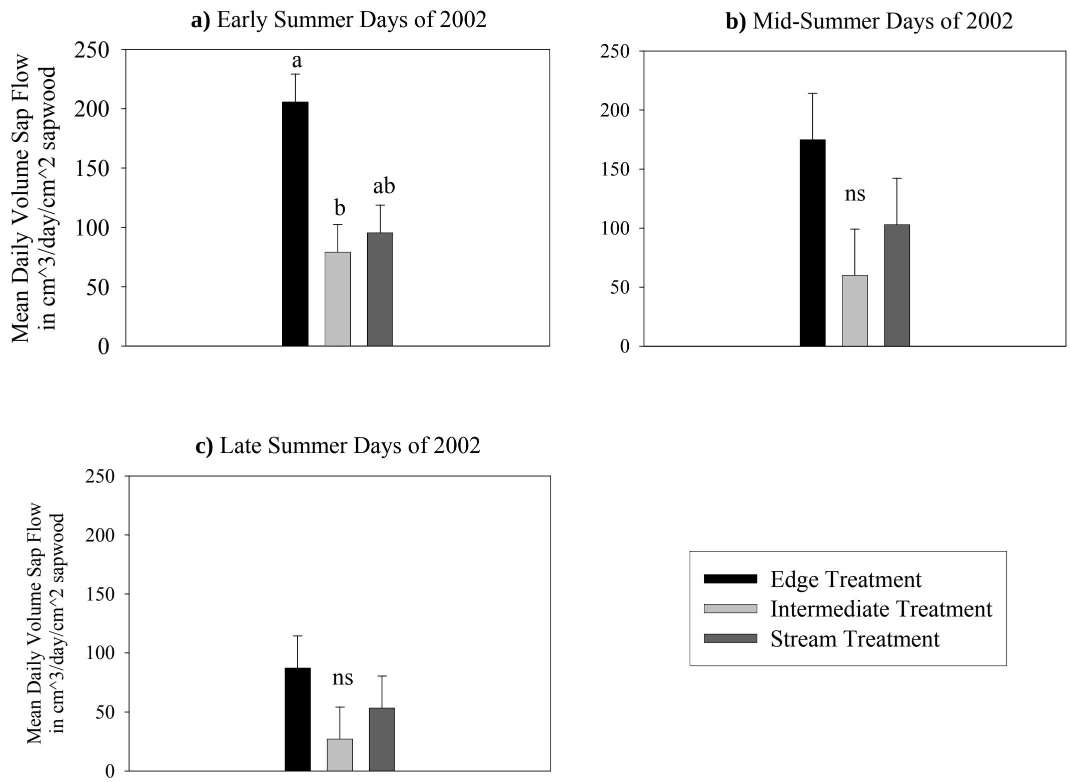
The edge treatment effect was not significant on mean daily sap flow volumes during 2003 (P=.2242). Figure 14 shows the differences between the mean daily sap flow volumes for the three edge treatments for the 2003 growing season. Detailed results of these tests of the differences between the edge, intermediate, and stream means are in the Appendix.

**Figure 14 Yearly edge treatment effect means (based on daily sap flow volumes in cm3/day/cm2 sapwood) with standard error bars for the 2002 and 2003 growing seasons. Different letters on the top of the bars represent significant differences between the means (P<.10 according to Tukey's multiple mean comparison test) and ns denotes no significant differences between the means.**



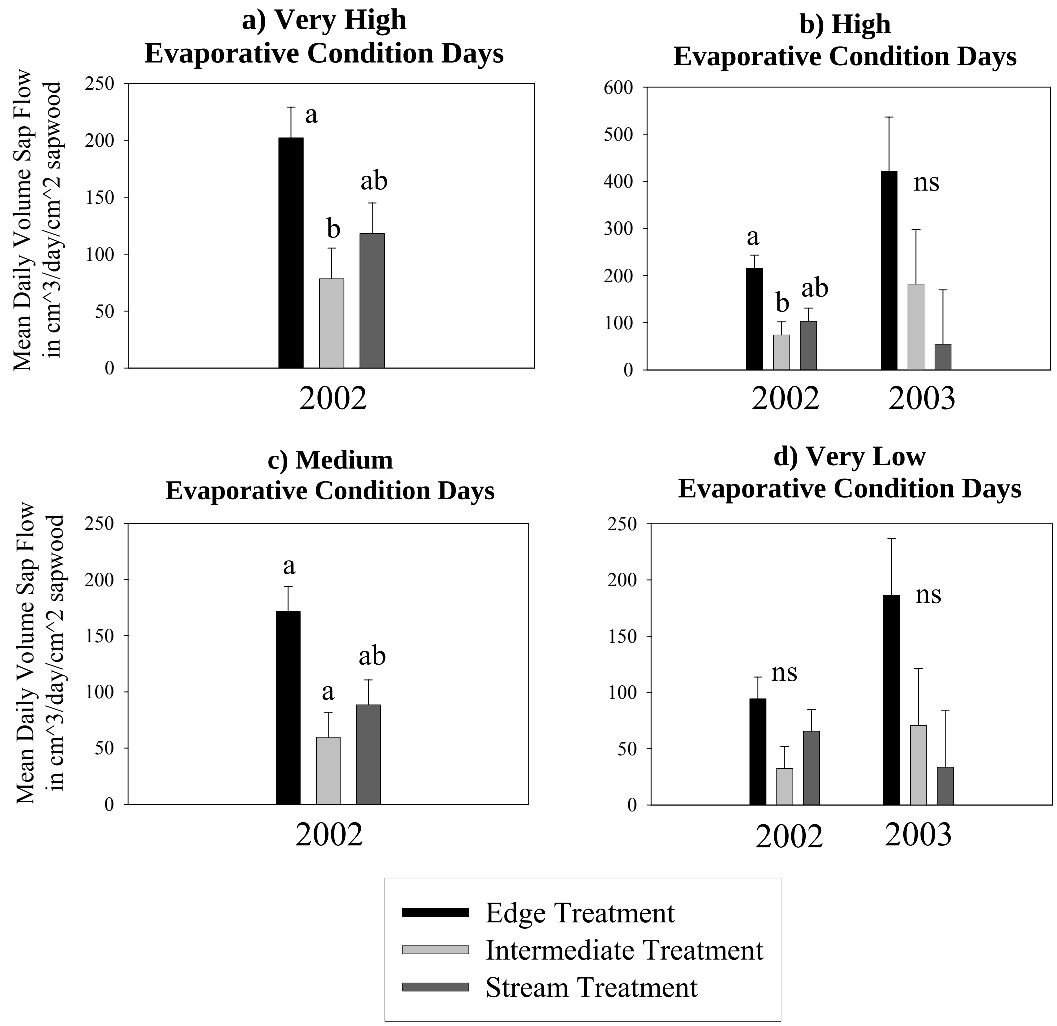

When days were divided into seasons (Early, Mid-, and Late Summer), ET volumes were influenced by the edge treatment effect only on Early Summer days of 2002 (P=.0568) (see Figure 15). During those Early Summer days, edge trees transpired a significantly greater volume of water than did intermediate trees (P=.0628) and trees located near the stream (P=.0881). The edge treatment did not significantly impact daily ET volumes during Mid- or Late Summer days of 2002. However, detailed results of these tests of the differences between the edge, intermediate, and stream means are in the Appendix.

**Figure 15 Edge treatment effect means (based on daily sap flow volumes in $cm^3/day/cm^2$ sapwood averaged by season) with standard error bars. Different letters on the top of the bars represent significant differences between the means (P<.10 according to Tukey's multiple mean comparison test) and ns denotes no significant differences between the means.**



When days for each year were divided into evaporative condition groups, very high, high, and medium evaporative condition days during 2002 experienced an edge treatment effect (P=.0890, P=.0700, and P=.0729, respectively) (see Figure 16). On high evaporative days of 2002 and on very low evaporative condition days of 2002 and 2003, the edge effect did not influence mean daily sap flow volumes (P>.10). Detailed results of these tests of the differences between the edge, intermediate, and stream means are in the Appendix.

**Figure 16 Edge treatment effect means (based on mean daily sap flow volumes for each evaporative condition group in $cm^3/day/cm^2$ sapwood) with standard error bars for the 2002 and 2003 growing seasons. Different letters on the top of the bars represent significant differences (p<.10 according to Tukey's multiple mean comparison test) and ns denotes not significant.**



Tests were then performed based on grouping by season and by evaporative condition groups. Early Summer was the only season to experience a significant edge effect for any evaporative condition group (see Figures 17, 18, 19). On high evaporative condition days in Early Summer 2002, the edge treatment effect was significant (P=.0574). On these days, the edge treatment mean was significantly greater than the intermediate treatment mean (P=.0623) and the stream treatment mean (P=.0920). On medium evaporative condition days during Early Summer 2002, the edge treatment mean was significantly greater than the intermediate treatment mean (P=.0858), with an overall treatment effect (P=.0822).

The edge effect did not significantly influence mean daily sap flow volumes on the remaining evaporative condition days and seasons during 2002 and 2003 (see Figures 17, 18, 19). Differences between edge treatment means and the interior (intermediate and stream) treatment means were not significant during these periods. However, for 12 out of 13 evaporative condition groups throughout the 2002 and 2003 growing seasons (6 Early Summer groups, 4 Mid-Summer groups, and 3 Late Summer groups), the edge treatment mean daily sap flow volumes were greater (though not significantly) than the intermediate and stream treatment mean daily sap flow volumes. Detailed results of these tests of the differences between the edge, intermediate, and stream means are in the Appendix.

**Figure 17 Early Summer edge treatment means (based on daily sap flow volumes in $cm^3$/day/$cm^2$ sapwood) for each group of evaporative condition days with standard error bars for the 2002 and 2003 growing seasons. Different letters on the top of the bars represent significant differences (p<.10 according to Tukey's multiple mean comparison test) and ns denotes not significant.**

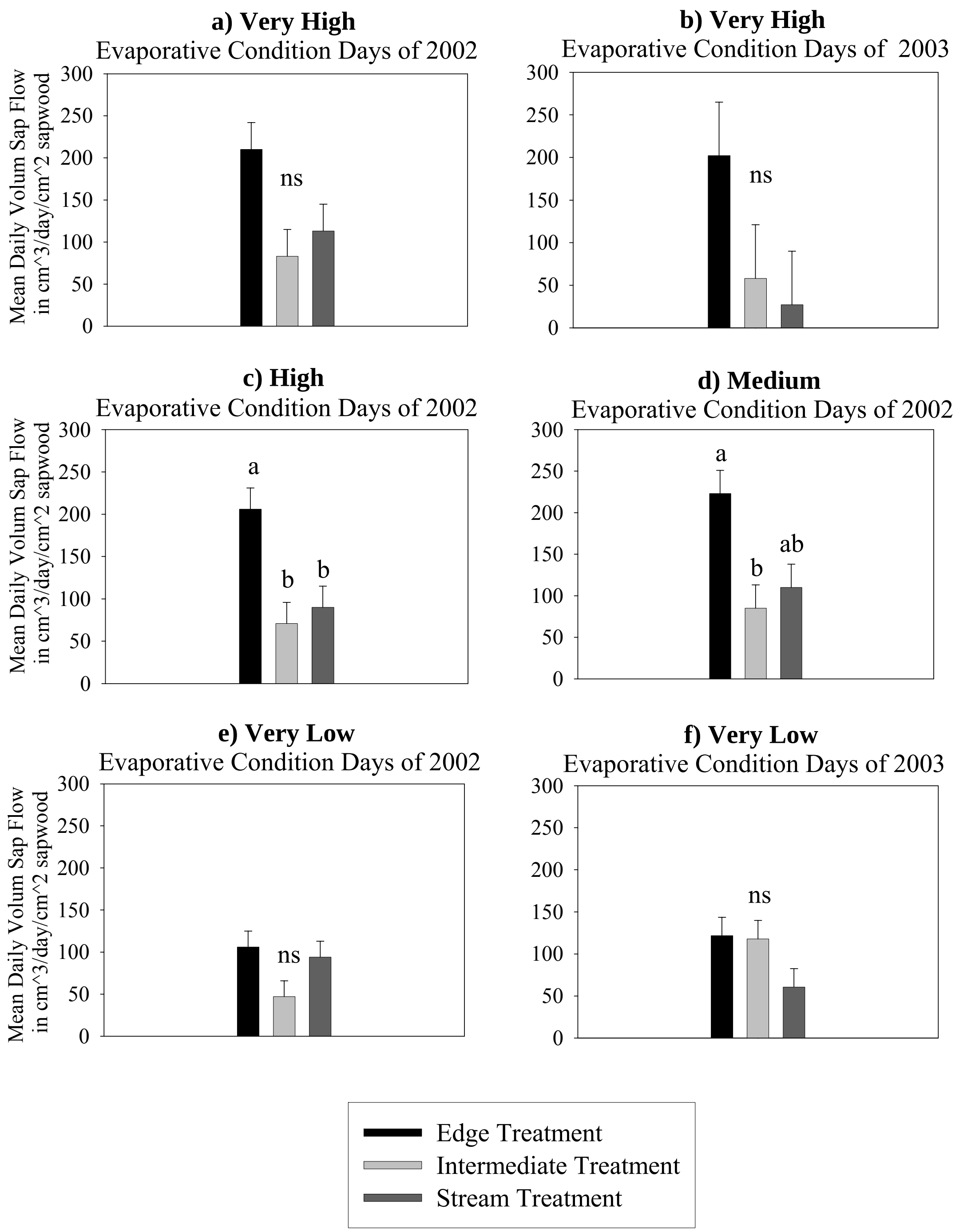


**Figure 18 Mid-Summer edge treatment means (based on daily sap flow volumes in cm$^3$/day/cm$^2$ sapwood) for each group of evaporative condition days with standard error bars for the 2002 and 2003 growing seasons. Different letters on the top of the bars represent significant differences (p<.10 according to Tukey's multiple mean comparison test) and ns denotes not significant.**

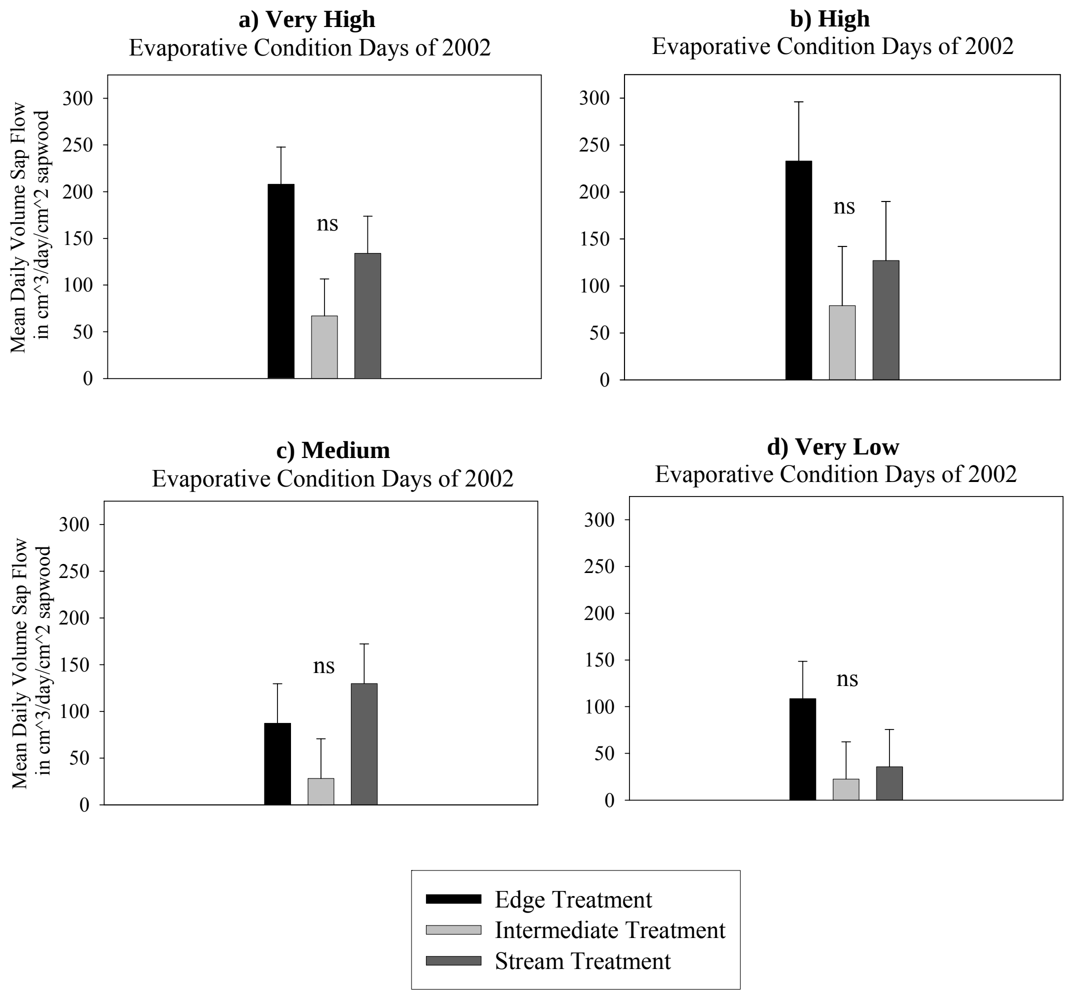
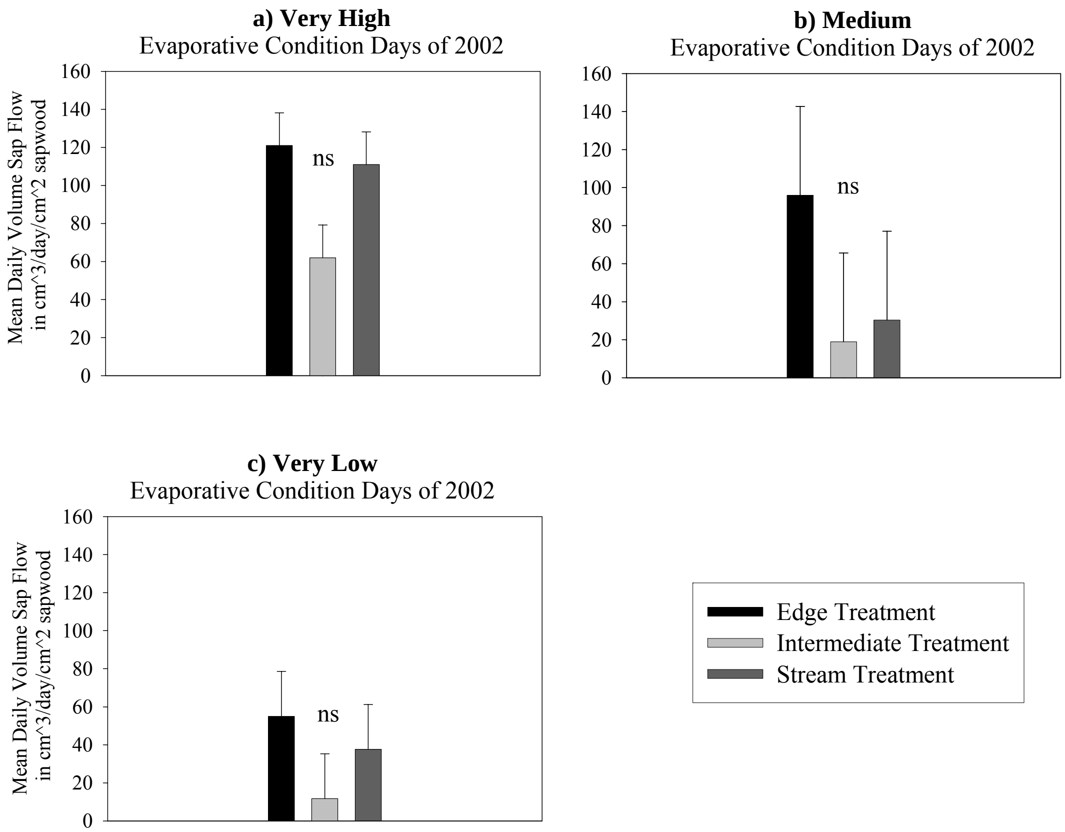


**Figure 19 Late Summer edge treatment means (based on daily sap flow volumes in $cm^3/day/cm^2$ sapwood) for each group of evaporative condition days with standard error bars for the 2002 and 2003 growing seasons. Different letters on the top of the bars represent significant differences (p<.10 according to Tukey's multiple mean comparison test) and ns denotes not significant.**



Mean daily sap flow volumes for the 2002 growing season ranged from 3 $cm^3/day/cm^2$ sapwood (for intermediate trees on very low evaporative condition days during Late Summer) to 465 $cm^3/day/cm^2$ sapwood (for edge trees on medium evaporative condition days during Late Summer) (see Table 3). Within-treatment variability can also be seen in Table 3. Within-treatment variability was highest for edge trees during Mid-Summer, for Intermediate trees during Late Summer, and for Stream trees during Early Summer. Within-treatment variability was lowest for intermediate trees during Mid-Summer and for stream trees during Late Summer.

