WATER USE OF LANDSCAPE TREES DURING POT-IN-POT PRODUCTION AND DURING ESTABLISHMENT IN THE LANDSCAPE

by

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ABSTRACT

Water conservation and pollution concerns from nutrient runoff will very likely dictate precise irrigation regimes for nursery managers in Virginia. Maximum plant growth with minimum input of water and fertilizer is becoming increasingly important. Therefore, water use and growth of red and sugar maple (*Acer rubrum* L. 'Franksred' and *Acer saccharum* Marsh.) were studied during two years of pot-in-pot (P+P) production and during three years after transplanting to field soil. Three major experiments were completed. The first experiment studied the effect of frequent irrigation (three-times-a-day) versus standard once-a-day irrigation and found that frequent irrigation increased trunk diameter growth of sugar maples in the second production cycle and for red maples in both production cycles. Height growth of neither species was affected by frequent irrigation. A study of sap flow pattern indicated that late day water stress of red maples was partially alleviated by frequent irrigation. In the second experiment, red and sugar maples were transplanted to field soil after one (1-yr) or two (2-yr) years of P+P production. Irrigation frequency requirement decreased as the trees grew and depended on environmental conditions, size at planting, source of water (rainfall versus irrigation) and species. Height and trunk diameter of 1-yr red maple was equal to that of 2-yr trees after only one year. Height and trunk diameter differences between 1-yr and 2-yr sugar maple trees persisted three years after transplanting. In the third experiment water use of 1-yr and 2-yr red and sugar maple while in P+P production was investigated. Four models of daily water-use were developed. A simple model that is suitable for growers includes species, trunk cross-sectional area (BA) and air temperature (TA) observations. An environmental model was developed using the Penman-van Bavel estimate of evapotranspiration (ET). ET required modifications based on tree characteristics, air temperature, windspeed and relative humidity to be an effective predictor of water-use. A complex model was based on a sine-cosine function of day-of-the-year. This model fits water-use data well for each species and production cycle and includes BA, ET and TA. An alternate simpler model requires only day-of-the-year, TA and BA, offering growers a relatively simple and accurate model of water use.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The purpose of this dissertation was to describe water use and growth patterns of red and sugar maples during 2 production cycles in pot-in-pot production (P+P) and through 3 years of field growth as they related to water use. Pot-in-pot production closely resembles above-ground container production, with essentially the same substrate, containers and plant material, except that the growing container itself is largely below the soil surface in P+P production. P+P production utilizes a permanent “socket pot” which remains in the ground while production containers are removed and replaced as needed.

Water use information is important because of increasing pressures to manage irrigation and fertilizer efficiently. Improper management leads to excessive water use, increased pollution and an unfavorable public image. To better manage water application, a more complete and precise understanding of plant water use is needed. Three major experiments were completed along with several supporting studies to gain knowledge about water use by using gravimetric methods, thermal balance sap flow gauges, porometer measurements, electrical conductivity blocks, and environmental models.

The objective of the first experiment was to determine the effect of irrigation frequency on the growth of red and sugar maple during the first (1-yr) and second (2-yr) P+P production years. Furthermore we wanted to determine if fast growing trees could reach merchantable size in only one season in the climate of western Virginia (USDA climate zone 6a).

The second study investigated the growth and irrigation requirement of 1-yr and 2-yr red and sugar maples planted to the field. The objectives were to determine 1) irrigation frequency required to maintain backfill soil at relatively high moisture availability, and 2) growth differences between 1-yr and 2-yr trees.

The third study modeled water use during P+P production, with the objectives of 1) to determine which environmental and descriptive variables most influence water use, 2) to reveal how these variables interact to determine water use in P+P production, 3) to develop a pragmatic irrigation scheduling model to be used by growers, and 4) to develop a more complete model which describes theoretical interrelationships that will be beneficial for further study.

Together these three studies provide a much more complete picture of water use during P+P production and after transplanting to the landscape.

CHAPTER ONE

LITERATURE REVIEW OF THE WATER USE OF CONTAINERIZED WOODY PLANTS

Introduction and History of Water Use Studies

The importance of water to the growth of plants has long been appreciated, as the presence of ancient irrigation systems worldwide indicates. Although ancient populations did not understand the true nature of water use within plants, they did know that an adequate supply of water during certain periods was crucial to plant growth and crop production (Gulhati and Smith, 1967; Kramer and Boyer, 1995).