**Table 3 Ranges of mean daily sap flow volumes (in cm3/day/cm2 sapwood) by edge treatment, season, and evaporative condition group for the 2002 growing season.**

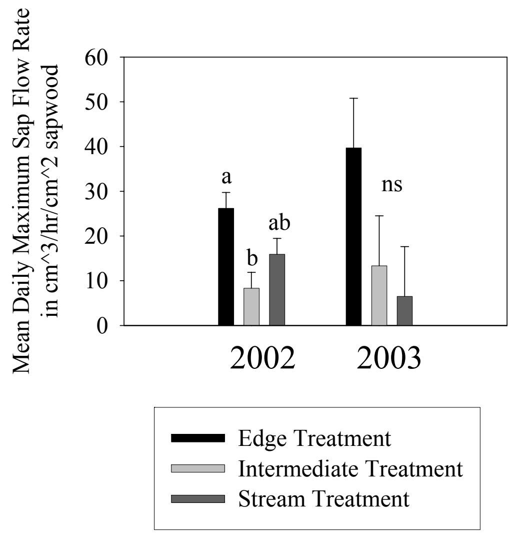
| | Very High Evaporative Conditions | High Evaporative Conditions | Medium Evaporative Conditions | Very Low Evaporative Conditions |
|---|---|---|---|---|
| **Early Summer** | | | | |
| Edge | 148 to 294 | 115 to 289 | 172 to 281 | 5 to 172 |
| Intermediate | 26 to 162 | 20 to 139 | 30 to 151 | 12 to 104 |
| Stream | 73 to 161 | 40 to 155 | 81 to 157 | 13 to 147 |
| **Mid-Summer** | | | | |
| Edge | 65 to 431 | 142 to 404 | 58 to 116 | 5 to 361 |
| Intermediate | 15 to 129 | 25 to 144 | 12 to 45 | 10 to 55 |
| Stream | 79 to 151 | 75-160 | 64 to 195 | 7 to 82 |
| **Late Summer** | | | | |
| Edge | 92 to 157 | n/a | 10 to 465 | 8 to 116 |
| Intermediate | 24 to 87 | n/a | 3 to 36 | 3 to 21 |
| Stream | 84 to 142 | n/a | 4 to 69 | 15 to 95 |

### 3.3.2 Test of Edge Effect Based on Mean Daily Maximum Sap Flow Rates

The edge treatment effect was significant on mean daily maximum sap flow rates ($P=.0820$) for the 2002 growing season. Differences between the mean daily maximum sap flow rates for the three edge treatments can be seen in Figure 16. Tukey's multiple mean comparison test determined that the mean daily sap flow volume of edge trees differed significantly ($P=.0740$) from intermediate trees. Differences between edge and stream mean sap flow rates and stream and intermediate mean sap flow rates were not significant ($P>.10$). Detailed results of these tests of the differences between the edge, intermediate, and stream means are in the Appendix.

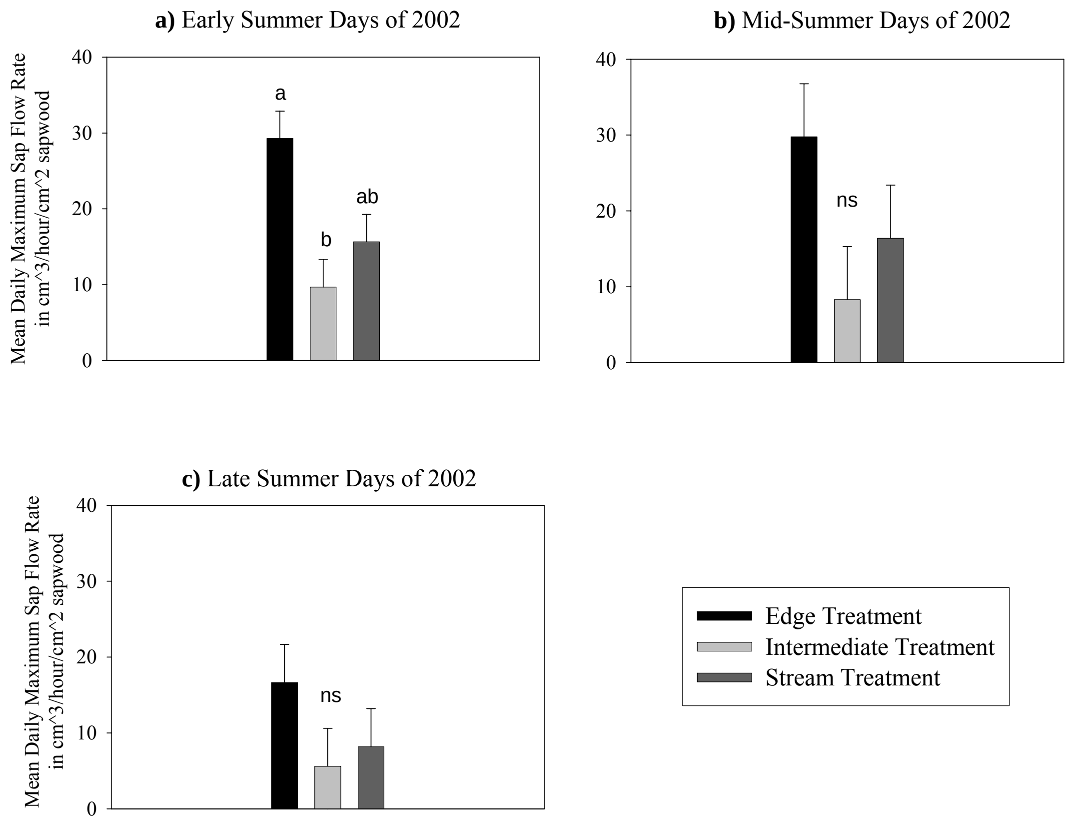
The edge treatment effect was not significant on mean daily maximum sap flow rates during 2003 ($P=.2242$) and differences between the mean daily maximum sap flow rates for the three edge treatments can be found in Figure 20. Detailed results of these tests of the differences between the edge, intermediate, and stream means based on yearly averages are in the Appendix.

**Figure 20 Edge treatment means for the 2002 and 2003 growing seasons (based on daily maximum sap flow rates in cm3/hour/cm2 sapwood) with standard error bars for the 2002 and 2003 growing seasons. Different letters on the top of the bars represent significant differences between the means (P<.10 according to Tukey's multiple mean comparison test), and ns denotes not significant.**



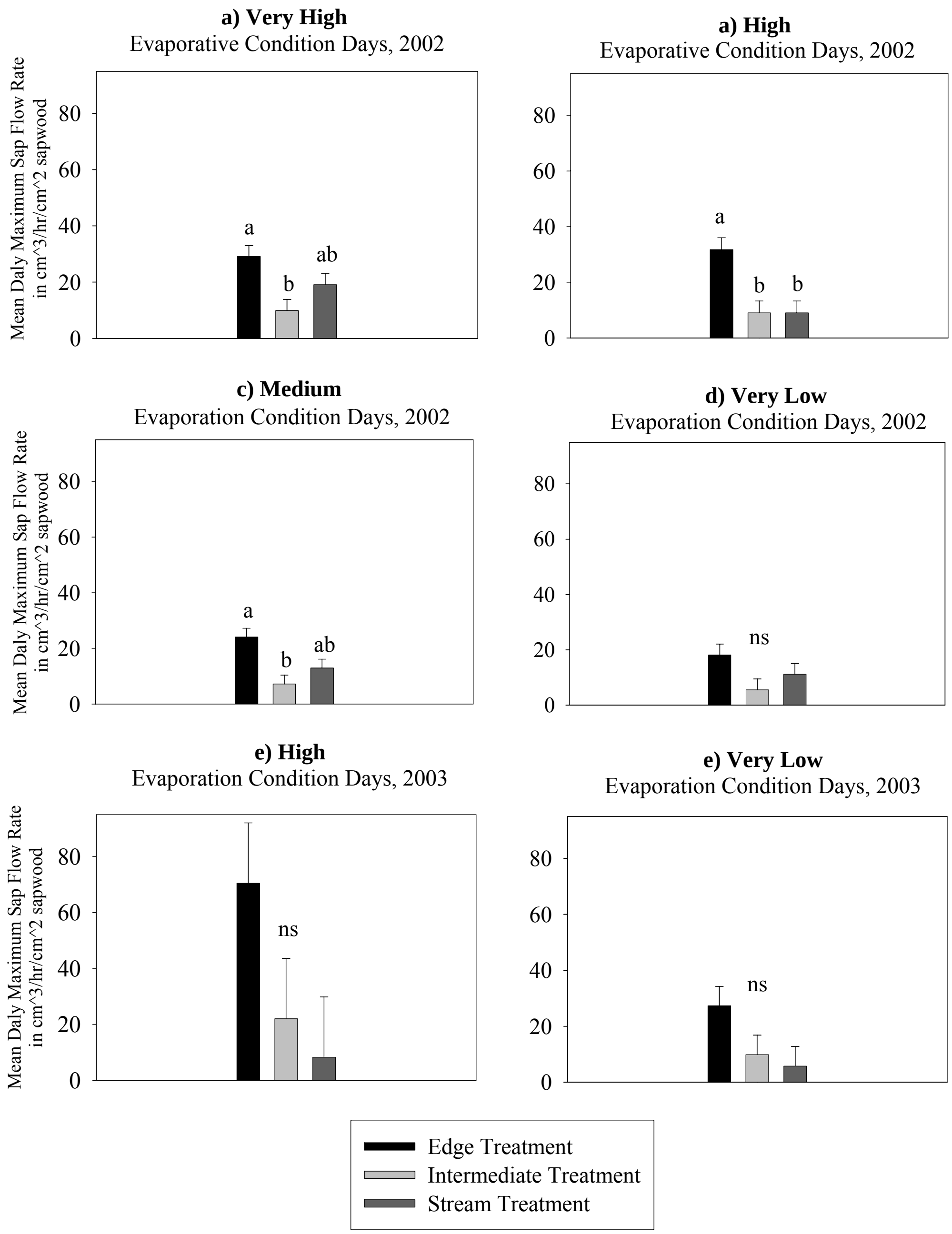

When days were divided into seasons (Early, Mid-, and Late Summer), maximum ET rates on Early Summer days were significantly influenced by the edge effect (P=.0653) (see Figure 21). On those days, the trees located near the riparian edge transpired greater peak rates than did intermediate trees (P=.0621). On the remaining days of 2002, the edge treatment effect did not significantly influence daily maximum ET rates (P>.10) (see Figure 21). Detailed results of these tests of the differences between the edge, intermediate, and stream means based on season averages are in the Appendix.

**Figure 21 Edge treatment effect means (based on daily maximum sap flow rates in $cm^3$/hour/$cm^2$ sapwood and averaged by season) with standard error bars. Different letters on the top of the bars represent significant differences between the means (P<.10 according to Tukey's multiple mean comparison test) and ns denotes no significant differences between the means.**



When days for each year were divided into evaporative condition groups, very high, high, and medium evaporative condition days during 2002 experienced an edge treatment effect (P=.0890, P=..0642, and P=.0792, respectively) on mean daily maximum sap flow rates (see Figure 22). On very low evaporative condition days during 2002 and 2003 and on high evaporative condition days during 2002, the edge effect did not influence (P>.10) mean daily maximum sap flow rates. Detailed results of these tests of the differences between the edge, intermediate, and stream means based on evaporative condition groups are in the Appendix.

**Figure 22 Edge treatment means for each evaporative condition group (based on daily maximum sap flow rates in cm3/hour/cm2 sapwood) with standard error bars for the 2002 and 2003 growing seasons. Different letters on the top of the bars represent significant differences between the treatments (P<.10 according to Tukey's multiple mean comparison test) and ns denotes not significant.**



Tests were then performed based on grouping days by season and by evaporative conditions. The edge effect significantly influenced mean daily maximum sap flow rates on Early Summer days with high evaporative conditions (P=.0586), on Early Summer days with medium evaporative conditions (P=.0916), and on Late Summer days with very high evaporative conditions (P=.0412) (see Figure 23). In Early Summer, the edge treatment mean daily maximum sap flow rate was significantly greater than the intermediate treatment mean daily sap flow rate during high (P=.0609) and medium (P=.0847) evaporative condition days (see Figure 23). During very high evaporative condition days during Late Summer 2002, the edge treatment mean daily maximum sap flow rate was greater than intermediate treatment mean (P=.0427) and the stream treatment mean (P=.0739) daily maximum sap flow rates (see Figure 25). Detailed results of these tests of the differences between the edge, intermediate, and stream means are in the Appendix.

The edge effect did not significantly influence mean daily maximum sap flow rates on the remaining evaporative condition days or seasons during 2002 and 2003 (see Figures 23, 24, 25). Differences between edge treatment means and the interior (intermediate and stream) treatment means were not significant during these periods. However, for 13 out of 13 evaporative condition groups throughout the 2002 and 2003 growing seasons (6 Early Summer groups, 4 Mid-Summer groups, and 3 Late Summer groups), the edge treatment mean daily sap flow rates were greater (though not significantly) than the intermediate and stream treatment mean daily sap flow rates.

**Figure 23 Early Summer edge treatment means for each evaporative condition group (based on daily maximum sap flow rates in cm3/hour/cm2 sapwood) with standard error bars for the 2002 and 2003 growing seasons. Different letters on the top of the bars represent significant differences between the treatments (P<.10 according to Tukey's multiple mean comparison test) and ns denotes not significant.**

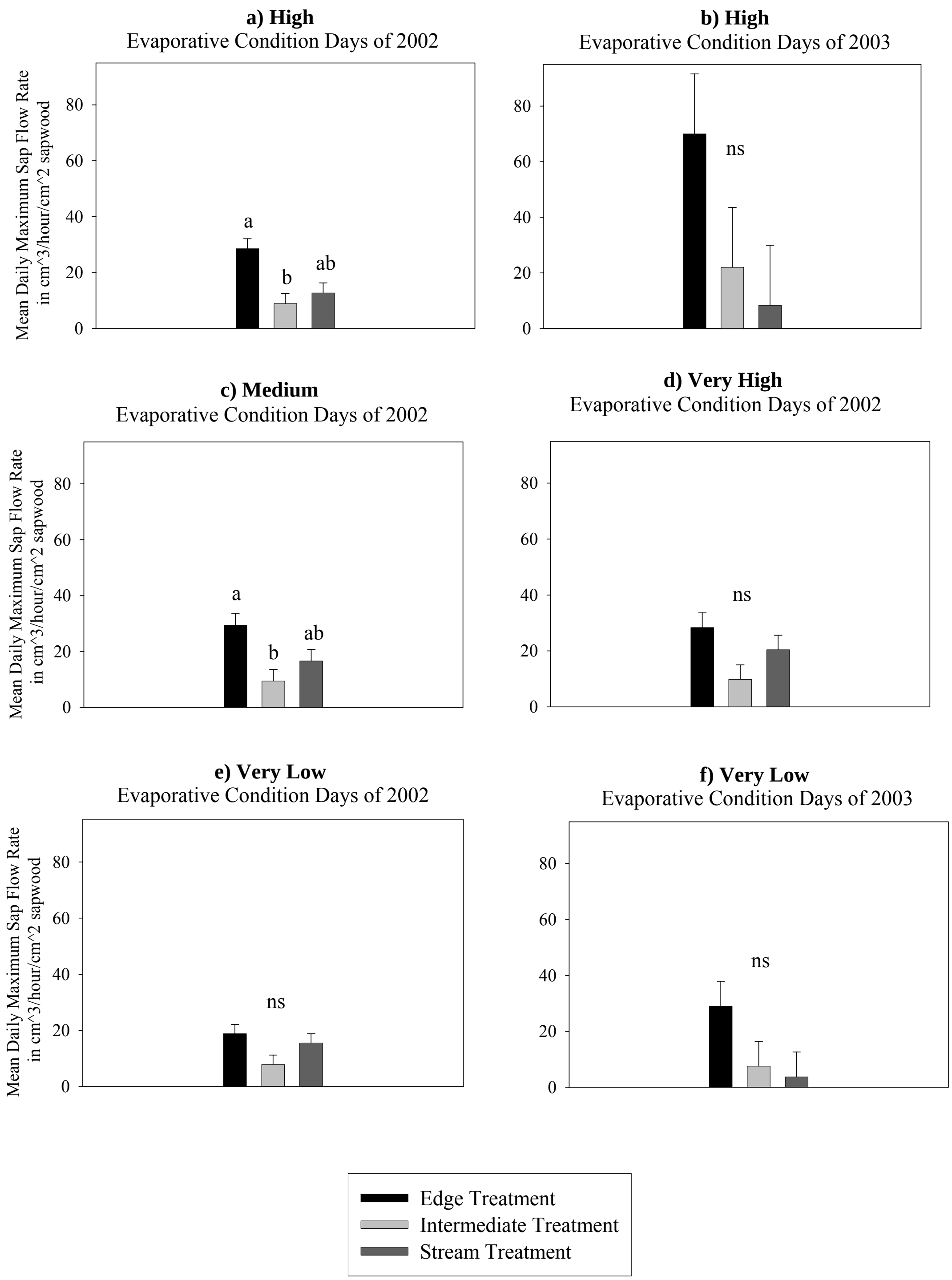


**Figure 24 Mid-Summer edge treatment means for each evaporative condition group (based on daily maximum sap flow rates in cm3/hour/cm2 sapwood) with standard error bars for the 2002 and 2003 growing seasons. Different letters on the top of the bars represent significant differences between the treatments (P<.10 according to Tukey's multiple mean comparison test) and ns denotes not significant.**

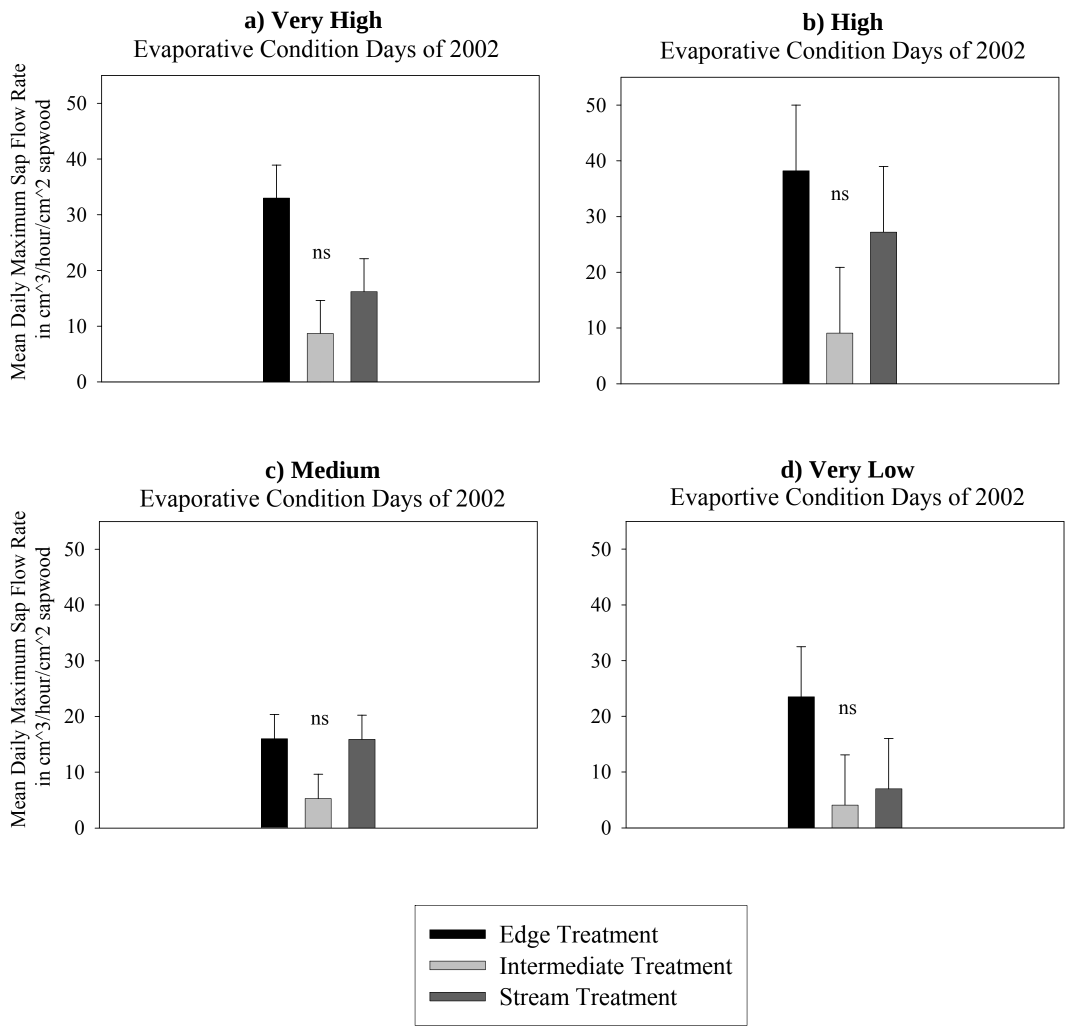
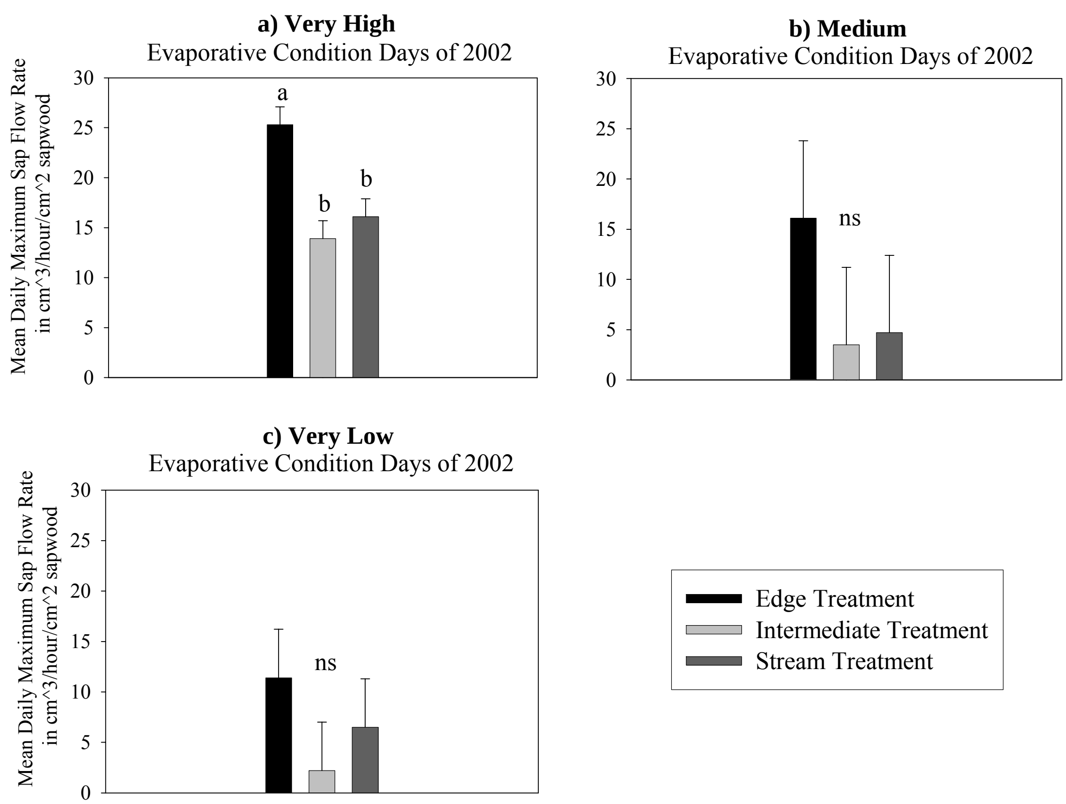


**Figure 25 Late Summer edge treatment means for each evaporative condition group (based on daily maximum sap flow rates in cm3/hour/cm2 sapwood) with standard error bars for the 2002 and 2003 growing seasons. Different letters on the top of the bars represent significant differences between the treatments (P<.10 according to Tukey's multiple mean comparison test) and ns denotes not significant.**



Mean daily maximum sap flow rates for the 2002 growing season ranged from 1 $cm^3/hour/cm^2$ sapwood (on a few very low evaporative conditions days) to 112 $cm^3/hour/cm^2$ sapwood (for a stream tree on an Early Summer very high evaporative conditions day) (see Table 4). Within-treatment variability can also be seen in Table 3. Within-treatment variability was highest for edge trees during Mid-Summer, for Intermediate trees during Early Summer, and for Stream trees during Early Summer. Within-treatment variability was lowest for edge, intermediate, and stream trees during Late Summer. Variability within evaporative condition groups was highest during very high and very low evaporative condition days (see Table 4).