Many have studied plants in an effort to understand how water is used and how much is required for plants to be productive. Aristotle believed that plants had a soul, or spirit, which enabled them to absorb only those materials necessary for growth from the soil, an idea that persisted until the 1800s. This theory was supported by observations that fertilized, or "fed" plants grew larger than unfertilized ones. As one of the presumed four basic elements (earth, air, fire and water), water was thought to function as the medium of transport in plants in much the same manner as it could be observed to function in animals (Campbell, 1990; Glass, 1999; Kramer and Boyer, 1995; Moore and Clark, 1995).

In 1648, Jan-Baptista van Helmont presented the first real challenge to the Aristotlean theory. In a famous experiment, he grew a young willow tree in a covered pot for four years, adding only rainwater. At the end of the experiment, he found that the tree had gained 164 lb. while the soil in the pot had lost only two ozs. Van Helmont concluded that the plant gained mass by the consumption of water alone, dismissing the weight of soil lost as measurement error (Moore and Clark, 1995). Although future experiments would show that plant mass did not arise from water alone as van Helmont concluded, he did show that water and was used in much greater quantities than the soil in which the plants grew (Kramer and Boyer, 1995; Moore and Clark, 1995).

In the 1670s, Ray and Willowby conducted experiments, sponsored by the Royal Society of London, to determine if sap circulated in plants as blood does in animals. The experiments showed that sap could flow in either direction in plants, but they could not identify a true circulatory system (Kramer and Boyer, 1995).

The next significant advance in understanding of water use stemmed from two detailed anatomical studies. Marcello Malpighi published *Anatome Plantarum* in 1675, which was soon followed by Nehemiah Grew's *The Anatomy of Plants* in 1682. Both are given credit for observations indicating that sap flowed first to leaves, where it underwent a change making it more nutritious, then moved to fruits or roots (Kramer and Boyer, 1995).

The highly quantitative work of Steven Hales greatly advanced scientific understanding of water use in plants. Much of his pioneering work with plants was published in *Vegetable Staticks* (Hales, 1727). Although Hales was probably not the first to notice that water was released as a vapor from the leaves of plants, he did understand the importance of this process. He developed various methods to measure transpiration (then called perspiration), water uptake and internal sap pressure. His meticulous measurements showed that transpiration varies with species, temperature, amount of sunlight and time of day (Hales, 1727 reprinted 1969).

Hales also made two observations that are important to understanding the forces involved in sap movement. First, he observed that sap sometimes exuded from severed stems, notably from grapevines and some trees (now known as root pressure). He noted that this phenomenon was most common in the spring, before or just as the leaves were emerging. Secondly, he observed that after leaves had emerged, the severed plant tops were capable of taking up water through the cut stem. Although he could not explain how sap was caused to move through the stem, he did recognize that two separate forces were at work. He speculated that leaves somehow acted to attract the sap and once in the leaves, the sap received a nutritional enhancement due to the action of sunlight (Hales, 1727 reprinted 1969).

Not until scientists had a clear understanding of photosynthesis could the connection between water use and photosynthesis be explained. The two processes are intimately linked by the need to acquire carbon dioxide (CO_2). Most transpiration occurs when the stomates are open to acquire CO_2. The importance of gas exchange was soon realized after methods of analyzing gasses were developed in the mid 1800s. Measuring gas exchange remains a common method of estimating water use.

The history of modeling plant water use can be traced back to Fick (1855), who mathematically explained diffusion (Nobel, 1991 pp. 10-12). Since this time, many researchers have attempted to explain water use and transpiration with increasingly complex models, based entirely on the physical and biological properties of the known components (Kramer and Boyer, 1995).

Water use is largely controlled by photosynthetic rate and water availability, although it is somewhat influenced by nutrient concentrations or by lack of a particular nutrient. Short term water use patterns may be influenced by numerous environmental factors as well as plant capacitance and transport capabilities (Kramer and Boyer, 1995; Nielsen and Orcutt, 1997)

Contemporary methods used to study whole-plant water use

Gravimetric

The gravimetric method simply measures changes in the weight of a containerized plant-soil system over time. Over a short time period the changes in weight are almost entirely attributable to water flux (Kramer and Boyer, 1995). Some benefits of this method are its accuracy, adaptability to a wide range of situations and limited disturbance of natural conditions. However, measurements may be very difficult to make correctly unless plants are protected from wind. In addition a plant growing in a container is in a much different environment than a plant growing in the soil. The plant in the container may be subject to altered patterns of soil water flow, aeration, rate of moisture depletion, and altered temperature regimes (Edwards, 1986; Fritschen et al., 1973; van Bavel, 1961).

Automatic weighing lysimeters

Automatic lysimeters are scales on which a containerized tree may be grown. The scale is connected to an output device that continually records weight. They can be very sensitive to small changes in plant water content and its surrounding soil, but they are both difficult and expensive to install and operate. Lysimeters can accommodate a wide variety of crops and can encompass relatively large soil volumes.

The principal advantages of automatic lysimeters are precision and accuracy, but they also provide an opportunity to study leachate. The measure of leachate volume may be useful for watershed determinations of surface water lost to lateral underground flow or aquifer recharge.

The primary disadvantages of automatic lysimeters are cost and difficulty of installation. There are also some concerns about relevance, most of which originate from changing the plant's natural environment. Other concerns are specific to the measurement device. Most of these concerns can be minimized with a few small precautionary steps during installation. Often the weighing apparatus is very sensitive to changes in temperature, and it becomes necessary to develop an equation or mechanism to correct for temperature differences. The temperature of the soil in a lysimeter can change very quickly if the lysimeter container is constructed of uninsulated metal, but the problem can be lessened by using plastic containers or by insulating the inside of the container and shading the container rim. Accurate measurements may be very difficult to make if the plant is not protected from wind. Finally, it is important to make sure that the surrounding area is large enough for the plant to experience the natural environmental conditions.

When working with lysimeters, it is very important to understand how environmental conditions impact the measurements. Although this method easily measures the amount of intercepted precipitation, evaporation of free water (dew and intercepted precipitation) from plant surfaces can be difficult to interpret. This is because without corroborating information, the source of lost water can not be identified as coming directly from the plant, or to be free water on external plant surfaces or soil. In addition, root mass may occupy a limited volume of the substrate, making partitioning of water loss difficult (Edwards, 1986; Fritschen et al., 1973; van Bavel and Myers, 1962).

A very large lysimeter was constructed around a 28 m tall Douglas-fir [*Pseudotsuga menzezii* (Mirb.) Franco.] by Fritschen et al. (1973). This lysimeter supported 28,900 kg, and could detect weight changes as little as 630 g. In this case, the lysimeter was constructed around a tree in its natural environment. In most other situations, plants are planted into existing lysimeter containers, which may be permanently or temporarily placed on the weighing mechanism. Growing a plant in a container or constructing a container around a plant inherently changes the root environment and may affect the measurements (Edwards, 1986; Fitzpatric, 1980; Knox, 1989; van Bavel, 1961).

Manual weighing lysimetry

The periodic reweighing method is much the same as the weighing lysimeter, but instead of constructing a scale around a plant or landscape, the plant is grown in a container at the desired location and periodically brought to an existing scale to be weighed. This method is essentially the same today as it was in the 1700s when Steven Hales used it to study water use (Kramer and Boyer, 1995). The method provides water-use data over the desired period of time instead of a continuous record. The reweighing method is not suitable for very large plants, but is a very effective method for use with a large number of small plants (Burger et al., 1987; Stanley and Harbaugh, 1992).

Gas Exchange

Gas exchange methods involve enclosing plants inside an airtight container and monitoring the difference in humidity between the incoming and outflowing air. Containers are usually composed of clear plastic to allow near natural light levels. Container size can vary from large plastic tents enclosing several trees to small cuvettes, which enclose only part of a leaf.

These methods have the advantage of being able to measure both water vapor and carbon dioxide content of air. This allows for estimating exchange rates and water use efficiency. One major criticism of this method is that using these clear containers modifies the environment in which the measurements are taken. Wind speed, temperature, humidity and carbon dioxide content are altered in these containers. This problem can be alleviated through the use of equipment designed to keep the internal environment similar to the external, or by carefully describing the internal environment.