**Table 4 Ranges of average daily maximum sap flow rates (in cm3/hour/cm2 sapwood) by edge treatment, season, and evaporative condition.**

| | Very High Evaporative Conditions | High Evaporative Conditions | Medium Evaporative Conditions | Very Low Evaporative Conditions |
|---|---|---|---|---|
| **Early Summer** | | | | |
| Edge | 18 to 39 | 19 to 38 | 21 to 41 | 1 to 30 |
| Intermediate | 3 to 17 | 3 to 16 | 4 to 16 | 2 to 15 |
| Stream | 13 to 112 | 9 to 10 | 12 to 21 | 3 to 22 |
| **Mid-Summer** | | | | |
| Edge | 12 to 72 | 19 to 77 | 11 to 21 | 1 to 86 |
| Intermediate | 2 to 16 | 3 to 16 | 2 to 8 | 2 to 9 |
| Stream | 12 to 20 | 11 to 51 | 11 to 21 | 1 to 18 |
| **Late Summer** | | | | |
| Edge | 18 to 34 | n/a | 2 to 75 | 1 to 24 |
| Intermediate | 4 to 21 | n/a | 1 to 6 | 1 to 4 |
| Stream | 14 to 19 | n/a | 1 to 9 | 3 to 16 |

### 3.3.3 Conclusions and Discussion

Daily maximum ET rates and daily volume ET of the study wetland were influenced by edge effects during the 2002 growing season ($P<.10$). Despite the variation caused by daily and seasonal environmental fluctuations in radiation intensities, wind speeds, relative humidity, and temperature, detection of the edge effect was possible. Data loss due to lightning strikes, frequent precipitation, and battery failure likely attributed to the inability to detect a significant edge treatment effect for the 2003 growing season, since the testable days were likely not representative of the whole season. Therefore, the discussion will focus on the 2002 growing season unless otherwise specified.

In a general study of seasonal ET, daily ET volumes and daily maximum ET rates during Early Summer were influenced by the edge effect. This suggests that vegetation planting strategies should focus on maximizing crown exposure throughout the growing season by reducing stand density. Further, if this finding is repeated in other studies of riparian ET, then planting strategies should arrange for a high proportion of trees to be exposed to edge effects. Since pollutant concentrations in both overland flow and stream flow are highest during Early Summer and Spring, planting a greater number of trees near the riparian edge could positively influence stream flow nutrient concentrations. Studies of the impact edge effects have on early and late Spring ET rates are necessary to confirm this proposition.

When testing the significance of the edge effect during the three seasons, Mid-Summer and Late Summer ET levels were not influenced by edge effects. High within-treatment variability and environmental heterogeneity throughout the stand likely prevented the detection of a significant edge effect during these times. This finding is important because it implies that planting strategies which do not take edge effects into account would have the same hydrological impact on the first-order stream as planting strategies which do take them into account.

When days were separated into evaporative condition groups, it was found that ET rates are most influenced by edge effects during Early Summer days with high and medium evaporative conditions. During these days, trees in close proximity to the riparian edge experienced a pronounced edge effect relative to trees located either near the stream or riparian edge. Days with very low evaporative conditions likely do not account for a very high portion of seasonal ET. However, days with very high evaporative conditions likely do. It seems likely that high within-treatment variability on very high evaporative condition days prevented the detection of the edge effect. Further studies on these prospectively significant days should be carried out. In this study, daily maximum sap flow rates were significantly influenced by edge effects on Late Summer days with very high evaporative conditions.

Trees exposed to the “edge effects” experienced higher maximum ET rates and daily ET volumes than intermediate trees on days with very high, high, and medium evaporative conditions, while they did not on days with very low evaporative conditions. This was expected, as wind speeds, temperature, relative humidity, and radiation are all needed at higher levels along the forest edge in order to create micrometeorological differences between interior and edge tree canopies (which would lead to a pronounced edge treatment effect).

Variability was highest among the edge trees during Mid-Summer and among the trees located near the stream during Early Summer, though variability among the 4 non-edge trees for the duration of the study was lower than expected. This was made evident in Figure 13, which shows diurnal ET trends for the 6 monitored trees on 6 randomly chosen days. This suggests that ET rates for interior trees are less responsive to changing environmental conditions than edge trees. In fact, intermediate tree ET never differed significantly from stream tree ET. Thus, it seems as if high day-to-day variation between the 2 edge trees may be responsible for masking the edge effect. Additional studies with increased replication are needed to establish if edge effects significantly impact riparian ET during Mid- and Late Summer.

Variability within evaporative condition groups was highest on days with very high and very low evaporative conditions, as was expected. As mentioned previously, ET levels on days with very low evaporative conditions are not likely to influence stream flow and the associated stream flow nutrient concentrations even if all trees were highly exposed. Days with very high evaporative conditions, however, likely do influence stream flow most of all. Therefore, further testing should focus on monitoring only very high, high, and medium evaporative condition days.

Test results based on daily maximum sap flow rates and total daily volume sap flow were similar. Two differences between the results were: 1) Edge trees were shown to have higher peak rates during very high evaporative conditions days of Late Summer 2002, while the daily volumes were not different, and 2) Edge trees were shown to have significantly higher daily sap flow volumes than stream trees during Early Summer of 2002. Other than these minor differences, the two methods of testing for the edge effect were comparable.

Overall, it was obvious that more replication and uniform sampling strategies would have aided in establishing the significance of the edge effect on ET rates of the riparian wetland under consideration. The two edge trees within the "edge" treatment group were not located near each other, and thus received differing radiation intensities throughout the day. This likely often prevented the statistical detection of the edge effect for this riparian system. Despite high variability within treatments and throughout the seasons, the edge effect was shown to be significant ($P<.10$) most frequently during Early Summer and on days with very high, high, and medium evaporative conditions.

# 4 Ecosystem Evapotranspiration

## *4.1 Introduction*

In order to use sap flow data practically, sap flow measurements for a set of particular trees must be scaled up to the ecosystem level. A variety of scaling methods have been used for this purpose (see Chapter 1). In this study, I used sapwood area (from the vegetation survey data previously explained in Chapter 2) as an areal scalar. While the ratio of active xylem to projected crown area is a commonly used scalar, using the ratio of sapwood area to stand area has the same effect. I compared daily riparian wetland ET estimates derived from six different scaling methods (each using sapwood area as a scalar) based on the following measurements: diameter at breast height (*DBH*), proximity of tree crown to riparian edge (*Edge*), proximity of tree crown to gap (*Gap*), canopy position (*Canopy*), % live crown (*LC*), and % crown density (*CD*). The primary goal of this study is not to test the accuracy of each of the six scaling parameters; rather, my intent is to compare these six parameters on a relative scale. The 4 zones within the riparian wetland are four trial forests for this purpose. No other known study has attempted to compare scaling variables, and I intend to demonstrate that choice of scaling parameter can influence ecosystem sap flow estimate validity. Results from the method which produces average ET estimates will then be used in Chapter 6.

Because of the many meteorological and biological factors that affect ET, no one ET estimation method is entirely satisfactory for estimating wetland ET (Mitsch and Gosselink 2000). Therefore, in the second portion of this chapter, I will compare the

ET estimates based on the six scaling variables to ET estimates derived from a commonly used ET energy balance model. First, ecosystem ET for each of the four zones will be quantified using a one-dimensional energy balance developed by Priestley and Taylor (Priestley and Taylor 1972). This model is an improvement on the earlier Penman and Penman-Monteith ET models since it involves a coefficient, $\alpha$, which is accepted as a unitless value =1.26 under well-watered/wetland conditions (Priestley and Taylor 1972; Stannard 1993; Eichinger, Parlange et al. 1996; Souch, Wolfe et al. 1996). It must be noted that this method, and all energy balance methods of ET estimation, are only valid over homogeneous surfaces. While riparian zones by definition invalidate this assumption, it is still necessary to complete these calculations in order to provide some reference value of stand ET.

Lastly, these estimates of daily average red maple ET based on scaled up sap flow will be compared to findings in previous studies of red maple ET. This will establish if the sap flow estimates derived from Chapter 4 are consistent with findings of other studies and will help to determine if the riparian red maples at this site transpire more water in general.

## *4.2 Materials and Methods*

As described in Chapter 2, the forested riparian wetland studied was divided into four zones which differ in stand density, species diversity, water availability, etc. It was possible that stand density differences between the zones would present problems when scaling up sap flow data to the ecosystem level. To resolve this issue, the relationship between measured sapwood area within a zone ($SA_{meas}$) and the actual stand area that the sapwood represents ($A_{actual}$) was quantified for each zone. This was done for each zone by utilizing the relationship:

$$\Sigma SA_{meas}/A_{transect} = \Sigma SA_{actual}/A_{actual}$$

**Equation 3**

Where: $\Sigma SA_{meas}$ = sum of measured Red maple sapwood area within a representative area
$A_{transect}$ = representative area that measured sapwood area represents
$\Sigma SA_{actual}$ = sum of actual sapwood area within zone
$A_{actual}$ = actual zone area that actual sapwood area represents.

The area of the riparian wetland studied was estimated at 19,378$m^2$. This was estimated by using a Global Positioning System (GPS) unit to delineate the ecosystem boundaries (see Figure 3). The zonal areas were: zone 1=3510$m^2$, zone 2= 4532$m^2$, zone 3= 6651$m^2$, and zone 4= 4685$m^2$.

To scale up the sap flow data from the six monitored trees to the ecosystem level, some method of accounting for variation in tree characteristics is needed. Granier (Granier 1987) suggested the use of DBH. His recommendation is widely followed since DBH is easily measured. However, it has been suggested that another scaling parameter is needed to differentiate among trees throughout any given area to account for topographic, soil water availability, and/or stand competition differences (Cermak and Kucera 1990; Hatton and Wu 1995b; Oren 1998). Leaf Area Index (LAI) is often suggested as a measure for scaling and is commonly used when assessing ET with remote sensing techniques. Unfortunately, these measures were not available for the 2002 growing season.

In this study, I compared the use of six scaling variables: diameter at breast height (*DBH*), distance of tree crown to riparian edge (*Edge*), distance of tree crown to gap (*Gap*), canopy position (*Canopy*), % live crown (*LC*), and % crown density (*CD*). Based on the vegetation survey data outlined in Chapter 2, each tree was assigned a group, according to the guidelines shown in Table 5 below.

**Table 5 Scaling class assignment descriptions for each of the six scaling groups.**

| Group | Class Assignment Standards |
|---|---|
| *DBH* | **35cm-** (35cm in diameter and below)<br>**35 to 50** (Between 35 to 50 cm in diameter)<br>**50+** (Greater than 50 cm in diameter) |
| *Proximity to Riparian Edge* | **Edge** (0-10m from edge)<br>**Intermediate** (10-25m from edge)<br>**Stream** (25m+ from edge) |
| *Proximity to Gap Edge* | **At** (0-5m from gap exposure)<br>**Near** (5-15m from gap)<br>**None** (15m+ from gap) |
| *Canopy Position* | **CoDom** (dominant or codominant crown positioning)<br>**IntSup** (intermediate or suppressed crown positioning) |
| *% Live Crown* | **High** (50+% live crown)<br>**Low** (50-% live crown) |
| *% Crown Density* | **High** (50+% crown density)<br>**Low** (50-% crown density) |

Once each tree was assigned a class from each variable group, actual sapwood area per group per zone was calculated using the equation:

$$SA_{actual} = (SA_{totalrep}/A_{totalrep}) * SA_{totalactual}$$

**Equation 4**

Where: $SA_{actual}$ = actual sapwood area per group within any given zone
$SA_{totalrep}$ = total sapwood area per group within a represented area
$A_{totalrep}$ = total land area per group within a represented area
$SA_{totalactual}$ = actual total sapwood area per group within a zone.

In this way, estimates of daily transpiration for each zone using each of these six scaling parameters were derived. Table 6 shows % zonal red maple sapwood area allocated to each scaling parameter group. Graphs of ET for each zone, based on these six methods (Figures 27 through 30) show how the methods vary in relation to one another throughout the growing season.

**Table 6 Percent sapwood area within each zone of each scaling variable group.**

| Scaling Parameter | Group | Zone 1 | Zone 2 | Zone 3 | Zone 4 |
|---|---|---|---|---|---|
| *Diameter at Breast Height* | **35 to 50** | 34.4 | 5.5 | 10.8 | 32.5 |
| | **35 Below** | 33.3 | 31.4 | 17.4 | 38.2 |
| | **50+** | 32.3 | 63.1 | 71.8 | 29.3 |
| *Proximity to Riparian Edge* | **Edge** | 18.9 | 40.5 | 27.2 | 1.0 |
| | **Intermediate** | 41.5 | 51.6 | 24.4 | 11.5 |
| | **Stream** | 39.5 | 7.9 | 48.4 | 87.5 |
| *Proximity to Gap Edge* | **Near** | 34.4 | 5.5 | 10.8 | 32.5 |
| | **None** | 33.3 | 31.4 | 17.4 | 38.2 |
| | **On** | 32.3 | 63.1 | 71.8 | 29.3 |
| *Canopy Position* | **CoDom** | 86.5 | 86.4 | 88.9 | 75.4 |
| | **IntSup** | 13.5 | 18.9 | 11.1 | 24.6 |
| *% Live Crown* | **High** | 46.5 | 47.3 | 30.4 | 38.2 |
| | **Low** | 53.5 | 52.7 | 69.6 | 61.8 |
| *% Crown Density* | **High** | 38.3 | 48.3 | 64.0 | 35.2 |
| | **Low** | 61.7 | 51.7 | 36.0 | 64.8 |

Priestley and Taylor (1972) established that:

$$\lambda E = \alpha \frac{\Delta(R-G)}{(\Delta+\gamma)}$$ **Equation 5**

Where: $\lambda$ = the latent heat of the vaporization of water (=2.501-0.002361*T) (MJ/kg)
and T = surface temperature in ◦C
E = evaporation (solving for) (mm day$^{-1}$)
$\alpha$ = Priestley-Taylor coefficient (unitless)
$\Delta$ = slope of the saturation vapor pressure curve

$$\Delta = \frac{4098 * vpsat}{(237.3+T)\wedge 2})$$

and $vpsat = 0.6108\wedge \frac{17.27*T}{237.3+T}$ (kPa/◦C)
R = net radiation (W m$^{-2}$)

$$R = Rsol - Rref$$

Rsol = solar radiation (W m$^{-2}$)
Rref = reflected radiation (=Rsol*alb)) (W m$^{-2}$)
and alb = albedo, surface reflectivity = 0.07+(0.053*LAI)
LAI = leaf area index of site under investigation
G = soil heat flux (W m$^{-2}$)
$\gamma$ = psychrometric constant at a given temperature and pressure (kPa/◦C)

Surface temperature and solar radiation measurements were measured in a nearby agricultural field by USDA Agricultural Research Service scientists. All meteorological variables were measured every 15 seconds, logged every 15 minutes, and averaged every 30 minutes during the study as is detailed in Chapter 2. LAI (leaf area index) measured at six locations throughout the riparian wetland averaged 2.57167 in 2003 (Herbert 2003). Soil heat flux (G) was considered zero, as time frames used in this study experienced negligible soil heat retention (Shuttleworth 1993). The psychrometric constant was quantified from a commonly referenced table according to surface temperature (Shuttleworth 1993). The Priestley-Taylor coefficient was assumed = 1.26, as recommended for wet surface conditions originally by Priestley and Taylor (Priestley and Taylor 1972; Eichinger, Parlange et al. 1996; Souch, Wolfe et al. 1996; Drexler, Snyder et al. 2004).

Daily ET estimates based on the Priestley-Taylor method are expected to depict higher daily volume ET than the sap flow-derived methods for a number of reasons:

1) Average daily solar radiation and average daily temperature values were used in daily Priestley-Taylor calculations, which is required for energy balance calculations of this sort (Priestley and Taylor 1972; Eichinger, Parlange et al. 1996; Souch, Wolfe et al. 1996; Drexler, Snyder et al. 2004), which is required for energy balance calculations. However, sap flow methods estimate ET on an instantaneous time frame and therefore provide much more precise estimates (though perhaps not as accurate).

2) No method of estimating soil heat flux was available for the 2002 growing season, so soil heat flux was estimated at %10 of solar radiation. This (likely) unavoidably overestimated the energy available for latent heat flux, which would result in overestimating daily ET.

3) Potential ET derived from the Priestley-Taylor equation is the combination of evaporation and transpiration, while sap flow is strictly a measure of transpiration. Even after accounting for this difference (by assessing pan evaporation and combining evaporation + transpiration), sap flow estimates have been known to underestimate potential ET, most likely due to physiological factors (stomatal resistance, delayed stomatal opening to evaporative conditions, etc.) (Wullschleger, Meinzer et al. 1998; Wilson, Hanson et al. 2001).

Days used for these comparisons were the same as used in Chapter 3, as these were the days with valid sap flow data.

Correlations among seven methods of daily ET estimation were analyzed using the Analyst Application of the SAS System v. 8.2 (see Appendix entry 3). The seven methods were: daily ET estimations based on the six previously mentioned sapwood scaling variable groups, and daily ET estimations derived from the Priestley-Taylor method.

## *4.3 Results*

### 4.3.1 Comparisons of Six Scaling Variable Methods of ET Estimation

First, it should be pointed out that it is not the goal of this chapter to recommend one scaling parameter over another. These results pertain to this ecosystem and serve only as an example of variability that can arise when scaling up sap flow estimates from individual trees to four different ecosystems with varying stand characteristics.

Figures 27 through 30 at the end of this chapter compare daily sap flow estimates based on the six scaling parameters, as will be discussed in detail. The trends shown throughout the zones in these graphs are summarized in Table 7.

**Table 7 Zonal comparisons of the six scaling variables used to estimate daily sap flow depth relative to the average of all of the variables.**

| | Zone 1 | Zone 2 | Zone 3 | Zone 4 |
|---|---|---|---|---|
| ***Diameter at Breast Height*** | Relatively high | Relatively low, often lowest | Relatively low, often lowest | Average, but spikes relatively quite high |
| ***Proximity to Riparian Edge*** | Average | Average | Average | Average |
| ***Proximity to Gap Edge*** | Average to below average | Average | Relatively high, often highest | Very low |
| ***Canopy Position*** | Relatively low, often lowest | Relatively low, often lowest | Usually lowest | Relatively low, often lowest |
| ***% Live Crown*** | Usually high, often second highest | Often follows same trend as % crown density, but usually average | Average | Usually high, often second highest |
| ***% Crown Density*** | Quite variable, middle to low, but spikes high | Often average, but spikes high | Often highest, but spikes low | Often average, but spikes high |

Overall, the *Proximity to Riparian Edge* scaling variable yielded average ET estimates relative to the other 5 scaling variable methods. Although the percentage of sapwood that came from the *Edge* group for each zone ranged from 40.5% in zone 2 to 1% in zone 4 (Table 6), the method based on *Proximity to Riparian Edge* provided average results throughout the growing season.

The *Canopy Position* variable consistently yielded low zonal ET estimates throughout the growing season relative to the other 5 methods. The percentage of sapwood area for the CoDom group (Table 6) was somewhat uniform between the zones, which could explain the consistent results, despite that the categorization of trees into four groups (dominant, co-dominant, intermediate, and suppressed) was not doable due to logistical limitations. In the only other known study which used *Canopy* as a scaling variable, they, too, found that ecosystem ET estimates based on sap flow tended to underestimate daily ET relative to energy balance-derived estimates (Wullschleger, Meinzer et al. 1998). Evidence is unclear as to why this would be the case.

The *% Live Crown* scaling variable yielded zonal ET estimates higher than average estimates (relative to the other 5 methods) throughout the growing season. When comparing across zones, the higher the % of sapwood area within the *High* group, the higher the ecosystem estimate ranged above average. That is, in zones where the estimates based on *% Live Crown* were average, a lower percentage (30 to 38%) of sapwood area was designated as *High*. In zones where the estimates based on *% Live Crown* rose above average, a higher percentage (46 to 47%) was designated as *Low*.

This seems to be in accordance with what is known about % live crown in relation to canopy position; lower light availability (as is the case with intermediate or suppressed crowns) leads to greater percentage live crown.

The *Proximity to Gap Edge* scaling parameter yielded average to below average daily ET estimates for zones 1,2 and 4, though for zone 3, it often yielded the highest daily sap flow estimates. Zones 1 and 4, which have fairly even distributions of red maples located on, near, and nowhere near gaps in the canopy, resulted in low ET estimations. Zone 2, which has ~30% of red maples not experiencing gap edge effects and ~63% experiencing gap edge effects, yielded average ET estimates. In stark contrast to the other zones, zone 3 boasted high daily sap flow estimates, likely due to the high % (~72%) of red maple crowns open to edge effects. Though zone 2 had nearly that many red maple crowns located on gap edges (~63%), nearly half that many crowns were located nowhere near a gap edge; this perhaps could have resulted in average daily ET estimates.

The *Diameter at Breast Height* scaling variable yielded unreliable ET estimates in relation to estimates based on the other 5 scaling variables. In zones 2 and 3, with a high proportion of sapwood area in the *50+* group and a low proportion of sapwood area in the *35 to 50* group, ET estimates were lower than estimates based on other variables. Zones 1 and 4, with more evenly distributed stands in terms of diameter at breast height, yielded consistently higher daily sap flow estimates. The high spikes in daily sap flow estimates in zone 4 could be attributed to the higher percentage of sapwood in the *35 below* group. It should be noted that estimates based on the *Diameter at Breast Height* parameter should be considered suspect, as the *50+* group is comprised of only one red maple.

The *% Crown Density* scaling variable yielded erratic ET estimates. This was expected, since % crown density is often not a parameter associated with determining daily sap flow rates (though it can be if loss in crown density is due to health-related issues which may impede transpiration processes). When sapwood area was evenly divided (as was the case for zone 2), then estimates based *on % Crown Density* roughly mimicked estimates based on *% Live Crown*. Having over 60% of sapwood area in the *Low* group yielded average daily ET estimates, though on days with very low evaporative conditions (i.e. Days 285, 286) this resulted high daily ET estimates.

After comparing these six scaling variables, it is clear that the choice of sap flow scaling parameter is an important issue to consider when working with localized sap flow data. As can be seen in Table 8, estimates of total daily ET can vary depending on which method of scaling is used. This idea has not been stressed in the literature. Discussions of scaling error and its associated issues suggest sapwood area as a method of scaling on an areal basis; the creation of scaling variables such as these presented here have not been suggested before, other than the *Diameter at Breast Height* method initially mentioned by Granier (Granier 1987) and the *Canopy Position* method suggested by Wullschleger (Wullschleger, Hanson et al. 2001). Often it is thought that scaling should be done based on tree age (or some measure of that, such as diameter at breast height), but that method ignores other influential environmental conditions. Additional studies are needed in order to verify if these trends are similar elsewhere. Only then can suggestions be made on which variables or measurements should be used in estimating ecosystem ET.

**Table 8 Range of daily ET estimates in mm day-1 for the 2002 growing season based on each scaling method.**

| | *DBH* | *Proximity to Edge* | *Proximity to Gap Edge* | *Canopy Position* | *% Live Crown* | *% Crown Density* | Average of 6 Methods |
|---|---|---|---|---|---|---|---|
| **Minimum** | 0.25 | 0.25 | 0.24 | 0.13 | 0.25 | 0.08 | 0.35 |
| **Maximum** | 6.77 | 4.18 | 4.3 | 3.83 | 5.11 | 7.53 | 4.8 |
| **Average** | 2.2 | 2.16 | 2.03 | 1.83 | 2.21 | 2.27 | 2.12 |

### 4.3.2 Priestley-Taylor Comparisons

The correlation matrices for the ET estimates based on the seven methods during each season (Early, Mid-, and Later Summer) and throughout all 4 zones are in the Appendix (see Appendix Tables 17-20). ET estimates based on the six sapwood scaling methods were highly correlated (P<.0001) for all of the zones throughout the 2002 growing season. As this was expected, the remainder of this discussion will focus on the pairwise comparisons of each of the six ET estimation methods with the Priestley-Taylor estimates (Table 9). The Priestley-Taylor estimate is assumed to be a baseline method of ET estimation against which accuracy comparisons will be made, as many prior studies have used energy balances as baselines against which to compare innovative approaches.

**Table 9 Correlation coefficients among the six scaling variable ET estimation methods and estimates based on Priestley-Taylor (PT) method for each season (Early, Mid, Late) by zone. Early Summer n=39, Mid-Summer n=19, Late Summer n=11. Where: *, **, ***, and **** denote significance at the 0.10, 0.01, 0.001, and 0.0001 probability levels, respectively, and ns denotes not significant at the 0.1 probability level.**

| **Zone 1** | **DBH** | **Proximity to Riparian Edge** | **Proximity to Gap Edge** | **Canopy Position** | **% Live Crown** | **% Crown Density** |
|---|---|---|---|---|---|---|
| PT, Early | 0.59**** | 0.56*** | 0.59**** | 0.52*** | 0.59**** | 0.58*** |
| PT, Mid | $0.23^{ns}$ | 0.41* | $0.14^{ns}$ | 0.39* | $0.31^{ns}$ | $-0.3^{ns}$ |
| PT, Late | $0.32^{ns}$ | $0.3^{ns}$ | $0.29^{ns}$ | $0.25^{ns}$ | $0.31^{ns}$ | $0.42^{ns}$ |
| **Zone 2** | | | | | | |
| PT, Early | 0.59**** | 0.59**** | 0.57*** | 0.53*** | 0.59**** | 0.59**** |
| PT, Mid | $0.2^{ns}$ | $0.21^{ns}$ | $0.16^{ns}$ | $0.21^{ns}$ | $0.31^{n}s$ | $-0.27^{ns}$ |
| PT, Late | $0.3^{ns}$ | $0.35^{ns}$ | $0.38^{ns}$ | $0.41^{ns}$ | $0.36^{ns}$ | $0.11^{ns}$ |
| **Zone 3** | | | | | | |
| PT, Early | 0.59**** | 0.59**** | 0.58*** | 0.51*** | 0.56*** | 0.61**** |
| PT, Mid | $0.33^{ns}$ | 0.41* | $0.16^{ns}$ | $0.32^{ns}$ | $0.33^{ns}$ | -0.42* |
| PT, Late | $0.28^{ns}$ | $0.3^{ns}$ | $0.31^{ns}$ | $0.29^{ns}$ | $0.3^{ns}$ | $0.52^{ns}$ |
| **Zone 4** | | | | | | |
| PT, Early | 0.6**** | 0.44** | 0.59**** | 0.55*** | 0.58*** | 0.57*** |
| PT, Mid | $0.19^{ns}$ | 0.56* | $0.28^{ns}$ | $0.17^{ns}$ | $0.32^{ns}$ | $-0.33^{ns}$ |
| PT, Late | $0.31^{ns}$ | $0.26^{ns}$ | $0.28^{ns}$ | $0.3^{ns}$ | $0.31^{ns}$ | $0.51^{ns}$ |

The *Diameter at Breast Height* (DBH) scaling method was of special interest, since this scaling variable was initially suggested by Granier in 1987 in association with his development of the thermal dissipation probe method. However, this study demonstrates that using *DBH* as a scaling variable may not be the best choice. Discounting Early Summer (when all six scaling parameters produced estimates correlated to PT estimates ($P<.0001$)), *DBH* often produced estimates which were weakly correlated to PT-derived estimates (see Appendix Table 17). In Mid-Summer, *DBH* was found to be weakly correlated with PT estimates for all 4 zones ($P>.15$). In Late Summer, estimates based on the *DBH* variable were not correlated with PT estimates for 3 out of 4 zones. This evidence suggests that scaling variables which account for factors other than tree age might be better when scaling up the flow estimates in a riparian forested wetland. Out of the twelve tested periods (3 seasons * 4 zones), only the 4 Early Summer estimates based on *DBH* were correlated to PT estimates ($P<.10$).

The *Proximity to Riparian Edge* (*Edge*) scaling variable was also of special interest, since the premise of this project was to discern if the edge effect results in significant differences between sap flow rates between edge and interior trees. In Early Summer, the *Edge* variable ET estimates were correlated ($P<.01$) to PT estimates. This is not exceptional, as many of the methods yielded correlated results in Early Summer. In Mid-Summer, estimates based on the *Edge* variable for zones 1, 3, and 4 yielded the only estimates correlated to PT ($P<.10$) estimates. In Late Summer, like estimates based on many scaling variables, ET estimates based on *Proximity to Riparian Edge* were not significantly correlated with PT estimates (P>.10). Out of the twelve tested periods, 7 estimates based on the *Edge* variable were correlated to PT estimates (P<.10), which was the highest number of correlated periods.

The *Proximity to Gap Edge* (*Gap*) scaling variable was a prospective choice since it seemed to play a substantial role in influencing sap flow rates in Chapter 4 and also because the increased radiation intensity and wind speeds associated with canopy gaps have received frequent attention in the literature. However, ET estimates based on the *Gap* method were frequently not correlated with PT estimates. In Mid- and Late Summer, estimates for 3 out of 4 zones were not correlated with PT estimates (P>.10). Out of the twelve tested periods, only the 4 Early Summer estimates based on the *Gap* variable were correlated to PT estimates (P<.10).

The *Canopy Position* (*Canopy*) scaling variable was considered since relative canopy position often dictates light intensity and wind speeds experienced by a tree canopy. In Early Summer, all zonal estimates based on *Canopy* were correlated with PT estimates (P<.01). In Mid-Summer, zone 1 estimates based on the *Canopy* variable were correlated (P<.05) with PT estimates, though estimates for zones 2, 3, and 4 were not correlated (P>.10). In Late Summer, *Canopy* estimates were not correlated with the PT estimates for each of the 4 zones. Out of the twelve tested periods, 5 estimates based on the *Canopy* variable were correlated to PT estimates (P<.10).

The *% Live Crown* (LC) scaling variable was considered since the portion of physiologically active crown may determine tree crown health and is also often associated with canopy position. In Early Summer, ET estimates based on *LC* for all 4 zones were significantly correlated with PT estimates (P<.10). In Mid-Summer and Late Summer, ET estimates based on the *LC* method were not correlated with PT estimates (P>.10). Out of the twelve tested periods, only the 4 Early Summer estimates based on the *LC* variable were correlated to PT estimates (P<.10).

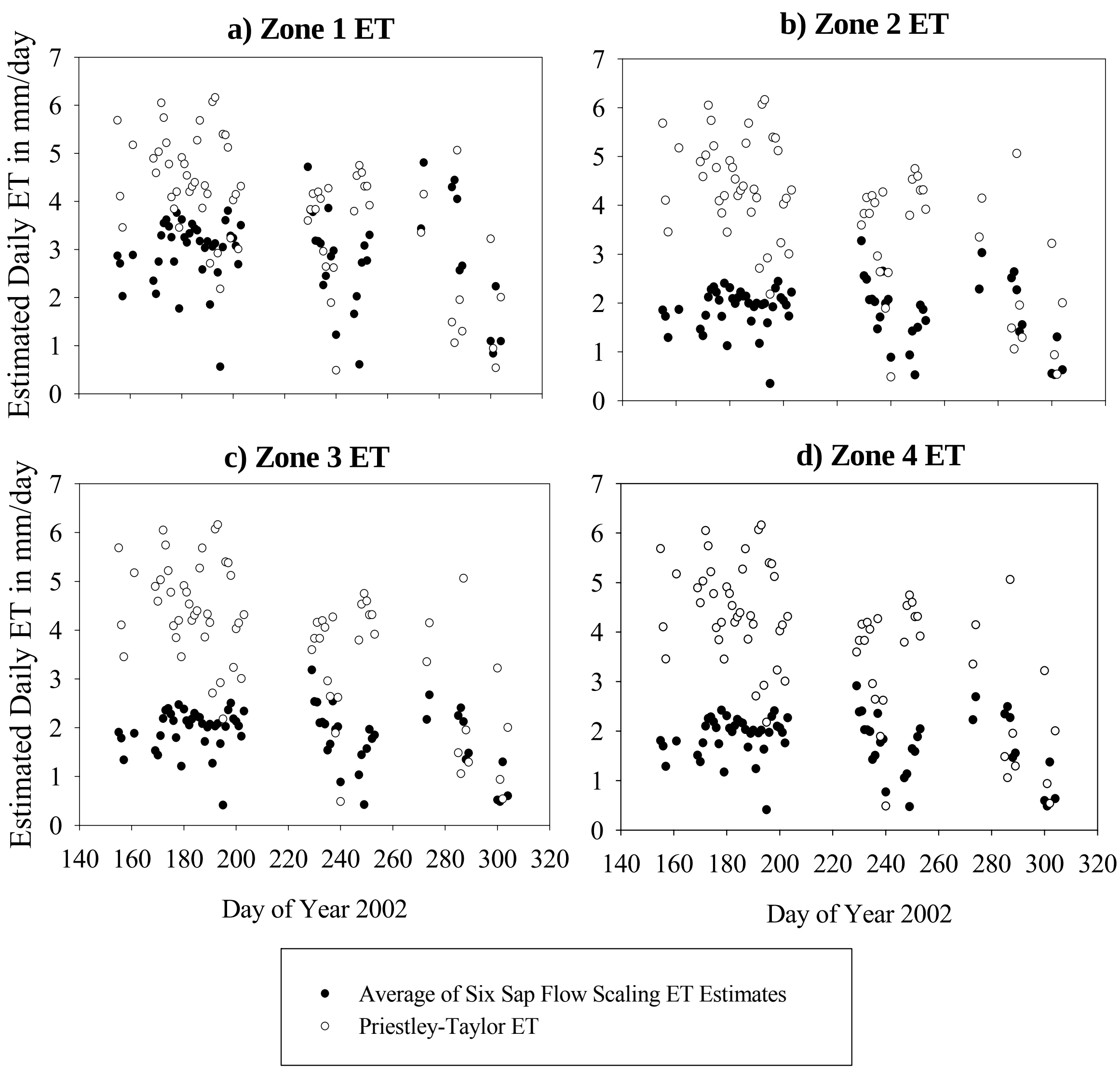
The *% Crown Density* scaling variable was tested since the density of a crown determines the quantity of leaf area that is able to transpire. If a low amount of leaf area (i.e. a low % crown density) is present in a crown, then high ET rates are more unlikely to result. If a high amount of leaf area is available to transpire in the crown, then higher ET rates are likely. In Early Summer, all 4 zonal estimates based on *LC* were highly correlated (P<.0001) with PT estimates. In Mid-Summer, LC estimates for zone 3 were highly correlated (P<.10) with PT estimates, though estimates for zones 1, 2, and 4 were not correlated with PT estimates (P>.10). In Late Summer, estimates based on the *LC* variable for all 4 zones were not correlated with PT estimates (P>.10). Out of the twelve tested periods, 5 estimates based on the *CD* variable were correlated to PT estimates (P<.10).

It was expected that no one parameter would provide estimates that are significantly correlated with Priestley-Taylor estimates. Often, significant correlations between sap flow and some other meteorologically-derived estimate of ET cannot be found (Dunn and Connor 1993; Wilson, Hanson et al. 2001). Based on the number of periods out of 12 (3 seasons * 4 zones), the *Proximity to Riparian Edge* variable seems to provide both the most consistently average estimates and the estimates most frequently correlated to PT estimates ($P<.10$).

All of the daily volumes based on the six methods were averaged to attain representative daily ecosystem ET estimates, which can be seen in comparison to the daily Priestley-Taylor estimates in Figure 21. The average of the sap flow scaling methods and the PT estimates were most similar on days with low evaporative conditions (i.e. days of year 238, 240, 288, 289, 301). However, for zone 1, days with similar estimates varied, since some days had very high, very low and medium evaporative conditions. Zone 1, however, varied from the other zones (see section 2.2) and it is unknown why this occurred. Zone 1 also demonstrated on a number of days (i.e. days of year 238, 239, 274, 285, 302) that the scaled up sap flow average estimate was greater than the Priestley-Taylor estimate. This usually occurred on days with very low evaporative conditions, but also occurred on days with higher temperatures. Reasons for this are also unclear.

Daily ET estimates based on scaled up sap flow averaged around 57% of the Priestley-Taylor estimates for zones 2, 3, and 4 and 91% for zone 1. These ratios are similar to ratios found for a stand of Maritime pine, which averaged a 55% ratio of sap flow estimates to energy balance-derived estimates (Granier 1990). Again, it is unclear why zone 1 estimates were so different.

Figure 26 Daily estimates of ET for each zone based on the average of the six sap flow scaling methods and the Priestley-Taylor method.




## 4.3.3 Conclusions and Discussion

Although there are few reported estimates of hourly sap flow for temperature hardwood species, three studies to date have reported values for Eastern hardwood forests including red maples. Sap flow monitoring in an Eastern upland oak forest in Tennessee in 1997 showed that understory red maples transpired a maximum daily depth of 2.2 mm/day

(Wullschleger, Hanson et al. 2001). Present study maximum daily ET based on the six scaling parameters frequently surpassed this level. Daily ET depths in zones 2, 3, and 4 often rose to 3 mm/day, and in zone 1, most days except those with very low evaporative conditions experienced ET levels greater than 3 mm/day (see Figures 27 through 30). The greater ET experienced in this study (if significant) is likely due to the shallow groundwater table and/or the presence of "edge effects". The maximum depth of water "lost" to ET in the upland oak forest occurred in mid-May before canopy closure and again in late June. The maximum depth of water lost to ET in this riparian wetland occurred mid-August and mid-October. This could be due to meteorological differences between the years of the studies.

Red maples in an upland oak forest in eastern Tennessee experienced unprecedented high hourly sap flow rates approaching $30cm^3/cm^2$sapwood/hour (Wilson, Hanson et al. 2001). In the present study, daily maximum sap flow rates frequently exceeded $30cm^3/cm^2$sapwood/hour. Of the 444 maximum sap flow rates recorded in 2002 (74 days, 6 trees each day, 1 maximum for each tree), 58 maximum flow rates were above $30cm^3/cm^2$sapwood/hour, and 11 out of those 58 were greater than $75cm^3/cm^2$sapwood/hour. The maximum daily sap flow rate experienced by any tree was $138cm^3/cm^2$sapwood/hour for tree 4 on day of year 187. The dissimilarities between the red maples in this study and those in TN are likely due the monitored red maples in TN being located in the understory. Most of the daily maximum sap flow rates recorded in this study were for trees 4 and 6 (both edge trees with intermediate canopy positioning).

An earlier study of red maple decoupling coefficients in an upland oak forest provided information on 12 red maples, some of which were dominant (Wullschleger, Wilson et al. 2000). Those 12 red maples in TN averaged daily sap flow depths of 0.7 to 2.5mm/day. Depending on the scaling parameter used, daily depth of sap flow in this study ranged from 0.08 to 7.53mm/day with the average of all of the methods being 0.35 to 4.8mm/day throughout the zones. The overall average daily depth of sap flow in the TN forest was 1.5mm/day, while the riparian wetland in this study averaged 2.12mm/day.

Another southeastern deciduous forest where sap flow monitoring of lower and mid-canopy red maples took place was in Duke Forest, NC (Oren and Pataki 2001). Daily sap flow rates for the 1993 growing season there ranged from 6 to 40$cm^3/cm^2$sapwood/hour. Daily sap flow rates for this study ranged up to 35$cm^3/cm^2$sapwood/hour.

Overall, no one scaling method reliably provided ET estimates strongly correlated to the Priestley-Taylor derived ET estimates. Figures 27 through 30 show the variability of the six methods based on sap flow scaling. Figure 21 shows the variability of the Priestley-Taylor method in comparison to an average of the six sap flow derived ET estimates. It is clear that estimates based on these seven methods varied throughout the seasons and throughout zones.

When comparing sap flow-derived ET estimates with other water balance or energy balance techniques, quantifiable differences are prevalent. Studies have shown that sap flow techniques provide lower ET daily and/or seasonal ET estimates than estimates based on water balances or energy balances (Dunn and Connor 1993;

Kostner, Granier et al. 1998; Wullschleger, Meinzer et al. 1998). Discrepancies between methods have been attributed to: radial variation in sap flow, delayed coupling between the atmosphere and stomatal response, daily radiation/shadowing regimes, and/or lack of accounting for the presence of understory ET.

More studies of this nature are needed in order to understand the dynamics of each of these methods so that the most efficient and accurate scaling variable can be determined. Though few conclusions can be extrapolated to other ecosystems based on the current data, it would be interesting to discern if these scaling variables result in similar findings in other ecosystems. Similar findings at other ecosystems are doubtful, since even within the four zones results for each scaling variable varied in relation to one another.