Whole tree enclosures or ventilated chambers

Large chambers offer a method to investigate water use and carbon assimilation in a non-intrusive manner, but they may alter natural vapor pressure deficit, temperature, solar radiation patterns and windspeed. These chambers allow for detecting changes in water use over relatively short periods of time. Instruments can also be run continuously, providing a record of changes over time (Greenwood and Beresford, 1979)

Sampling methods

Porometers can provide good estimates of instantaneous stomatal conductance and resistance. Because porometers are typically attached to leaves for only 20 to 30 seconds, the environmental changes due to the cuvette are minor. The main problems with porometers are the small sample size and the instantaneous nature of the measurements. The cuvettes can not be used continuously, nor can the same leaf be measured repeatedly without large errors. However, porometers are very useful for comparing species and environmental differences. Stomatal conductance is very sensitive to small differences in environmental variables and even varies within regions of a single leaf. This variation means that numerous samples must be taken to get a realistic mean. Maintenance of a consistent sampling protocol is also critical. Such a protocol should specify leaf orientation, a relative measurement position on the leaf, position in canopy, leaf age, and exposure to sun and wind. For transpiration estimates, an accurate measure of leaf surface area is needed. This estimate can then be used to scale-up to the whole plant level. Accurate measurement of leaf surface area is usually accomplished using destructive methods. The need for destructive sampling of the leaves and the high amount of labor involved in taking measurements are the prime reasons this method is not common for long term studies.

Measures of stomatal resistance (r_s) are commonly used as components in complex environmental models such as those proposed by Monteith (1963), Brown and Rosenberg (1973) and Verma and Rosenberg (1977). A branch often serves to represent the entire canopy. This method offers a compromise between the other two methods discussed above by greatly reducing the cost of large ventilated chambers while providing a larger sample size than the porometer. However, estimates must still be scaled-up to the whole tree level, and the altered microenvironment may cause a bias in the results.

Cut-shoot or cut-tree

In this method individual branches or entire stems are cut from the plant. The cut piece is then weighed, and water use is calculated as the amount of weight lost (rapid weighing). Branches may also be placed in a reservoir of water, with water use being the amount of water removed from the reservoir (potometer).

Rapid weighing

The rapid weighing method was once commonly used because it could be easily carried out in the field, but the measurements require destructive sampling and are only accurate for a short period after cutting. Data may also be misleading because of the Iwanoff effect. The Iwanoff effect is an opening of the stomates and a corresponding increase in transpiration because of an initial release of tension when the part is severed from the plant. Even after the first few minutes the transpiration may not be representative because the detached portion is no longer in competition for water with the rest of the plant (Franco and Magalhaes 1965).

Potometer

The potometer method can be used with relatively large trees, up to 30 cm in trunk diameter (Knight et al., 1981). This method has the advantage of using the entire plant shoot to estimate transpiration in its natural environment, and is also relatively simple and inexpensive. There can be a significant and misleading uptake of water in the initial 30 to 50 hours after cutting, and a corresponding change in internal water potential (ψ) (Knight et al., 1981). The increased water availability will cause water use estimates to be inflated, as it has been commonly observed that transpiration varies with internal water potential. Increasing water availability influences internal storage and stem diameter and its impact depends on species and environmental conditions (Roberts, 1977).

Tracer elements

Radioactive elements tritium and phosphorous-32 have been used to estimate transpiration of whole trees, but the use of these elements is uncommon due to increasing governmental regulation. An alternative to using radioactive elements is to use deuterium or other stable isotopes. The tracer technique involves the injection of a known amount of a detectable tracer element into the trunk of a tree. The tracer is then carried in the xylem to the crown. Cut tissues or transpired water vapor can be sampled. If leaves are sampled, they will often give a fairly good estimate of instantaneous transpiration, although estimates may be somewhat erratic due to leaf position and exposure. Transpired water vapor is collected by placing a plastic bag over an individual branch. Using the plastic bag can integrate water use estimates over an entire day, and the same leaves can be used from day to day, increasing uniformity of sampling. However, if the same leaves are used, they may become acclimated to the microenvironment within the plastic bag changing the transpiration rate (Calder et al., 1986; Dugas et al., 1993; Kline et al., 1970; Waring and Roberts, 1979).