**Figure 27 Zone 1 daily ET estimates based on each of the six scaling variables for the 2002 growing season.**

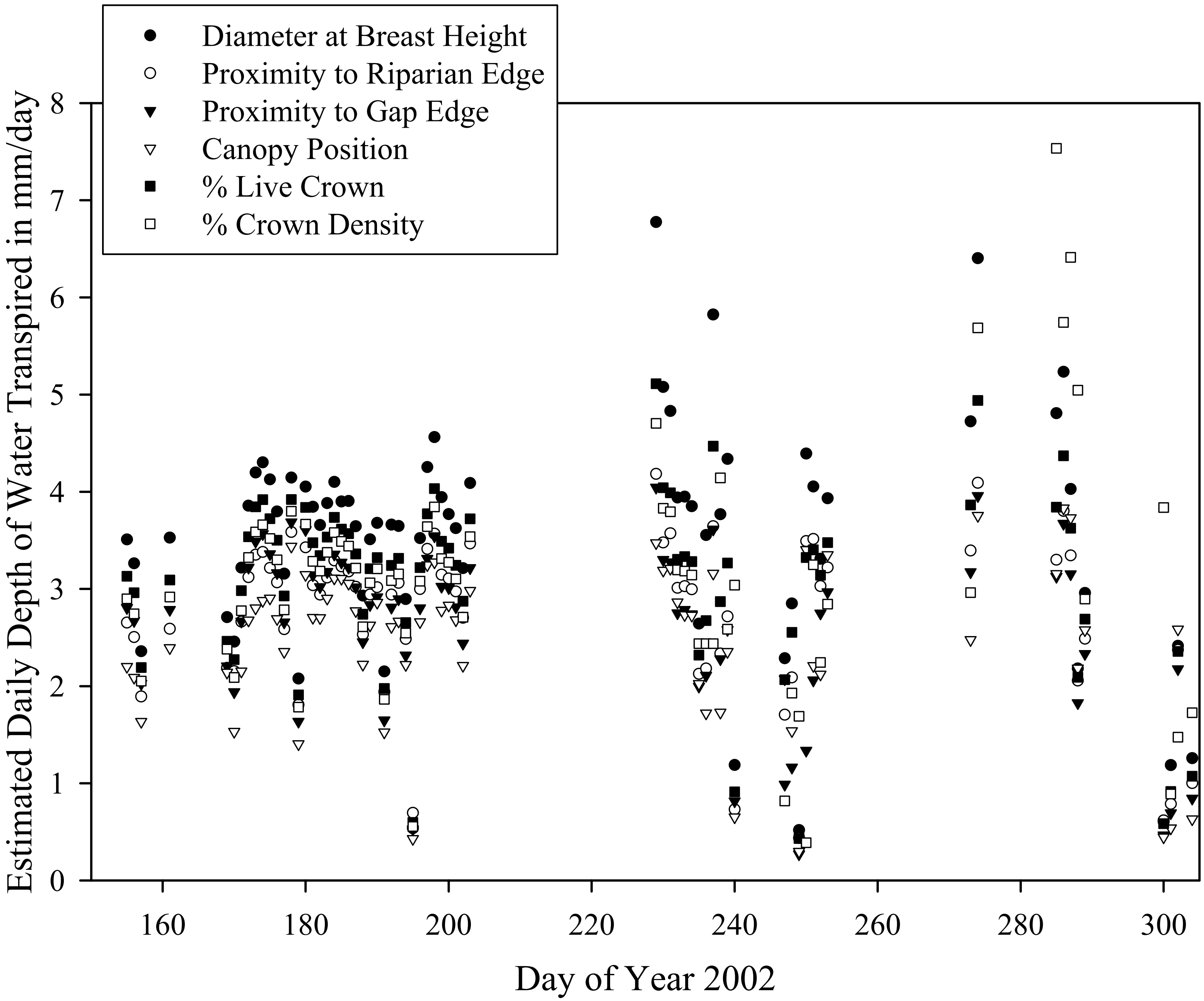


**Figure 28 Zone 2 daily ET estimates based on each of the six scaling variables for the 2002 growing season.**

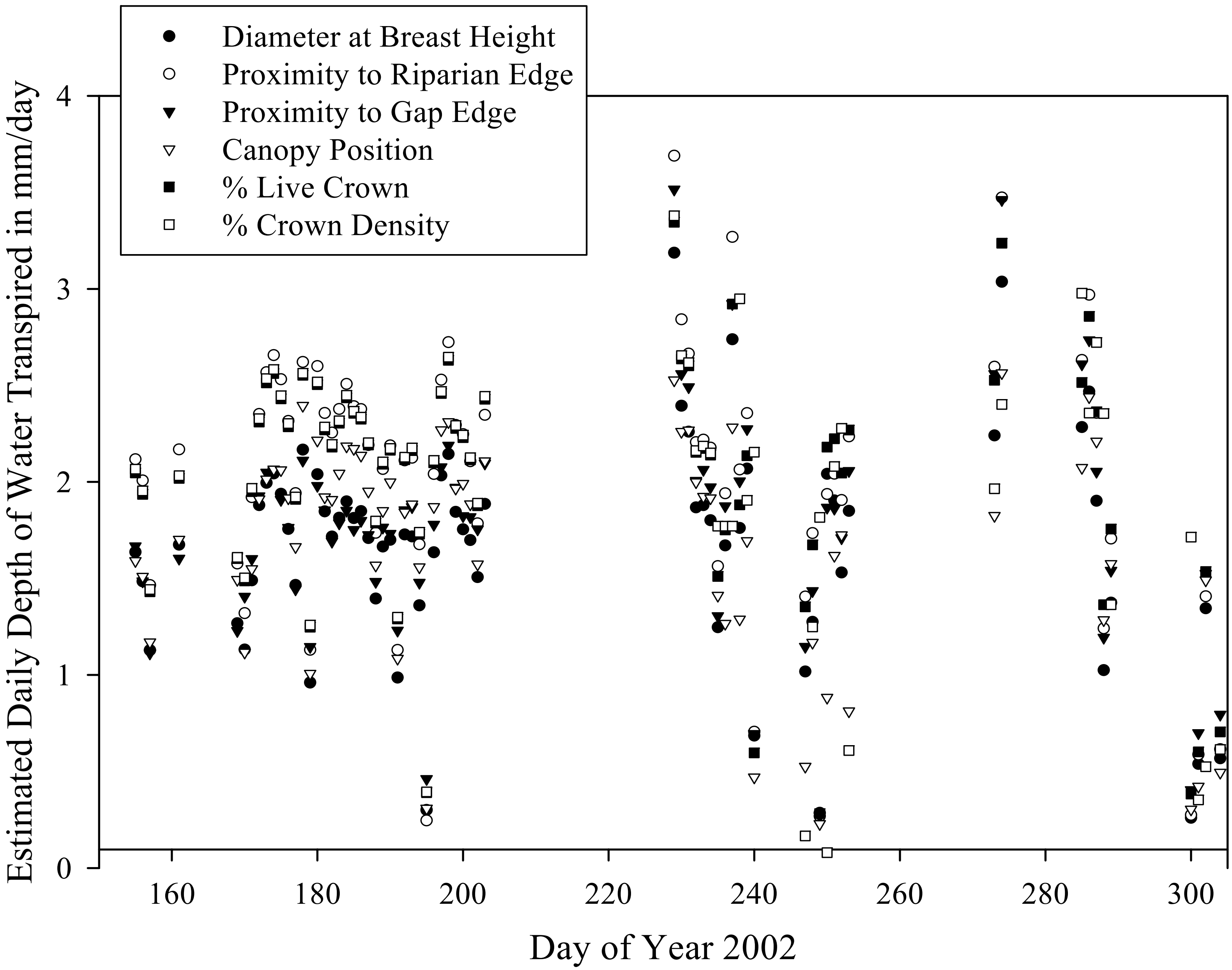


**Figure 29 Zone 3 daily ET estimates based on each of the six scaling variables for the 2002 growing season.**

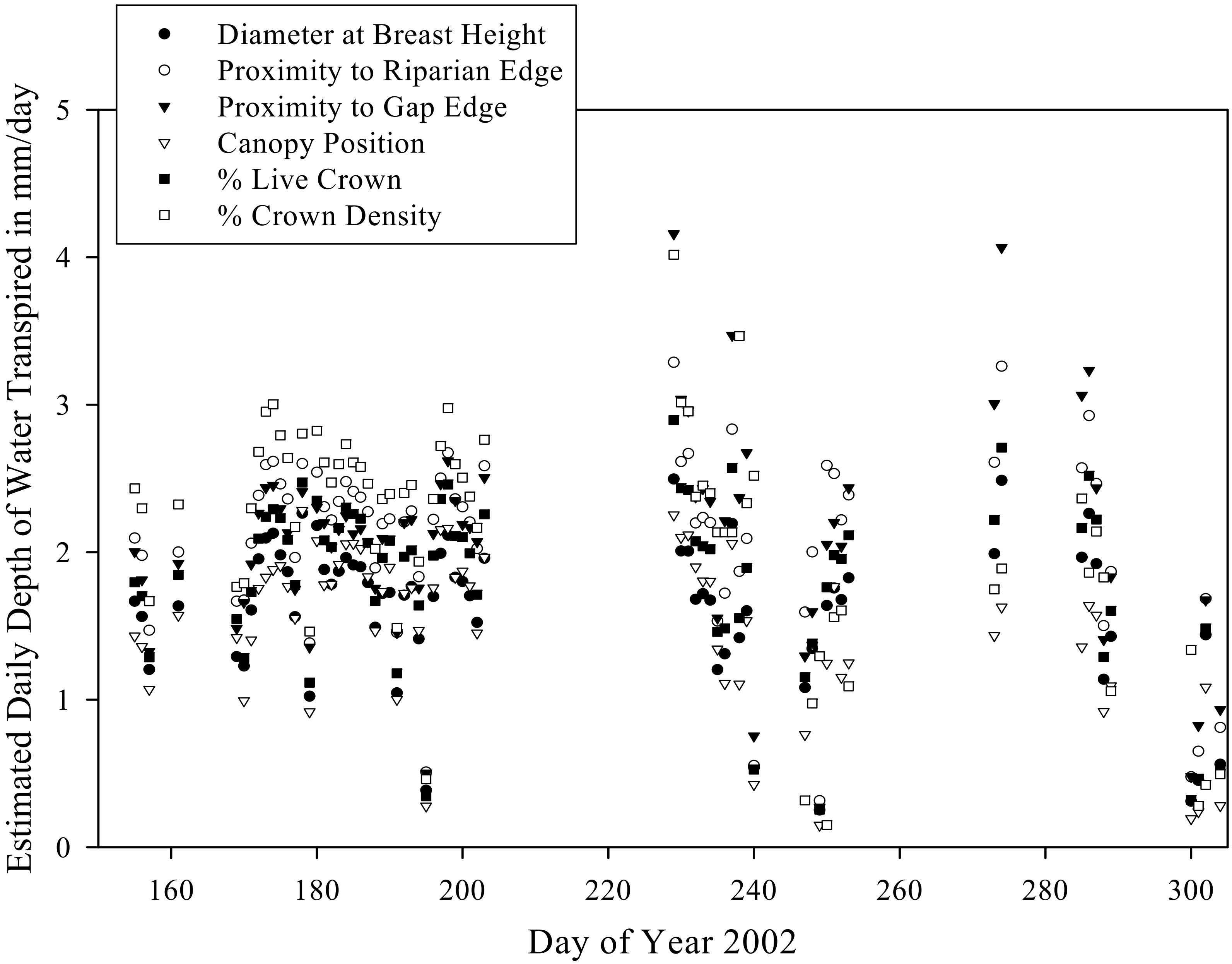
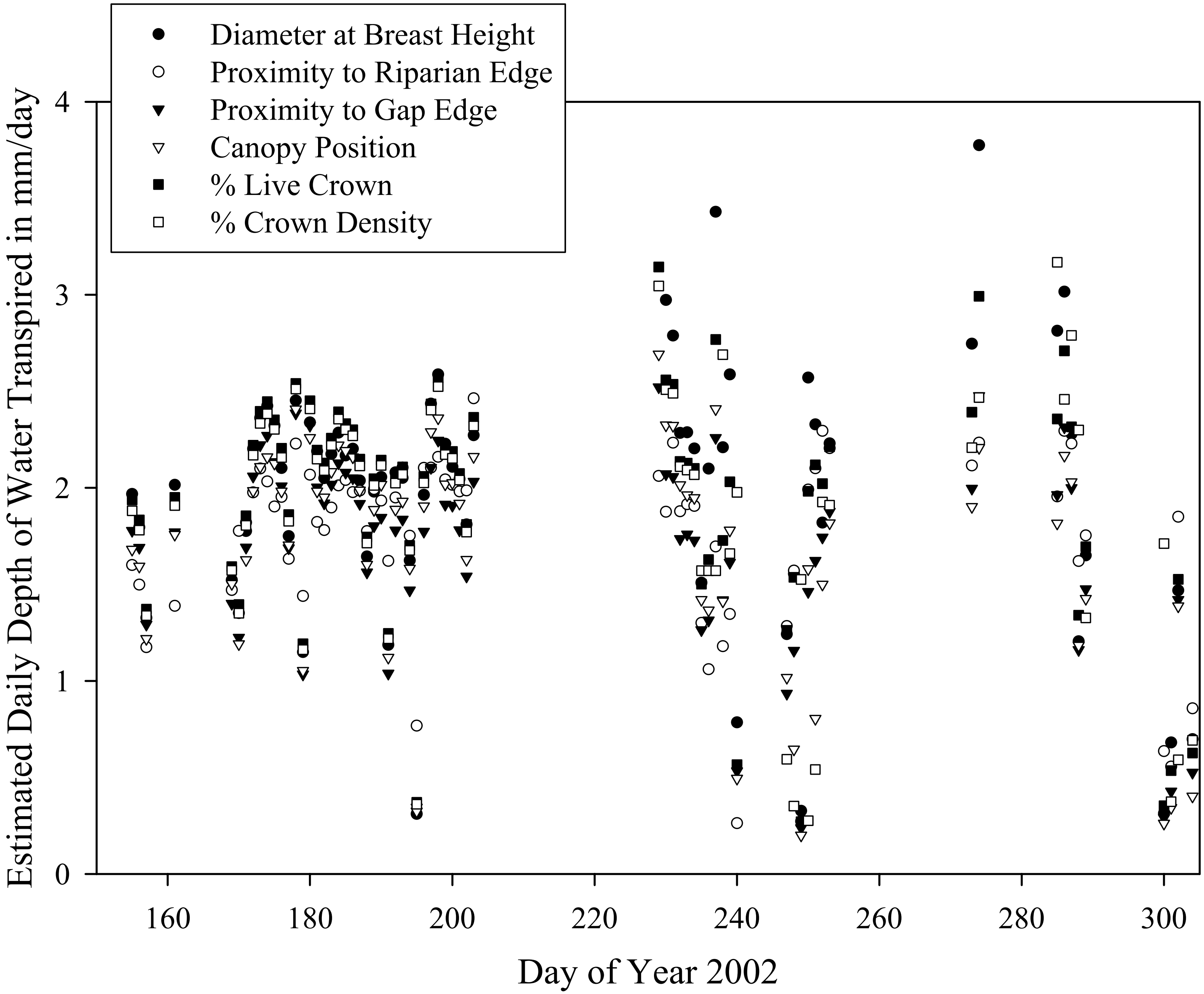


**Figure 29 Zone 4 daily ET estimates based on each of the six scaling variables for the 2002 growing season.**



# 5 Streamflow and Sap Flow Correlation Study

## *5.1 Introduction*

Understanding and evaluating the impact of ET on riparian ecosystems is important for determining water budgets and interpreting nutrient cycles. Riparian forests intercept groundwater flow bound for the stream channel. Ultimately, this intercepted water returns to the atmosphere, while the nutrients absorbed from the groundwater remain within the woody vegetation (hence performing a nutrient-removing or “buffering” function). Therefore, diurnal riparian ET rates must be understood to understand water and nutrient dynamics within a riparian ecosystem. The effect of diurnal riparian ET rates on streamflow has not been studied fully. This is likely due to the fact that ET rates are often assessed based on water balances (which cannot provide instantaneous measurements of ET due to storage changes) and energy balances (which are valid when analyzing longer time frames and not valid for riparian forest due to fetch limitations).

Streamflow rates provide instantaneous measures of riparian ecosystem hydrology and reflect recent ET rates. Thus, in this study, I examined the correlation between daily maximum sap flow rates and daily streamflow losses under baseflow conditions. In turn, hydrographs depicting those correlations will be developed. Those relationships can then be used to help predict the effect of ET on streamflow and subsequent nutrient cycles.

## *5.2 Materials and Methods*

Streamflow data were needed to assess the impact of ET on hydrology within the wetland. Streamflow sampling stations equipped with V-notch weirs were previously installed by the USDA Environmental Quality Lab. Locations of these stations can be seen in Figure 3. Stations are numbered upstream to downstream and they divide the area into 4 distinct zones. Streamflow data from stations 2, 3 will be used when analyzing zone 2 ET. Streamflow data from stations 3 and 4 will be used when analyzing zone 3 ET. Streamflow sampling station 2 (where streamflow is relatively low) is equipped with a 60° V-notch weir. Stations 3 and 4 are equipped with 90° V-notch weirs. All data were averaged every 30 min. Days influenced by elevated groundwater levels due to recent precipitation events were not used; therefore, the results of this study can only be extrapolated to days with baseflow conditions.

Sap flow data for zones 2 and 3 (see Chapter 2) were also needed to assess the impact of ET on hydrology within the study wetland. ET rates from sap flow rates scaled up based on *Distance from Edge* (from Chapter 4) were used for this purpose.

First, daily sap flow and streamflow trends were plotted for each evaporative condition group (Figures 31 and 32) to assess the differences between trends during very high, high, medium, and very low evaporative condition days. Sap flow and streamflow trends were then averaged by evaporative condition group in order to quantify correlations.

Diurnal ET trends influence diurnal streamflow trends (Bowie and Kam 1968). Although useful, estimation of daily ET rates based on daily streamflow rates has not been done. Daily maximum sap flow rates (DMSFR) and daily streamflow losses (DSL) were correlated in order to evaluate linkages between streamflow and sap flow trends within the riparian system. Since streamflow peaks during the night (when ET does not impact streamflow), DSL were calculated by:

$$Stream_{max} - Stream_{min} = Stream_{loss}$$

**Equation 6**

Where: $Stream_{max}$ = maximum streamflow rate between 00:00 and 06:00
$Stream_{min}$ = minimum streamflow rate between 08:00 and 20:00
$Stream_{loss}$ = streamflow loss during the day

Correlation analysis was performed between DSL and DMSFR using the Analyst Application of SAS v. 8.2. The Appendix contains information on these tests. Correlation analysis was first performed for Zone 2 DMSFR and DSL at Stations 2 and 3, and Zone 3 DMSFR and DSL at Stations 3 and 4. After the initial correlation analysis was completed, correlation analysis was then performed for each evaporative condition group (see Chapter 3).

Since streamflow varies due precipitation events, days were separated into stream groups based on 00:00 streamflow rates. 00:00 streamflow rates are typical of nighttime streamflow rates, which are not influenced by sap flow. Daily streamflow levels for each station were divided into high, medium, and low groups according to Table 10 guidelines. This method of grouping days decreased noise, as indicated by an analysis of variance (see Appendix Item 4) of Zone 3 daily volume ET showing the streamflow grouping was significant (P=.0118). Grouping days by evaporative conditions (Chapter 3) also decreased noise (P=.0024).

**Table 10 Guidelines used to separate days into streamflow groups. Units in Liters/Hour streamflow.**

| | Low | Medium | High |
|---|---|---|---|
| Station 2 | 0 to 200 | 200 to 350 | 350 to 600 |
| Station 3 | 0 to 500 | 500 to 800 | 800 to 1600 |
| Station 4 | 0 to 500 | 500 to 1000 | 1000 to 2000 |

Correlation analysis between DSL and DMSFR was then performed based on all combinations of evaporative condition groups and streamflow groups when sufficient days (n>2) were available.

Lastly, a correlation analysis between DSL at all 3 stations and daily ET estimates estimated using the Priestley-Taylor energy balance equation (in mm per day) was performed for the entire 2002 growing season (see Chapter 4 for description of Preistley-Taylor methods).

## *5.3 Results*

Streamflow and sap flow trends for all evaporative condition groups and streamflow groups are shown in Figures 31 and 32. These graphs depict the average impact daily ET trends have on daily streamflow trends. Daily streamflow losses at stations 3 and 4 roughly mimicked each other, except for when station 4 streamflow rates neared zero due to high sap flow rates and/or low groundwater inputs (see Figure 31d).

Average streamflow losses were greatest under very high and high evaporative condition days on days with high streamflow (see Figures 31a, 31d, and 32a).

Daily sap flow rates typically began to climb around 07:00, peaked around 12:00 and ended their decline around 20:00. In contrast, streamflow rates peaked right before sap flow began (around 07:00), bottomed out around 15:00, and rose gradually until morning.

ET rates peaked between 11:00 and 12:00 except on days with very low evaporative conditions when peak times varied. Minimum streamflow rates occurred between 15:00 and 16:00, indicating a nearly 4-hour lag between peak sap flow rates and minimum streamflow rates.

**Figure 30 Average daily streamflow and sap flow trends on very high and high evaporative condition days.**

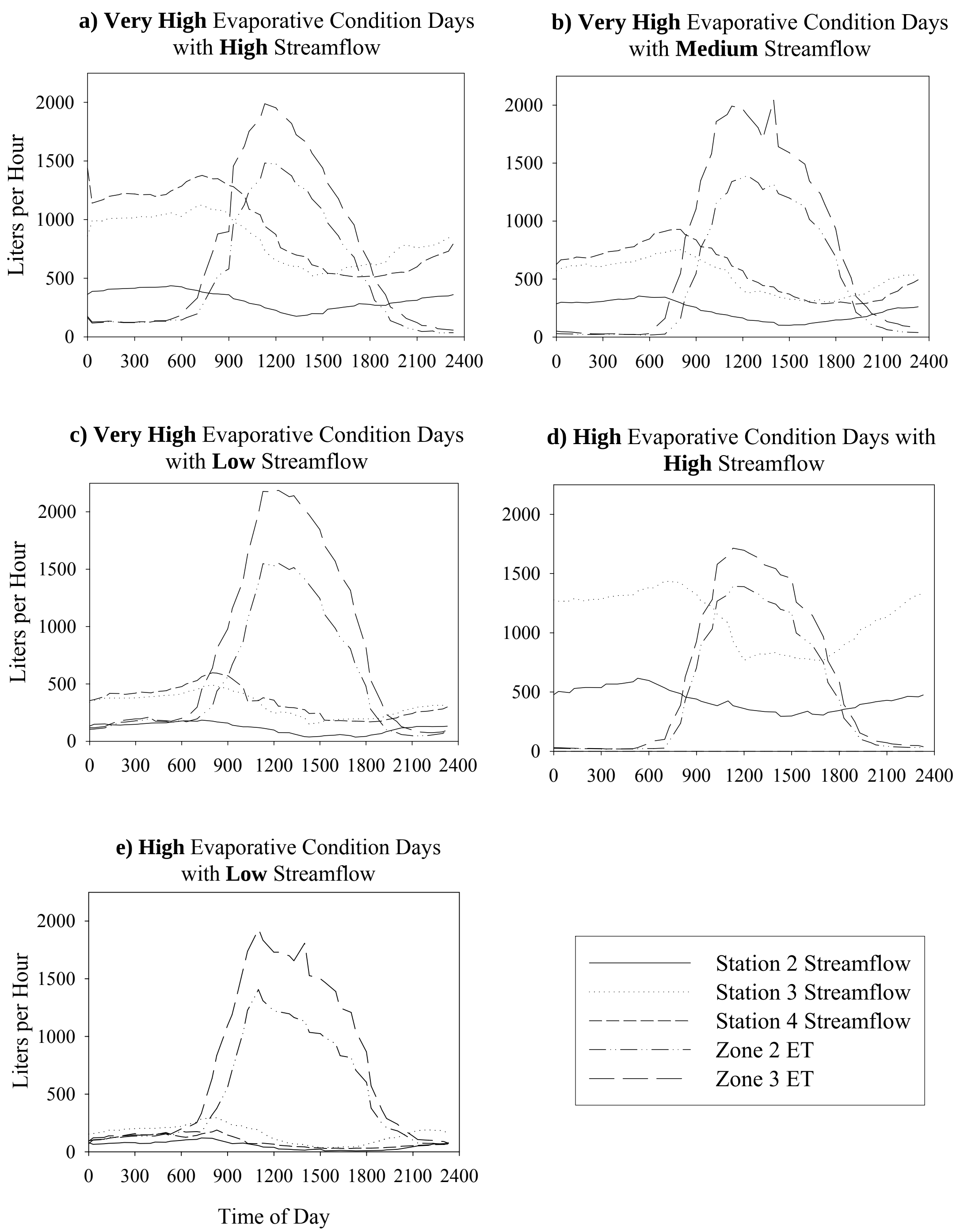


**Figure 31 Average daily streamflow and sap flow trends on medium and very low evaporative condition days.**

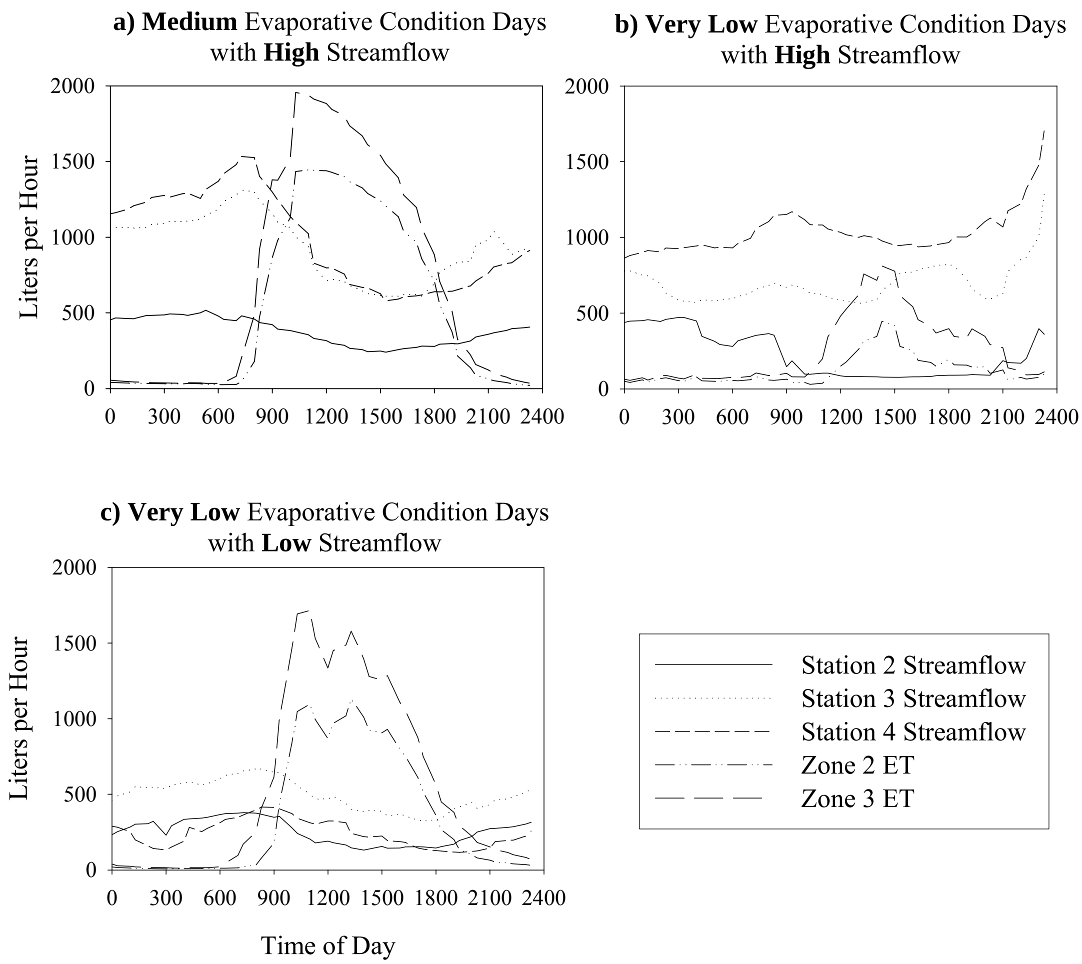


Table 11 indicates the correlation between DMSFR and DSL for the 2002 growing season. Zone 2 DMSFR were correlated (P<.05) with Station 2 daily streamflow losses. Station 3 streamflow losses were not correlated (i.e. P>.25) with Zone 2 or Zone 3 DMSFR, nor did Station 4 DSL correlate with Zone 3 DMSFR.

**Table 11 Correlation coefficients between maximum sap flow rates and streamflow losses during the 2002 growing season. * indicates significance at the P<.05 level, ns denotes not significant at the .25 probability level, number in parentheses dictates number of sample days tested, and n/a means not available.**

| | **Station 2** Streamflow Losses | **Station 3** Streamflow Losses | **Station 4** Streamflow Losses |
|---|---|---|---|
| **Zone 2** Maximum Sap Flow Rates | -0.44* (28) | ns (39) | n/a |
| **Zone 3** Maximum Sap Flow Rates | n/a | ns (39) | ns (36) |

Table 12 indicates the correlation between DMSFR and DSL for groups of days with similar evaporative conditions. Zone 2 DMSFR were correlated (P<.05) with Station 2 DSL only on days with very high evaporative conditions. Zone 2 DMSFR were correlated with Station 3 DSL on days very low evaporative conditions P<.10, respectively). Zone 3 DMSFR were not correlated (P>.10) with Station 3 DSL regardless of evaporative conditions. Zone 3 DMSFR were correlated (P<.10) with Station 4 DSL.

**Table 12 Correlation coefficients between daily maximum ET (sap flow) rates and daily streamflow losses as calculated by evaporative condition group (*very high, high, medium, and very low*). * and ** denote significance at the .05 and .10 probability levels, respectively. ns denotes not significant at .10 probability level, number in parentheses dictates number of sample days tested, and n/a means not available.**

| | Very High | High | Medium | Very Low |
|---|---|---|---|---|
| **Zone 2** Daily Max ET & **Station 2** Daily Streamflow Losses | -0.586* (15) | ns (6) | ns (5) | n/a |
| **Zone 2** Daily Max ET & **Station 3** Daily Streamflow Losses | ns (20) | ns (10) | ns (6) | 0.993** (3) |
| **Zone 3** Daily Max ET & **Station 3** Daily Streamflow Losses | -0.546* (20) | ns (10) | ns (6) | ns (3) |
| **Zone 3** Daily Max ET & **Station 4** Daily Streamflow Losses | ns (20) | 0.670** (7) | ns (6) | ns (3) |

Table 13 shows the results from the correlation analysis between DMSFR and DSL or groups of days with similar nighttime (baseflow) streamflow rates. Zone 2 DMSFR were correlated with Station 2 DSL on days with High streamflow (P<.05).

**Table 13 Correlation coefficients between daily maximum ET (sap flow) rates and daily streamflow losses, as calculataed for streamflow groups (*high, medium, and low*). * denotes significance at the .05 probability level. Ns denotes not significant at the .10 probability level, and number in parentheses dictates number of sample days tested.**

| | High | Medium | Low |
|---|---|---|---|
| **Zone 2** Daily Max ET & **Station 2** Daily Streamflow Losses | 0.611* (14) | ns (11) | ns (14) |
| **Zone 2** Daily Max ET & **Station 3** Daily Streamflow Losses | ns (10) | ns (9) | ns (9) |
| **Zone 3** Daily Max ET & **Station 3** Daily Streamflow Losses | ns (14) | ns (11) | ns (14) |
| **Zone 3** Daily Max ET & **Station 4** Daily Streamflow Losses | ns (11) | ns (11) | ns (14) |

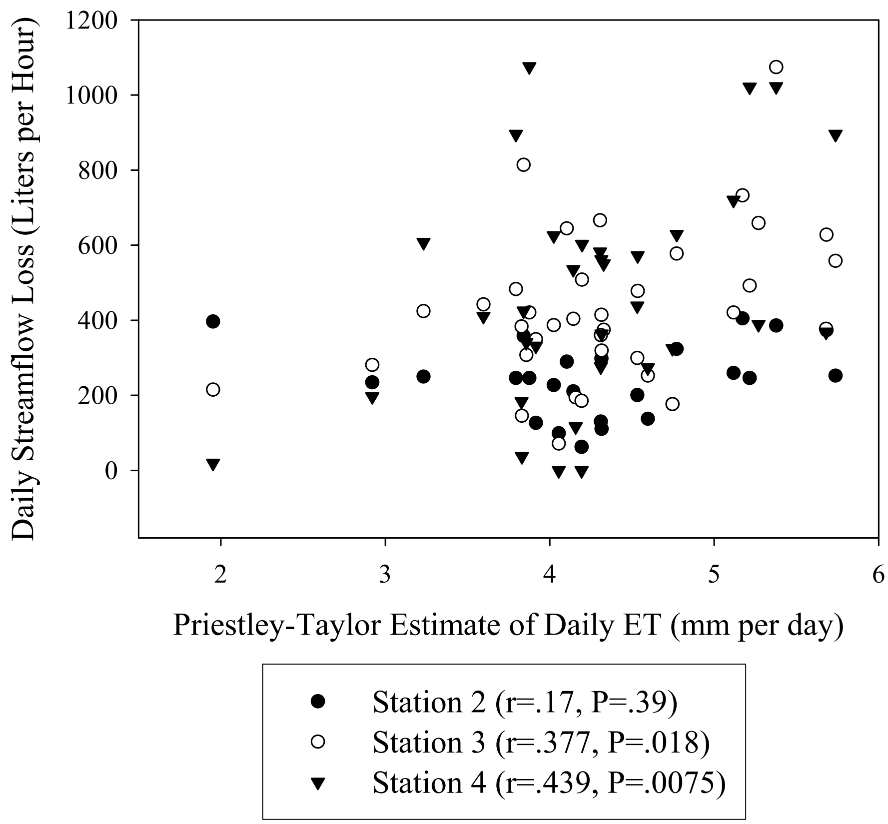
Table 14 indicates results from the correlation analysis between DMSFR and DSL for groups of days with similar evaporative and streamflow conditions. Zone 2 DMSFR were not correlated (P>.10) with Station 2 or Station 3 DSL under any conditions. Except on days with high evaporative conditions and low streamflow conditions (when P<.10), Zone 3 and Zone 4 DMSFR were not correlated with DSL at Stations 3 and 4.

**Table 14 Correlation coefficients between maximum daily sap flow rates (ET) and daily streamflow losses as calculated for streamflow group (*high, medium, and low*) and evaporative condition group combinations. * and ** denote significance at the .05 and .10 probability levels, respectively, $^{ns}$ denotes not significant at the .10 probability level, number in parentheses dictates number of sample days tested, and n/a means not available.**

| **Zone 2 ET & Station 2 Streamflow** | **High Streamflow** | **Medium Streamflow** | **Low Streamflow** |
|---|---|---|---|
| Very High Evaporative Conditions | ns (3) | ns (7) | ns (5) |
| High Evaporative Conditions | ns (3) | n/a | ns (3) |
| Medium Evaporative Conditions | ns (3) | n/a | n/a |
| **Zone 2 ET & Station 3 Streamflow** | | | |
| Very High Evaporative Conditions | ns (7) | ns (8) | ns (5) |
| High Evaporative Conditions | ns (3) | n/a | ns (7) |
| Medium Evaporative Conditions | ns (3) | ns (3) | n/a |
| **Zone 3 ET & Station 3 Streamflow** | | | |
| Very High Evaporative Conditions | ns (7) | ns (8) | ns (5) |
| High Evaporative Conditions | ns (3) | n/a | 0.789* (7) |
| Medium Evaporative Conditions | ns (3) | ns (3) | n/a |
| **Zone 3 ET & Station 4 Streamflow** | | | |
| Very High Evaporative Conditions | ns (7) | ns (8) | ns (5) |
| High Evaporative Conditions | n/a | n/a | 0.67** (7) |
| Medium Evaporative Conditions | ns (3) | ns (3) | n/a |

Correlation analysis results between Priestley-Taylor-derived daily ET estimates and DSL at the three streamflow sampling stations are shown in Figure 33. Daily streamflow losses at Station 2 were not correlated (P>.05) with daily ET estimates calculated from the Priestley-Taylor energy balance equation. DSL at Stations 3 and 4 were correlated (P<.05) with daily Priestley-Taylor-derived ET estimates.

**Figure 32 Relationships between Priestley-Taylor-derived daily ET estimates and daily streamflow losses incurred at each sampling station.**



## *5.4 Discussion and Conclusions*

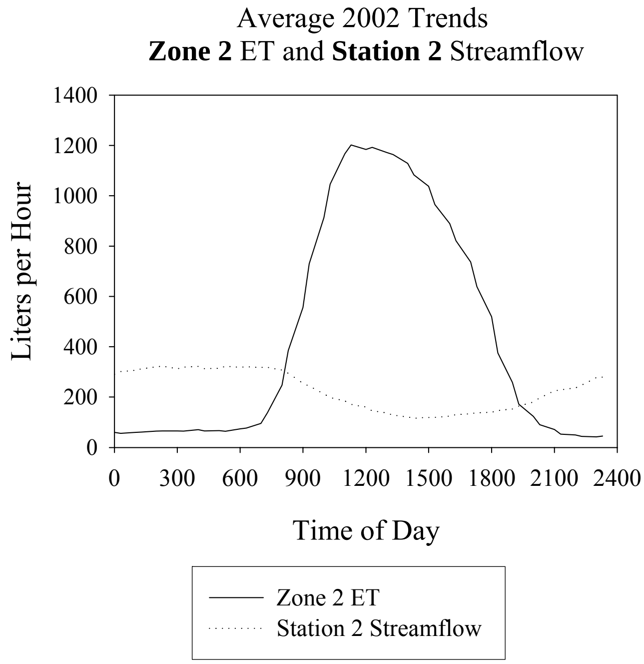
Average streamflow losses were greatest under very high and high evaporative conditions on days with high streamflow. This was expected, as high ET rates would consequentially have a high impact on streamflow. The greatest streamflow losses also occurred during days with high streamflow. This was not expected, as it was thought that evaporative conditions would play a more influential role in determining streamflow losses.

ET rates peaked between 11:00 and 12:00, except on days with very low evaporative conditions when peak times varied. Minimum streamflow rates occurred between 15:00 and 16:00. This 4-hour lag between peak sap flow rates and minimum streamflow rates could play a major role in determining stream nutrient fluxes.

Streamflow levels increased from upstream to downstream station, as groundwater flow accumulates as it progresses downstream. Therefore, Station 2 streamflow rates were the lowest of Stations 2, 3, and 4 streamflow (as it is located upstream in the wetland). Interestingly, Station 2 streamflow also indicated the least diurnal fluctuation due to ET. This could be attributed to a narrower (and thus smaller) forest influencing streamflow at this station.

Maximum sap flow rates of Zone 2 were correlated with Station 2 streamflow losses when averaged for the 2002 growing season. This finding will allow Zone 2 maximum sap flow rates to be estimated using streamflow data and the relationship shown in Figure 33.

**Figure 33 Correlated (P<.05) average daily hydrological trends during the 2002 growing season between Zone 2 sap flow rates and Station 2 streamflow rates.**




It is generally accepted that upstream riparian ET rates influence downstream streamflow rates. However, results for Zones 2 and 3 suggest this is not the case here. On days with very high evaporative conditions (when sap flow is perhaps most influential), zonal daily maximum sap flow rates were correlated to streamflow losses at their immediate *upstream* sampling stations (see Chapter 2 and Figure 34). In addition, daily maximum sap flow rates for Zones 2 and 3 were not correlated with streamflow losses at their immediate *downstream* sampling stations. On days with very low evaporative conditions, zonal ET was correlated with streamflow losses at their immediate downstream sampling stations (see Figures 34). Results indicate that maximum sap flow rates are correlated with both upstream and downstream streamflow losses depending on environmental conditions.

**Figure 34 Correlated relationships between daily maximum sap flow rates and daily streamflow losses on days with similar evaporative conditions.**

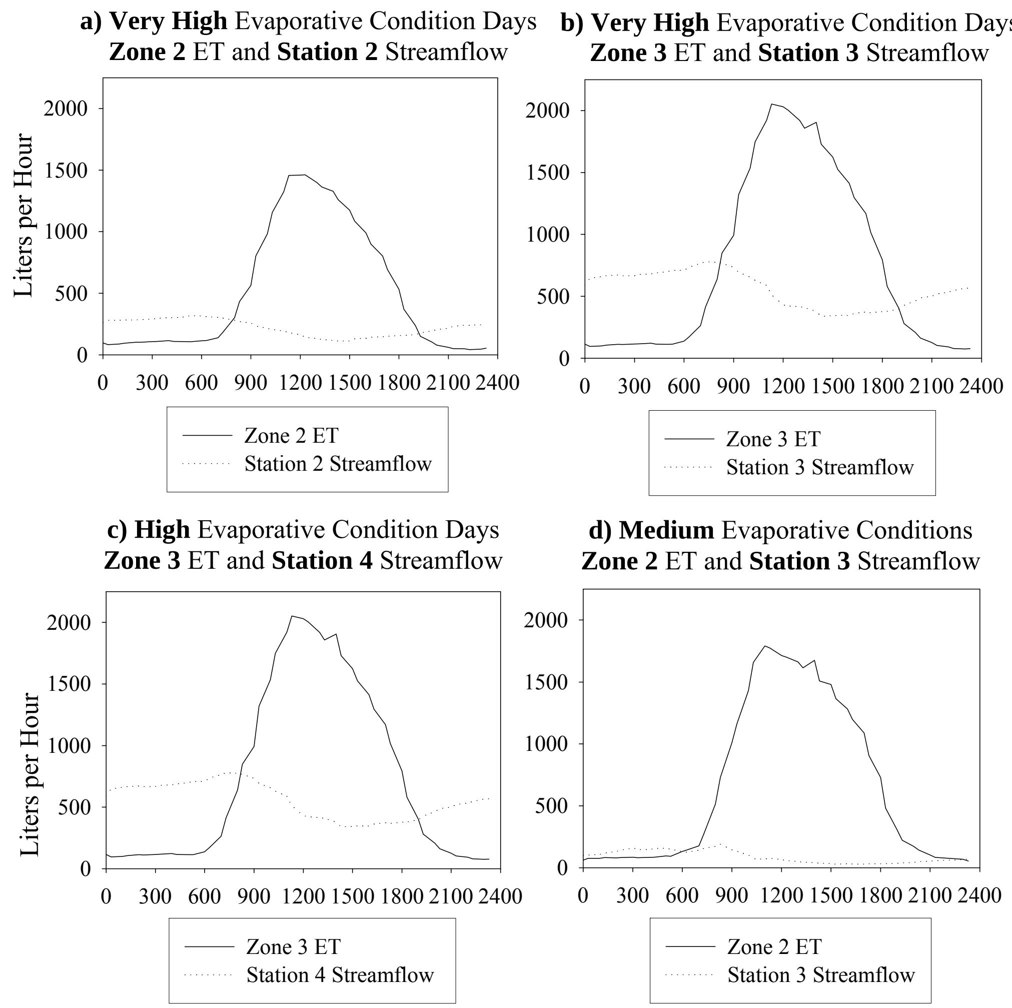


Figure 35 shows the relationship between DMSFR and DSL on days with high streamflow conditions, where Zone 2 DMSFR were correlated with Station 2 DSL. No correlations existed between maximum sap flow rates and streamflow losses during medium or low streamflow conditions.

**Figure 35 Correlated (P<.05) relationships between daily maximum sap flow rates and daily streamflow losses on days with high streamflow conditions.**

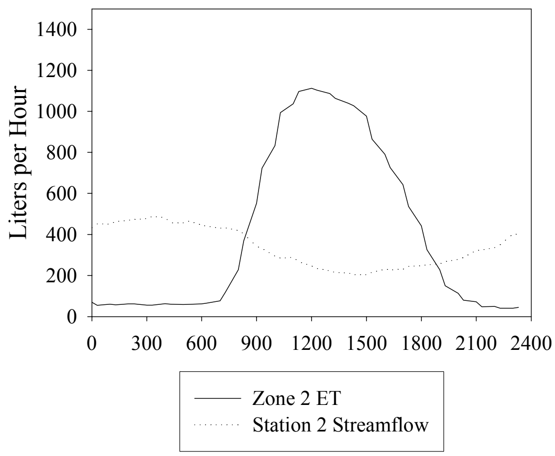
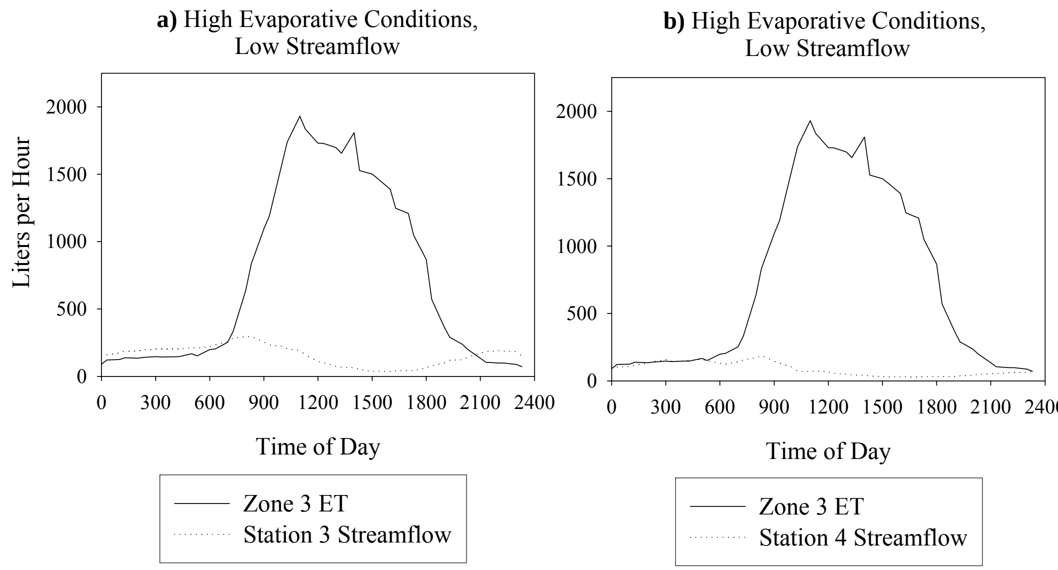



Figure 36 indicates the relationships between DMSFR and DSL under specific evaporative and streamflow conditions. These relationships could be utilized when estimating maximum ET rates from streamflow rates on specific days with similar streamflow and evaporative conditions. Using these graphs, ET rates for Zone 3 could be estimated using streamflow data gathered on days with low streamflow.

**Figure 36 Correlated (P<.10) relationships between sap flow rates and streamflow rates under specific combinations of evaporative and streamflow conditions.**




Results of the correlation analysis between Priestley-Taylor-derived daily ET estimates and DSL at the three streamflow sampling stations indicated that DSL at Stations 3 and 4 were correlated (P<.05) with daily Priestley-Taylor-derived ET estimates, but DSL at Station 2 were not (P>.05). This suggests that streamflow losses at Station 2 may be more influenced by other conditions, such as a) a highly variable water table (and thus groundwater input), or b) the immediately upstream riparian forest being too narrow to influence streamflow losses.

Overall, the limited number of days with available sap flow and streamflow often prevented the detection of correlations between daily maximum sap flow rates and daily streamflow losses for days with specific environmental conditions (i.e. streamflow conditions and evaporative conditions). I would suggest monitoring sap flow and streamflow on predetermined days (with specific streamflow conditions and similar evaporative conditions) for future studies to develop similar relationships.