The tracer technique has two major sources of error. The first is the assumption of complete mixing of the tracer into the sap of the tree. To ensure adequate mixing, several holes are drilled into the trunk. The tracer is then inserted into the holes and the holes are sealed. This type of error can be estimated by taking numerous observations at different parts of the canopy (Dye et al., 1992; Kline et al. 1970). Another source of error is estimating the time when tracer concentration returns to pre-injection levels. The tracer technique assumes that all of the tracer material moves entirely through the system during the time of the experiment. In reality it is possible for the tracer to move down the stem, slowing as it moves out of the injured area of the injection holes; or, it may become bound with the cellular water along the way. Another assumption of the tracer method is that the tracer moves through the system in the same manner as the material studied. Some level of biological selectivity has been noted for some tracer elements, but the effect is minor.

Thermal sap flow gauges

Thermal methods of sap flow measurement are similar to radioactive tracers, but heat replaces the tracer. Two fundamentally different techniques may be used. The heat pulse velocity (HPV) technique creates and monitors a volume of sap as it moves up the stem, similar to the way a radioactive pulse may be followed up the stem. The thermal heat balance (THB) technique applies a known amount of tracer (heat) continuously to a stem. Eventually a near steady-state condition is achieved. When properly calibrated, the system can calculate the amount of heat, and thus the amount of sap, which is flowing up the stem, from small changes in temperature.

Either technique for sapflow calculation can be used in numerous configurations of heaters and thermocouple sensors, but there are two primary configurations. The external configuration utilizes heaters and sensors applied to the surface of the stem. This configuration is best for small stems. The internal configuration implants both heaters and sensors into the sapwood. With the proper calibrations, this method can provide acceptable measurements of flow in relatively large stems. With this configuration, the entire stem may not need to be surrounded. Some hybrid configurations exist in which only some of the components are implanted in the tree.

When using either technique, constant and regular conditions must be ensured. Some key procedures are to select stem sections that are free of knots, branches and wounds, and to prevent solar heating of the stem. Insulating and covering the stem with reflective material can minimize solar heating.

Heat pulse velocity

The HPV technique was first developed to measure sap flow in a manner similar to following radioactive tracers up the stem; however, heat can move out of the stem by conduction. Conduction can be estimated by using an additional thermocouple below the heater.

The HPV technique estimates mean flow for the time it takes to make a reading. This technique requires less sophisticated and expensive equipment than the THB technique and consumes less power. The HPV technique requires careful calibration for the type of conducting sapwood (ring porous, diffuse porous or coniferous). Understanding flow patterns and measuring flow capacity is also important, particularly for large irregular stems. Implantation of heaters and sensors may also alter the natural flow patterns and lead to erroneous results (Smith and Allen, 1996; Swanson, 1994).

Thermal heat balance

The THB technique applies a known amount of heat to a stem that must escape in some direction. This technique is similar to the HPV in the ways that the thermocouples and heater(s) may be arranged, but the measurements are quantitative and continuous.

The continuous nature of THB results is an important advantage over the HPV technique, allowing tracking of transpiration over relatively long periods, but this requires more power.

These methods are relatively inexpensive and are easily used with data loggers at remote locations, but they use complex devices that must be accurately calibrated. They also can produce misleading results if used outside specific tolerances. Questions remain about the assumed flow rates in stems, including variation in flow rate in different parts of the stem.

Environmentally based models

Models of water use are derived from empirical and theoretical relationships. Either model type may include plant or evaporative surface characteristics along with measurements of environmental conditions. Because different combinations of forces are dominant at different scales (global, regional or local), models may work well at one level but be totally unacceptable at another.

Environmental models have been developed for a number of different scales and for different purposes. For example, the smallest scale level might be applicable to a single stomate, and the largest could model water flux at a regional or even a global scale. For this review I will focus on models at the single plant level. A common, but not always successful, practice is to apply models of larger or smaller scale to single trees by scaling down or up from stand or leaf level models, respectively.

Many different variables can be used to predict water use at the plant level. These variables can be classified into two types, those that describe the plant's environment and those that describe the plant itself. If the studied plants are very uniform in size, shape and species, the plant characteristics may not be very important in the model, but if there is significant variability in the plants, the plant descriptors may explain most of the variability. The two most common theoretical environmental predictors are temperature and amount of sunlight (expressed as day length, latitude, function of season derived from empirical observations or quantitative solar radiation). Humidity and wind are also components in some models. Other specialized measurements are key components in some models (e.g., pan evaporation, vertical windspeed, wind gust speed and frequency, incoming and outgoing component radiation, soil water content and atmometer evaporation).