No DMSFR for any one zone correlated consistently with DSL from any one streamflow station. I expected upstream sap flow rates to correlate with downstream streamflow rates, but this was seldom the case. Availabilty of more days for testing would allow determining the correlation between upstream streamflow rates and downstream sap flow rates. It would be useful to ascertain if a) streamflow input into an area influences riparian ET due the upstream area "controlling" the water availability of the downstream area, b) streamflow output from an area is influenced by upstream sap flow, c) neither is true, or d) either is true under which conditions. All of these aspects of riparian hydrology must be explored further in order to continue to improve riparian vegetation planting strategies based on the impact ET has on streamflow.

# 6 Discussion and Conclusions

## *6.1 Edge Effect Study Conclusions*

Results from the Edge Effect Study for the 2002 growing season indicate that trees located on the forest edge which were exposed to increased radiation intensities and wind speeds experienced greater daily volume sap flow and higher maximum daily sap flow rates than trees not exposed to the "edge effects" ($P<.10$). This finding is notable since the edge effect was significant despite the variation caused by daily and seasonal environmental fluctuations in radiation intensities, wind speeds, relative humidity, and temperature.

Forest edge trees were then shown to transpire more water daily than interior trees during Early Summer. This suggests that vegetation planting strategies for Zone 2 of riparian forested areas (see Figure 1) should focus on maximizing crown exposure throughout the growing season by reducing stand density. Further, if this finding is repeated in other studies of riparian ET, then planting strategies should arrange for a high proportion of trees to be exposed to edge effects. Since pollutant concentrations in both overland flow and stream flow are highest during Spring and Early Summer, planting a greater number of trees near the riparian edge could positively influence stream flow nutrient concentrations. Further studies of the impact edge effects have on early and late Spring ET rates are necessary to confirm this proposition.

Edge effects did not influence ET levels during Mid-Summer or Late Summer. High within-treatment variability and environmental heterogeneity throughout the stand likely prevented the detection of a significant edge effect during these times. This suggests that, during Mid- and Late Summer, planting strategies which do not take edge effects into account would have the same hydrological impact on the first-order stream as planting strategies which do take them into account.

When days were separated into evaporative condition groups, it was found that ET rates are most influenced by edge effects during Early Summer days with high and medium evaporative conditions. During these days, trees in close proximity to the riparian edge experienced a pronounced edge effect relative to trees located either near the stream or riparian edge. Days with very low evaporative conditions likely do not account for a very high portion of seasonal ET. However, days with very high evaporative conditions likely do. It seems likely that high within-treatment variability on very high evaporative condition days prevented the detection of the edge effect. Further studies of days with very high evaporative conditions should be carried out.

Results based on daily maximum sap flow rates and total daily sap flow volumes were similar. Two differences between the results were: 1) Edge trees had higher peak rates during very high evaporative conditions days of Late Summer 2002, while the daily volumes were not different, and 2) Edge trees had significantly higher daily sap flow volumes than stream trees during Early Summer of 2002. Other than these minor differences, the two methods of testing for the edge effect were comparable, which suggests that either test can be used to assess the influence edge effects have on riparian ET.

Overall, it was obvious that more replication and uniform sampling strategies would have increased the statistical power of detecting the edge effect on ET rates of the riparian wetland under consideration. The two edge trees within the “edge” treatment group were not adjacent, and thus received differing radiation intensities throughout the day. This likely often prevented the statistical detection of the edge effect for this riparian system. Despite high variability within treatments and throughout the seasons, the edge effect was significant ($P<.10$) during Early Summer and on days with very high, high, and medium evaporative conditions.

Finally, findings from the Edge Effect Study suggest that riparian buffer vegetation planting strategies should be improved to optimize the number of trees exposed to edge effects by staggering plantings along the forest edge and/or by decreasing stand density to increase available energy within existing stands. Increasing the number of trees exposed to “edge effects” could increase the volume of water transpired by the buffer, thereby increasing nutrient uptake and buffering capability of the system. Edge effects, since found to significantly influence ET rates during Early Summer, could help decrease streamflow nutrient levels during this ecologically sensitive season.

## *6.2 Ecosystem ET Study Conclusions*

In the Ecosystem ET Study, I compared ET estimates for four ecosystems based on seven scaling variables. Results from this study demonstrated that, despite the widespread use of *DBH* as a scaling variable, it may not be the best choice. Further results indicated that scaling variables which account for factors other than tree age might be better when scaling up the flow estimates in a riparian forested wetland.

Often, correlations between sap flow and some other meteorologically-derived estimate of ET were not significant (Dunn and Connor 1993; Wilson, Hanson et al. 2001). However, when ecosystem ET estimates for twelve periods (3 seasons * 4 zones) were compared to estimates derived from the Priestley-Taylor (P-T) energy balance method, estimates based on *DBH, Proximity to Gap Edge, and % Live Crown,* were correlated (P<.10) to PT estimates for only 4 out of 12 periods. Estimates based on *Canopy Position and % Crown Density* were correlated (P<.10) to PT estimates for 5 out of 12 periods. Estimates based on *Proximity to Riparian Edge* were correlated (P<.10) to PT estimates for 7 out of 12 periods.

It should be noted that ecosystem estimates based on all of the 6 scaling methods did not correlate (P>.10) with Priestley-Taylor-derived estimates during Late Summer and were correlated (P<.10) with PT-derived estimates during Early Summer. This suggests that ET rates of an Early Summer canopy were more coupled to atmospheric changes than ET rates of a Late Summer canopy. This could be due to the Early Summer canopy being less full, which would allow for less shadowing and more available energy; perhaps these conditions are more reflected in the Priestley-Taylor model than those of a closed Late Summer canopy.

Although there are few reported estimates of hourly sap flow for temperature hardwood species, three studies to date have reported values for Eastern hardwood forests including red maples. Sap flow monitoring in an Eastern upland oak forest in Tennessee in 1997 showed that understory red maples transpired a maximum daily depth of 2.2 mm/day (Wullschleger, Hanson et al. 2001).

Daily depth of water transpired by each of the four ecosystems frequently approached 3-mm per day. In zone 1, daily ET frequently surpassed 3-mm. Previous to this study, the reported depth of water transpired by a stand of red maples was 2.2-mm per day (Wullschleger, Wilson et al. 2000). The greater ET experienced in this study (if significant) is likely due to the shallow groundwater table and/or the presence of "edge effects". The maximum depth of water "lost" to ET in the upland oak forest occurred in mid-May before canopy closure and again in late June. The maximum depth of water lost to ET in this riparian wetland occurred mid-August and mid-October. This could be due to meteorological differences between the years of the studies.

Daily maximum sap flow rates frequently exceeded $30cm^3/cm^2$sapwood/hour. In comparison, red maples in an upland oak forest in eastern Tennessee experienced unprecedented high hourly sap flow rates approaching $30cm^3/cm^2$sapwood/hour (Wilson, Hanson et al. 2001). In the present study, of the 444 maximum sap flow rates recorded in 2002 (74 days, 6 trees each day, 1 maximum for each tree), 58 maximum flow rates were above $30cm^3/cm^2$sapwood/hour, and 11 out of those 58 were greater than $75cm^3/cm^2$sapwood/hour. In a different study of 12 red maples in TN, average daily sap flow depths ranged from 0.7 to 2.5mm/day (Wullschleger, Wilson et al. 2000). Depending on the scaling variable used, daily depth of sap flow for this study's riparian wetland ranged from 0.08 to 7.53mm/day with the average of all of the methods being 0.35 to 4.8mm/day throughout the zones. The overall average daily depth of sap flow in the TN forest was 1.5mm/day, while the riparian wetland in this study averaged 2.12mm/day. The dissimilarities between the red maples in this study and those in TN are likely due the monitored red maples in TN being located in the understory. Most of the daily maximum sap flow rates recorded in this study were for trees 4 and 6 (both edge trees with intermediate canopy positioning).

When comparing sap flow-derived daily ET estimates with Priestley-Taylor energy balance ET estimates, differences were apparent. Studies have shown that sap flow techniques provide lower ET daily and/or seasonal ET estimates than estimates based on water balances or energy balances (Dunn and Connor 1993; Kostner, Granier et al. 1998; Wullschleger, Meinzer et al. 1998). Discrepancies between methods have been attributed to: radial variation in sap flow, delayed coupling between the atmosphere and stomatal response, daily radiation/shadowing regimes, and/or lack of accounting for the presence of understory ET.

More studies of this nature are needed in order to understand the dynamics of each of these methods so that the most efficient and accurate scaling variable can be determined. Though few conclusions can be extrapolated to other ecosystems based on the current data, it would be interesting to discern if these scaling variables result in similar findings in other ecosystems.

### *6.3 Streamflow and Sap Flow Linkage Study Conclusions*

ET rates peaked between 11:00 and 12:00, except on days with very low evaporative conditions when peak times varied. Minimum streamflow rates normally occurred between 15:00 and 16:00. This 4-hour lag between peak sap flow rates and minimum streamflow rates could play a major role in determining stream nutrient fluxes.

Streamflow levels increased from upstream to downstream station, as groundwater flow accumulates as it progresses downstream. Therefore, Station 2 streamflow rates were the lowest of Stations 2, 3, and 4 streamflow (as it is located upstream in the wetland). Interestingly, Station 2 streamflow also experienced the least diurnal fluctuation due to ET. This could be attributed to a narrower (and thus smaller) forest influencing streamflow at this station.

Average streamflow losses were greatest under very high and high evaporative condition days on days with high streamflow. This was expected, as high ET rates would consequentially have a high impact on streamflow.

Maximum sap flow rates of Zone 2 were correlated with Station 2 streamflow losses when averaged for the 2002 growing season. This finding will allow Zone 2 maximum sap flow rates to be estimated using streamflow data and the relationship shown in Figure 36.

Results indicated that upstream riparian ET rates correlated with both downstream and upstream streamflow rates. Daily maximum sap flow rates for Zones 2 and 3 on days with very high evaporative conditions (when sap flow is perhaps most influential), were correlated to streamflow losses at their immediate *upstream* sampling stations. On days with medium and very low evaporative conditions, maximum ET rates for both zones were correlated with streamflow losses at their immediate downstream sampling stations. These results indicate that maximum sap flow rates are correlated with both upstream and downstream streamflow losses depending on environmental (both streamflow and evaporative) conditions.

# Appendix

## 1. SAS v. 8.2 Program: Analysis of Variance (and Unplanned Mean Comparison Tests) of Edge Treatment Effect Using Total Daily Sap Flow Volumes.

**When testing by year:**

```
proc sort data=x;
by year edgetreatment treerep;
run;
proc means data=x noprint;
var dailysapflowvolume;
output out=y mean= ;
by year edgetreatment treerep;
run;
Proc mixed data=y;
class edgetreatment;
model dailysapflowvolume=edgetreatment;
lsmeans edgetreatment/adjust=tukey;
by year;
run;
```

**When testing by year and evaporative condition group:**

```
proc sort data=x;
by year evapgroup edgetreatment treerep;
run;
proc means data=x noprint;
var dailysapflowvolume;
output out=y mean= ;
by year edgetreatment treerep;
run;
Proc mixed data=y;
class year evapgroup edgetreatment;
model dailysapflowvolume=edgetreatment;
lsmeans edgetreatment/adjust=tukey;
by year;
run;
```

**When testing by year, evaporative condition group, and season:**

```
proc sort data=x;
by year season evapgroup edgetreatment treerep;
run;
proc means data=x noprint;
var dailysapflowvolume;
output out=y mean= ;
by year season edgetreatment treerep;
run;
Proc mixed data=y;
class year season evapgroup edgetreatment;
model dailysapflowvolume=edgetreatment;
lsmeans edgetreatment/adjust=tukey;
by year;
run;
```

## 2. SAS v. 8.2 (Analyst Application): Correlation of Six ET Scaling Parameters. Tested by Zone, Meteorological Group.

**Correlated: DBH, Edge, Gap, Canopy, LC, CD, PT**
**Where: DBH** = ET estimates based on diameter at breast height scaling varia
**Edge** = ET estimates based on proximity to riparian edge scaling variable
**Gap** = ET estimates based on proximity to gap edge scaling variable
**LC** = ET estimates based on % live crown scaling variable
**CD** = ET estimates based on % crown density scaling variable
**PT** = ET estimates based on Priestley-Taylor equation
**By: EvapGroup, Zone**
**Where: EvapGroup** = evaporative condition group (very high, high, medium, or very low)
**Zone** = zone 1,2,3 or 4 of the wetland.

## 3. SAS v. 8.2 (Analyst Application): Correlations Between Daily Streamflow Losses and Daily Maximum Sap Flow Rates.

**Correlated: Zn2ET with St2Strm**
**Zn2ET with St3Strm**
**Zn3ET with St3Strm**
**Zn4ET with St4Strm**
**Where: Zn2ET =** maximum daily ET rate for wetland zone 2
**Zn3ET =** maximum daily ET rate for wetland zone 3
**St2Strm =** daily streamflow loss incurred at station 2
**St3Strm =** daily streamflow loss incurred at station 3
**St4Strm =** daily streamflow loss incurred at station 4

**By: EvapGroup, StrmGroup**

**Where: EvapGroup** = evaporative condition group (very high, high, medium, or very low)
**StrmGroup =** streamflow condition group (high, medium, or low).

## 4. SAS v. 8.2: Analysis of Variance for Ecosystem ET for Zones 2 and 3.

```
proc mixed data=AnovaData;
class evapgroup strmgroup;
model st3strm=evapgroup|strmgroup|zn2et;
run;
proc mixed data=AnovaData;
class evapgroup strmgroup;
model st3strm=evapgroup|strmgroup|zn3et;
run;
```

**Where: EvapGroup=** evaporative condition group
**StrmGroup** = nighttime streamflow condition group
**St3Strm** = daily streamflow losses at Station 3
**Zn3ET** = daily ecosystem ET estimate for Zone 2
**Zn2ET** = daily ecosystem ET estimate for Zone 3.

**Figure 37 Monitored red maple #1 (see Table 1 in Chapter 3).**

**Figure 38 Monitored red maple #2 (see Table 1 in Chapter 3).**

**Figure 39 Tree crown of monitored red maple #3 (see Table 1 in Chapter 3).**

**Figure 40 Tree crown of monitored red maple #4 (see Table 1 in Chapter 3).**


Figure 41 Tree crown of monitored red maple #5 (see Table 1 in Chapter 3).


Figure 42 Tree crown of monitored red maple #6 (see Table 1 in Chapter 3).

**Table 11 Early Summer meteorological descriptions for each day of year 2002 leading to evaporative condition groupings.**

| 2002 Early Summer Day of Year | Precip-itation | Solar Radiation | % Relative Humidity | Wind Speeds | Temp-erature | Evaporative Condition Group |
|---|---|---|---|---|---|---|
| 179 | - | - | - | - | - | Very Low |
| 195 | - | - | - | Med | - | Very Low |
| 169 | - | + | + | - | - | Average |
| 157 | - | + | Med | - | + | High |
| 170 | - | + | Med | - | Med | High |
| 178 | - | + | Med | Med | + | Very High |
| 191 | + | - | - | Med | - | Very Low |
| 188 | + | - | + | - | - | Very Low |
| 194 | + | - | + | Med | - | Very Low |
| 202 | + | - | Med | - | Med | Very Low |
| 172 | + | + | + | - | - | Average |
| 173 | + | + | + | - | - | Average |
| 175 | + | + | + | - | + | Average |
| 180 | + | + | + | - | + | High |
| 181 | + | + | + | Med | + | Very High |
| 184 | + | + | + | Med | + | Very High |
| 185 | + | + | + | Med | + | Very High |
| 186 | + | + | + | Med | + | Very High |
| 187 | + | + | + | Med | - | Average |
| 189 | + | + | + | Med | Med | Very High |
| 190 | + | + | + | + | + | Very High |
| 192 | + | + | + | + | - | Average |
| 193 | + | + | + | + | + | Very High |
| 197 | + | + | + | + | - | Average |
| 198 | + | + | + | + | Med | Very High |
| 155 | + | + | Med | - | - | High |
| 156 | + | + | Med | - | - | High |
| 161 | + | + | Med | - | + | High |
| 171 | + | + | Med | Med | - | High |
| 174 | + | + | Med | Med | + | Very High |
| 176 | + | + | Med | Med | - | High |
| 177 | + | + | Med | Med | + | Very High |
| 182 | + | + | Med | Med | + | Very High |
| 183 | + | + | Med | Med | Med | Very High |
| 196 | + | + | Med | Med | Med | Very High |
| 199 | + | + | Med | Med | Med | Very High |
| 200 | + | + | Med | + | + | Very High |
| 201 | + | + | Med | + | + | Very High |
| 203 | + | + | Med | + | + | Very High |

**Table 12 Mid-Summer and Late Summer meteorological descriptions for each day of year 2002 leading to evaporative condition groupings.**

| 2002 Mid-Summer Day of Year | Precip-itation | Solar Radiation | % Relative Humidity | Wind Speeds | Temp-erature | Evaporative Condition Group |
|---|---|---|---|---|---|---|
| 240 | - | - | - | - | + | Very Low |
| 244 | - | - | Med | + | + | Very Low |
| 235 | - | Med | Med | - | + | Average |
| 236 | - | Med | Med | Med | Med | Average |
| 243 | + | - | - | + | + | Very Low |
| 238 | + | - | Med | Med | + | Very Low |
| 229 | + | + | + | - | - | High |
| 230 | + | + | + | - | - | High |
| 231 | + | + | + | - | - | High |
| 232 | + | + | + | - | - | High |
| 233 | + | + | + | - | - | High |
| 234 | + | + | + | - | - | High |
| 237 | + | + | + | Med | Med | Very High |
| 246 | + | + | + | Med | Med | Very High |
| 247 | + | + | + | Med | Med | Very High |
| 248 | + | + | + | Med | Med | Very High |
| 249 | + | + | + | Med | Med | Very High |
| 250 | + | + | + | Med | Med | Very High |
| 251 | + | + | + | Med | + | Very High |
| 252 | + | + | + | Med | - | High |
| 253 | + | + | + | + | Med | Very High |
| 245 | + | + | Med | Med | + | Very High |
| 239 | + | Med | + | - | + | Average |
| 241 | + | Med | Med | Med | Med | Average |
| 242 | + | Med | Med | + | Med | Average |

| 2002 Late Summer Day of Year | Precipitation | Solar Radiation | % Relative Humidity | Wind Speeds | Temperature | Evaporative Condition Group |
|---|---|---|---|---|---|---|
| 289 | - | - | - | Med | Med | Very Low |
| 301 | - | - | - | Med | - | Very Low |
| 302 | - | - | - | + | Med | Average |
| 285 | + | - | - | - | + | Average |
| 286 | + | - | - | - | Med | Very Low |
| 288 | + | - | - | - | - | Very Low |
| 304 | + | - | - | + | - | Average |
| 300 | + | - | + | Med | Med | Average |
| 273 | + | + | + | - | + | Average |
| 274 | + | + | + | Med | + | Very High |
| 287 | + | + | + | Med | Med | Very High |

**Table 13 Meteorological descriptions for each day of year 2003 leading to evaporative condition groupings.**

| 2003 Day of Year | Time Period | Precipitation | Solar Radiation | % Relative Humidity | Wind Speeds | Temperature | Evaporative Condition Group |
|---|---|---|---|---|---|---|---|
| 152 | Early | - | - | - | - | - | Very Low |
| 153 | Early | - | - | - | - | - | Very Low |
| 154 | Early | - | - | Med | + | - | Very Low |
| 155 | Early | + | + | + | - | - | Very Low |
| 156 | Early | + | + | Med | Med | - | High |
| 187 | Early | + | + | Med | Med | + | High |
| 211 | Mid | + | - | - | - | Med | Very Low |
| 212 | Mid | + | - | - | - | Med | Very Low |

**Table 14 P-value results of Chapter 3 tests of edge effect based on mean daily sap flow volumes. Results are arranged by relevant test (left-hand column) and by: overall edge treatment effect (overall), Tukey's adjusted Edge vs. Intermediate effect, and Tukey's adjusted Edge vs. Stream effect.**

| **Yearly** | Overall | Edge vs. Intermediate | Edge vs. Stream |
|---|---|---|---|
| 2002 | 0.0805 | 0.0763 | 0.1775 |
| 2003 | 0.2242 | 0.3865 | 0.2165 |
| **Seasonal** | | | |
| Early Summer | 0.0568 | 0.0628 | 0.0881 |
| Mid-Summer | 0.2608 | 0.2445 | 0.4903 |
| Late Summer | 0.4075 | 0.3834 | 0.6868 |
| **Evaporation Group** | | | |
| Very High 2002 | 0.0997 | 0.0941 | 0.2171 |
| High 2002 | 0.0724 | 0.0741 | 0.1273 |
| Medium 2002 | 0.0769 | 0.0755 | 0.1501 |
| Very Low 2002 | 0.2255 | 0.2069 | 0.603 |
| High 2003 | 0.2201 | 0.4179 | 0.2075 |
| Very Low 2003 | 0.2307 | 0.3645 | 0.2291 |
| **Early Summer** | | | |
| Very High 2002 | 0.1391 | 0.1385 | 0.2402 |
| High 2002 | 0.0574 | 0.0623 | 0.092 |
| Medium 2002 | 0.0822 | 0.0858 | 0.1368 |
| Very Low 2002 | 0.211 | 0.2145 | 0.8952 |
| High 2003 | 0.2592 | 0.3688 | 0.2671 |
| Very Low 2003 | 0.2347 | 0.9917 | 0.2652 |
| **Mid-Summer** | | | |
| Very High 2002 | 0.1831 | 0.1668 | 0.4761 |
| High 2002 | 0.3431 | 0.3315 | 0.5319 |
| Medium 2002 | 0.363 | 0.6338 | 0.7753 |
| Very Low 2002 | 0.3797 | 0.3947 | 0.4869 |
| **Late Summer** | | | |
| Very High 2002 | 0.169 | 0.1764 | 0.9092 |
| Medium 2002 | 0.5266 | 0.5425 | 0.6269 |
| Very Low 2002 | 0.5069 | 0.4841 | 0.8642 |

**Table 15 P-value results of Chapter 3 tests of edge effect based on mean daily maximum sap flow rates. Results are arranged by relevant test (left-hand column) and by: overall edge treatment effect (overall), Tukey's adjusted Edge vs. Intermediate effect, and Tukey's adjusted Edge vs. Stream effect.**

| **Yearly** | *Overall* | *Edge vs. Intermediate* | *Edge vs. Stream* |
|---|---|---|---|
| 2002 | 0.0805 | 0.0763 | 0.1775 |
| 2003 | 0.2242 | 0.3865 | 0.2165 |
| **Seasonal** | | | |
| Early Summer | 0.0568 | 0.0628 | 0.0881 |
| Mid-Summer | 0.2608 | 0.2445 | 0.4903 |
| Late Summer | 0.4075 | 0.3834 | 0.6868 |
| **Evaporation Group (tested by season and evaporation condition group)** | | | |
| Very High 2002 | 0.0997 | 0.0941 | 0.2171 |
| High 2002 | 0.0724 | 0.0741 | 0.1273 |
| Medium 2002 | 0.0769 | 0.0755 | 0.1501 |
| Very Low 2002 | 0.2255 | 0.2069 | 0.603 |
| High 2003 | 0.2201 | 0.4179 | 0.2075 |
| Very Low 2003 | 0.2307 | 0.3645 | 0.2291 |
| **Early Summer (tested by season and evaporation condition group)** | | | |
| Very High 2002 | 0.1391 | 0.1385 | 0.2402 |
| High 2002 | 0.0574 | 0.0623 | 0.092 |
| Medium 2002 | 0.0822 | 0.0858 | 0.1368 |
| Very Low 2002 | 0.211 | 0.2145 | 0.8952 |
| High 2003 | 0.2592 | 0.3688 | 0.2671 |
| Very Low 2003 | 0.2347 | 0.9917 | 0.2652 |
| **Mid-Summer (tested by season and evaporation condition group)** | | | |
| Very High 2002 | 0.1831 | 0.1668 | 0.4761 |
| High 2002 | 0.3431 | 0.3315 | 0.5319 |
| Medium 2002 | 0.363 | 0.6338 | 0.7753 |
| Very Low 2002 | 0.3797 | 0.3947 | 0.4869 |
| **Late Summer (tested by season and evaporation condition group)** | | | |
| Very High 2002 | 0.169 | 0.1764 | 0.9092 |
| Medium 2002 | 0.5266 | 0.5425 | 0.6269 |
| Very Low 2002 | 0.5069 | 0.4841 | 0.8642 |

**Table 16 P-value results of Chapter 3 tests of edge effect based on mean daily sap flow volumes. Results are arranged by relevant test (left-hand column) and by: overall significance of edge treatment effect (overall), Tukey's adjusted Edge vs. Intermediate effect, and Tukey's adjusted Edge vs. Stream effect.**

| **Yearly** | *Overall* | *Edge vs. Intermediate* | *Edge vs. Stream* |
|---|---|---|---|
| 2002 | 0.082 | 0.074 | 0.247 |
| 2003 | 0.2316 | 0.3476 | 0.2351 |
| **Seasonal** | | | |
| Early Summer | 0.0653 | 0.0621 | 0.1458 |
| Mid-Summer | 0.2404 | 0.2248 | 0.4666 |
| Late Summer | 0.389 | 0.3879 | 0.5362 |
| **Evaporation Group** | | | |
| Very High 2002 | 0.089 | 0.0799 | 0.3053 |
| High 2002 | 0.07 | 0.0642 | 0.1872 |
| Medium 2002 | 0.0729 | 0.0679 | 0.1769 |
| Very Low 2002 | 0.2243 | 0.2062 | 0.5052 |
| High 2003 | 0.2482 | 0.3747 | 0.2497 |
| Very Low 2003 | 0.2128 | 0.3169 | 0.2187 |
| **Early Summer (tested by season and evaporation condition group)** | | | |
| Very High 2002 | 0.1767 | 0.1617 | 0.5766 |
| High 2002 | 0.0586 | 0.0609 | 0.102 |
| Medium 2002 | 0.0916 | 0.0847 | 0.2242 |
| Very Low 2002 | 0.2014 | 0.1937 | 0.781 |
| High 2003 | 0.2482 | 0.3747 | 0.2497 |
| Very Low 2003 | 0.2446 | 0.3372 | 0.2583 |
| **Mid-Summer (tested by season and evaporation condition group)** | | | |
| Very High 2002 | 0.1271 | 0.1212 | 0.2555 |
| High 2002 | 0.3429 | 0.3238 | 0.7982 |
| Medium 2002 | 0.2819 | 0.3275 | 0.9998 |
| Very Low 2002 | 0.3856 | 0.4016 | 0.4911 |
| **Late Summer (tested by season and evaporation condition group)** | | | |
| Very High 2002 | 0.0412 | 0.0427 | 0.0739 |
| Medium 2002 | 0.5173 | 0.545 | 0.5994 |
| Very Low 2002 | 0.4898 | 0.4643 | 0.7652 |

**Table 17 Zone 1 correlation coefficients for Early, Mid-, and Late Summer for the 7 ET estimation methods used in Chapter 5. Early Summer n=39, Mid-Summer n=19, Late Summer n=11. Where: *, **, ***, and **** denote significance at the .10, .01, .001, and .0001 probability levels, and where ns denotes not significant at the .10 probability level.**

| Early Summer | DBH | Proximity to Riparian Edge | Proximity to Gap Edge | Canopy Position | % Live Crown | % Crown Density | Priestley-Taylor |
|---|---|---|---|---|---|---|---|
| DBH | 1 | | | | | | |
| Edge | 0.98**** | 1 | | | | | |
| Gap | 0.98**** | 0.98**** | 1 | | | | |
| Canopy | 0.96**** | 0.98**** | 0.96**** | 1 | | | |
| LC | 0.99**** | 0.99**** | 0.99**** | 0.97**** | 1 | | |
| CD | 0.99**** | 0.99**** | 0.99**** | 0.98**** | 0.99**** | 1 | |
| PT | 0.59**** | 0.56*** | 0.59**** | 0.52*** | 0.59**** | 0.58*** | 1 |
| **Mid-Summer** | | | | | | | |
| DBH | 1 | | | | | | |
| Edge | 0.94**** | 1 | | | | | |
| Gap | 0.88**** | 0.84**** | 1 | | | | |
| Canopy | 0.87**** | 0.92**** | 0.79**** | 1 | | | |
| LC | 0.98**** | 0.97**** | 0.91**** | 0.9**** | 1 | | |
| CD | 0.48* | 0.38* | 0.66* | 0.24$^{ns}$ | 0.47* | 1 | |
| PT | 0.23$^{ns}$ | 0.41* | 0.14$^{ns}$ | 0.39* | 0.31$^{ns}$ | -0.3$^{ns}$ | 1 |
| **Late Summer** | | | | | | | |
| DBH | 1 | | | | | | |
| Edge | 0.97**** | 1 | | | | | |
| Gap | 0.98**** | 0.99**** | 1 | | | | |
| Canopy | 0.89*** | 0.96**** | 0.96**** | 1 | | | |
| LC | 0.99**** | 0.99**** | 0.99**** | 0.94**** | 1 | | |
| CD | 0.65* | 0.65* | 0.65* | 0.69* | 0.66* | 1 | |
| PT | 0.32$^{ns}$ | 0.3$^{ns}$ | 0.29$^{ns}$ | 0.25$^{ns}$ | 0.31$^{ns}$ | 0.42$^{ns}$ | 1 |

**Table 18 Zone 2 correlation coefficients for Early, Mid-, and Late Summer for the 7 ET estimation methods used in Chapter 5. Early Summer n=39, Mid-Summer n=19, Late Summer n=11. Where: *, **, ***, and **** denote significance at the .10, .01, .001, and .0001 probability levels, and where ns denotes not significant at the .10 probability level.**

| Early Summer | DBH | Proximity to Riparian Edge | Proximity to Gap Edge | Canopy Position | % Live Crown | % Crown Density | Priestley-Taylor |
|---|---|---|---|---|---|---|---|
| DBH | 1 | | | | | | |
| Edge | 0.99**** | 1 | | | | | |
| Gap | 0.97**** | 0.94**** | 1 | | | | |
| Canopy | 0.97**** | 0.97**** | 0.93**** | 1 | | | |
| LC | 0.99**** | 0.99**** | 0.96**** | 0.98**** | 1 | | |
| CD | 0.99**** | 0.99**** | 0.96**** | 0.97**** | 0.99**** | 1 | |
| PT | 0.59**** | 0.59**** | 0.57*** | 0.53*** | 0.59**** | 0.59**** | 1 |

| Mid-Summer | | | | | | | |
|---|---|---|---|---|---|---|---|
| DBH | 1 | | | | | | |
| Edge | 0.98**** | 1 | | | | | |
| Gap | 0.99**** | 0.99**** | 1 | | | | |
| Canopy | 0.84**** | 0.87**** | 0.86**** | 1 | | | |
| LC | 0.98**** | 0.98**** | 0.97**** | 0.85**** | 1 | | |
| CD | $0.36^{ns}$ | $0.38^{ns}$ | 0.41* | 0.63* | $0.3^{ns}$ | 1 | |
| PT | $0.2^{ns}$ | $0.21^{ns}$ | $0.16^{ns}$ | $0.21^{ns}$ | $0.31^{ns}$ | $-0.27^{ns}$ | 1 |

| Late Summer | | | | | | | |
|---|---|---|---|---|---|---|---|
| DBH | 1 | | | | | | |
| Edge | 0.99**** | 1 | | | | | |
| Gap | 0.99**** | 0.99**** | 1 | | | | |
| Canopy | 0.96**** | 0.97**** | 0.94**** | 1 | | | |
| LC | 0.99**** | 0.99**** | 0.97**** | 0.98**** | 1 | | |
| CD | 0.66* | 0.69* | 0.65* | 0.7* | 0.69* | 1 | |
| PT | $0.3^{ns}$ | $0.35^{ns}$ | $0.38^{ns}$ | $0.41^{ns}$ | $0.36^{ns}$ | $0.11^{ns}$ | 1 |

**Table 19 Zone 3 correlation coefficients for Early, Mid-, and Late Summer for the 7 ET estimation methods used in Chapter 5. Early Summer n=39, Mid-Summer n=19, Late Summer n=11. Where: *, **, ***, and **** denote significance at the .10, .01, .001, and .0001 probability levels, and where ns denotes not significant at the .10 probability level.**

| Early Summer | DBH | Proximity to Riparian Edge | Proximity to Gap Edge | Canopy Position | % Live Crown | % Crown Density | Priestley-Taylor |
|---|---|---|---|---|---|---|---|
| DBH | 1 | | | | | | |
| Edge | 0.99**** | 1 | | | | | |
| Gap | 0.96**** | 0.98**** | 1 | | | | |
| Canopy | 0.95**** | 0.96**** | 0.93**** | 1 | | | |
| LC | 0.99**** | 0.99**** | 0.96**** | 0.99**** | 1 | | |
| CD | 0.99**** | 0.99**** | 0.97**** | 0.93**** | 0.98**** | 1 | |
| PT | 0.59**** | 0.59**** | 0.58*** | 0.51*** | 0.56*** | 0.61**** | 1 |
| **Mid-Summer** | | | | | | | |
| DBH | 1 | | | | | | |
| Edge | 0.98**** | 1 | | | | | |
| Gap | 0.96**** | 0.91**** | 1 | | | | |
| Canopy | 0.92**** | 0.88**** | 0.89**** | 1 | | | |
| LC | 0.99**** | 0.96**** | 0.96**** | 0.94**** | 1 | | |
| CD | $0.38^{ns}$ | $0.25^{ns}$ | 0.56* | $0.49^{ns}$ | 0.42* | 1 | |
| PT | $0.33^{ns}$ | 0.41* | $0.16^{ns}$ | $0.32^{ns}$ | $0.33^{ns}$ | -0.42* | 1 |
| **Late Summer** | | | | | | | |
| DBH | 1 | | | | | | |
| Edge | 0.99**** | 1 | | | | | |
| Gap | 0.97**** | 0.98**** | 1 | | | | |
| Canopy | 0.98**** | 0.97**** | 0.92**** | 1 | | | |
| LC | 0.99**** | 0.99**** | 0.97**** | 0.99**** | 1 | | |
| CD | 0.68* | 0.71* | 0.68* | 0.7* | 0.71* | 1 | |
| PT | $0.28^{ns}$ | $0.3^{ns}$ | $0.31^{ns}$ | $0.29^{ns}$ | $0.3^{ns}$ | $0.52^{ns}$ | 1 |

**Table 20 Zone 4 correlation coefficients for Early, Mid-, and Late Summer for the 7 ET estimation methods used in Chapter 5. Early Summer n=39, Mid-Summer n=19, Late Summer n=11. Where: *, **, ***, and **** denote significance at the .10, .01, .001, and .0001 probability levels, and where ns denotes not significant at the .10 probability level.**

| Early Summer | DBH | Proximity to Riparian Edge | Proximity to Gap Edge | Canopy Position | % Live Crown | % Crown Density | Priestley-Taylor |
|---|---|---|---|---|---|---|---|
| DBH | 1 | | | | | | |
| Edge | 0.83**** | 1 | | | | | |
| Gap | 0.98**** | 0.8**** | 1 | | | | |
| Canopy | 0.98**** | 0.85**** | 0.98**** | 1 | | | |
| LC | 0.99**** | 0.85**** | 0.99**** | 0.99**** | 1 | | |
| CD | 0.99**** | 0.85**** | 0.99**** | 0.99**** | 0.99**** | 1 | |
| PT | 0.6**** | 0.44** | 0.59**** | 0.55*** | 0.58*** | 0.57*** | 1 |

| Mid-Summer | | | | | | | |
|---|---|---|---|---|---|---|---|
| DBH | 1 | | | | | | |
| Edge | 0.68** | 1 | | | | | |
| Gap | 0.94**** | 0.83**** | 1 | | | | |
| Canopy | 0.88**** | 0.67* | 0.92**** | 1 | | | |
| LC | 0.96**** | 0.84**** | 0.99**** | 0.9**** | 1 | | |
| CD | $0.38^{ns}$ | $0.09^{ns}$ | 0.44* | 0.58** | $0.36^{ns}$ | 1 | |
| PT | $0.19^{ns}$ | 0.56* | $0.28^{ns}$ | $0.17^{ns}$ | $0.32^{ns}$ | $-0.33^{ns}$ | 1 |

| Late Summer | | | | | | | |
|---|---|---|---|---|---|---|---|
| DBH | 1 | | | | | | |
| Edge | 0.88*** | 1 | | | | | |
| Gap | 0.97**** | 0.97**** | 1 | | | | |
| Canopy | 0.94**** | 0.98**** | 0.99**** | 1 | | | |
| LC | 0.98**** | 0.95**** | 0.99**** | 0.99**** | 1 | | |
| CD | 0.7* | 0.67* | 0.7* | 0.71* | 0.72* | 1 | |
| PT | $0.31^{ns}$ | $0.26^{ns}$ | $0.28^{ns}$ | $0.3^{ns}$ | $0.31^{ns}$ | $0.51^{ns}$ | 1 |

# Bibliography


Alliance for the Chesapeake Bay, C. B. P. (1996). Riparian forest buffers. White Papers. A. R. S. USDA.

Angier, J. T., G. W. McCarty, et al. (2001). "Impact of first-order riparian zone on nitrogen removal and export from an agricultural ecosystem." The Scientific World **1 (S2)**: 642--651.

Arneth, A., F. Kelliher, et al. (1996). "Environmental regulation of xylem sap flow and total conductance of Larix gmelinii trees in eastern Siberia." Tree Physiology **16**: 247-255.

Bowie, J. and W. Kam (1968). Use of water by riparian vegetation; Cottonwood Wash, AZ. Geological Survey Water Supply Papers. U. G. Survey.

Burns, R. M. and B. H. Honkala (1990). Silvics of North America: 1. Conifers; 2. Hardwoods. Agriculture Handbook 654. F. S. U.S. Department of Agriculture, Government Printing Office, Washington DC. **2:** 877.

Cermak, J., E. Cienciala, et al. (1995). "Individual variation of sap-flow rate in large pine and spruce trees and stand transpiration: a pilot study at the central NOPEX site." Journal of Hydrology **168**: 17-27.

Cermak, J. and J. Kucera (1990). "Scaling up transpiration data between trees, stands, and watersheds." Silva Carelica **15**: 101-120.

Cermak, J. and N. Nadezhdina (1998). "Sapwood as the scaling parameter- defining according to xylem water content or radial pattern of sap flow." Annals of Scientific Forestry **55**: 509 --521.

Clearwater, M. J., F. C. Meinzer, et al. (1999). "Potential errors in measurement of nonuniform sap flow using heat dissipation probes." Tree Physiology **19**: 681-687.

Drexler, J., R. Snyder, et al. (2004). "A review of models and micrometerological methods used to estimate wetland evapotranspiration." Hydrological Processes **18**: 2071-2101.

Dunn, G. M. and D. J. Connor (1993). "An analysis of sap flow in mountain ash ({E}ucalyptus regnans) forests of different age." Tree Physiology **13**: 321--336.

Dunne, T. and L. Leopold (1978). Water in environmental planning. San Francisco, CA, W. H. Freeman and Company.

Dynamax, I. (1997). A thermal dissipation sap velocity probe for measurement of sap flow in plants. Houston, TX, Dynamax, Inc.**:** 24.

Eichinger, W., M. Parlange, et al. (1996). "On the concept of equilibrium evaporation and the value of the Priestley-Taylor coefficient." Water Resources Research **32**: 161 --164.

EPA (1994). Tree coring and interpretation. E. R. Team, Environmental Protection Agency**:** 6.

Giambelluca, T., A. Ziegler, et al. (2003). "Transpiration in a small tropical forest patch." Agricultural and Forest Meteorology **117**: 1-22.

Granier (1990). "Vapour flux density and transpiration rate comparisons in a stand of Maritime pine (Pinus pinaster) in Les Landes forest." Agricultural and Forest Meteorology **51**: 309--319.

Granier, A. (1987). "Evaluation of transpiration in a Douglas-fir stand by means of sap flow measurements." Tree Physiology **3**: 309--320.
Granier, A., P. Biron, et al. (1996). "Transpiration of trees and forest stands: short and long-term monitoring using sapflow methods." Global Change Biology **2**: 265--274.
Hatton, T. J., S. J. Moore, et al. (1995a). "Estimating stand transpiration in a Eucalyptus populnea woodland with the heat pulse method: measurement errors and sampling strategies." Tree Physiology **15**: 219--227.
Hatton, T. J. and H. Wu (1995b). "Scaling theory to extrapolate individual tree water use to stand water use." Hydrological Processes **9**: 527--540.
Herbert, R. (2003). Personal communication., USDA Beltsville Agricultural Research Center.
Hipps, L., D. Cooper, et al. (1998). A summary of processes which are connected to evaporation of riparian and heterogeneous upland vegetation in arid regions. American Meteorological Society, Special Symposium on Hydrology, Phoenix, AZ.
Kostner, B., A. Granier, et al. (1998). "Sapflow measurements in forest stands: methods and uncertainties." Annals of Scientific Foresters **55**: 13-27.
Kustas, W., D. Stannard, et al. (1996). "Variability in surface energy flux partitioning during Washita '92: resulting effects on Penman-Monteith and Priestley-Taylor parameters." Agricultural and Forest Meteorology **82**: 171--193.
Lowrance, R., G. Vellidis, et al. (1997). "Herbicide transport in a managed riparian forest buffer system." Transactions of the ASAE **40**(4): 1047-1057.
Mitsch, W. J. and J. G. Gosselink (2000). Wetlands. New York, New York, John Wiley & Sons, Inc.
O'Brien, J., S. Oberbauer, et al. (2004). "Whole tree xylem sap flow responses to multiple environmental variables in a wet tropical forest." Plant, Cell, and Environment **27**: 551-567.
Oren, R. (1998). "Scaling xylem sap flux and soil water balance and calculating variance: a method for partitioning water flux in forests." Annals of Scientific Forestry **55**: 191--216.
Oren, R. and D. Pataki (2001). "Transpiration in response to variation in microclimate and soil moisture in southeastern deciduous forests." Oecologia **127**: 549--559.
Palone, R. and A. Todd (1998). Chesapeake Bay riparian handbook: A guide for establishing and maintaining riparian forest buffers, US Department of Agriculture Forest Service, Northeastern Area**:** 40 p.
Peterjohn, W. and D. Correll (1984). "Nutrient dynamics in an agricultural watershed: Observations on the role of a riparian forest." Ecology **65**: 1466-1475.
Phillips, N., R. Oren, et al. (1996). "Radial patterns of xylem flow in non-, diffuse- and ring-porous tree species." Plant, Cell and Environment **19**: 983--990.
Priestley, C. H. B. and R. J. Taylor (1972). "On the assessment of surface heat flux and evaporation using large-scale parameters." Monthly Weather Review **100**: 81--92.
SAS (2005). SAS v. 8.2. Cary, North Carolina, SAS Institute.
Shuttleworth, W. J. (1993). Handbook of Hydrology. New York, McGraw Hill.

Simpson, D. (2003). Personal communication.
Souch, C., C. Wolfe, et al. (1996). "Wetland evaporation and energy partitioning: Indiana Dunes National Lakeshore." Journal of Hydrology **184**: 189--208.
Stannard, D. (1993). "Comparison of Penman-Monteith, Shuttleworth-Wallace, and modified Priestley-Taylor evapotranspiration models for wildland vegetation in semiarid rangeland." Water Resources Research **29**: 1379--1392.
Wilson, K., P. Hanson, et al. (2001). "A comparison of methods for determining forest evapotranspiration and its components: sap-flow, soil water budget, eddy covariance and catchment water balance." Agricultural and Forest Meteorology **106**: 153-168.
Wullschleger, S., P. Hanson, et al. (2001). "Transpiration from a multi-species deciduous forest as estimated by xylem sap flow techniques." Forest Ecology and Management **143**: 205--213.
Wullschleger, S., F. Meinzer, et al. (1998). "A review of whole-plant water use studies in trees." Tree Physiology **18**: 499--512.
Wullschleger, S., K. Wilson, et al. (2000). "Environmental control of whole-plant transpiration, canopy conductance and estimates of the decoupling coefficient for large red maple trees." Agricultural and Forest Meteorology **104**: 157--168.
Zhang, L. and W. Mitsch (2004). "Modelling hydrological processes in created freshwater wetlands: an integrated system approach." Environmental Modelling and Software.