Often environmentally based models include terms which represent interactions between two or more variables. Theoretical models are often modified by an empirically derived crop coefficient. Many different theoretical relationships have been described in predictive models, although only a few are useful and accurate components of models used for estimating whole-plant water use in a variety of environmental conditions.

Vapor Pressure Deficit or Mass Transport

Vapor pressure deficit is an important component of many water use equations because it is a measure of the difference in concentration of water vapor between the inside of the leaf and the external environment.

Surrounding a leaf is a layer of still air, known as the boundary layer, which insulates the leaf from the surrounding environment. Diffusion is the primary force by which water vapor crosses this layer. The thickness of this layer is determined by many factors, the most important environmental factor being wind. Early efforts to predict water use used vapor pressure directly, multiplying the figure by a function of windiness. (Monteith,1963; Penman, 1948).

Vapor pressure deficit equations are based on Fick's law (Fick, 1855) which can predict the rate of diffusion (J) of any vapor from the concentration gradient (C_1 - C_2 / Δx), a diffusion constant (D) and the cross-sectional area (A) of the exposed surface or region (Giancoli, 1991).

$$J = \frac{C_1 - C_2}{\Delta x} DA$$

In the case of a leaf in the environment, wind reduces the thickness of the boundary layer (Δx), where diffusion is the dominant force in transpiration. The diffusion constant changes slightly with temperature and pressure, but this variation can be integrated into prediction equations. The concentration inside the leaf is usually assumed to be saturated with water vapor. The effective cross-sectional area, which is used for calculation, is a fraction of the entire leaf surface, being only the area through which water vapor may pass unhindered by the cuticle and depends on stomatal density and aperture. Cuticular water loss may also be a component of some equations. Stomatal aperture is species dependent and is impacted by numerous factors. Some models make use of the correlation of stomatal aperture with environmental variables to estimate percent opening and resultant water use, although average values may be used for longer periods.

Most vapor pressure deficit models do not perform well when plants are stressed by drought. Temperature differences and non-saturated surface conditions can increase errors. In addition, when an entire canopy is considered, windspeed does not affect all leaves in a canopy in the same way. The aerodynamic and eddy correlation methods attempt to explain this variability in a way that windspeed alone cannot. Unfortunately these methods do not work well for single plants, and eddy correlation requires much sophisticated instrumentation (Kramer and Boyer, 1995; Rosenberg et al., 1983).

Blaney-Criddle Method

Blaney and Criddle (1950) developed a simple equation that uses an empirically derived monthly coefficient which varies from crop to crop and the monthly consumptive use factor (f). f is derived from an equation (0.01(1.8Ta + 32)p) which integrates average monthly air temperature (Ta) and the monthly percentage of annual daylight hours (p). The Blaney-Criddle method is particularly useful in the western United States and other locations where humidity tends to be low (Reagan 1991; Rosenberg et al., 1983). Reagan (1991, 1994) successfully calculated crop coefficients for containerized woody plants with a Blaney Cridle-type equation, which was modified to calculate daily estimates of water use.

Bowen Ratio

The Bowen Ratio (expressed below) is an energy balance type of prediction describing the relationship between sensible heat flux (H) and latent heat flux (LE).

$$\beta = H/LE$$

The relationship between H and LE can be understood by the heat balance equation, which shows how the sum total of incoming and outgoing streams of energy must sum to zero.

$R_{net} + B + H + LE = 0$; where

R_{net} is the incoming net radiation and B is the soil heat flow. From these two expressions, the amount of water lost as vapor can be calculated as:

$LE = -(R_{net} + B)/(1 + \beta)$

For prediction, β may be calculated as $\gamma(\Delta T/\Delta e)$; where γ is the psycometric constant, ΔT is the change in temperature and Δe is the change in vapor pressure. The instrumentation for this method is relatively simple. For daily prediction of LE, measurements of T e and R_{net} should be integrated over 30 to 60 minute periods and the totals summed rather than calculating LE from daily means. (Bowen, 1926; Dawson, 1996; Lowry and Lowry, 1989; Rosenberg et al., 1983)

Stomatal Resistance

As indicated earlier, stomatal resistance data can be integrated into environmental equations either as a component in a theoretical model, (e.g., Penman-Montieth) or as a less structured predictor. These equations usually use vapor pressure deficit as the numerator and the sum of aerial and canopy resistances as the denominator. This arrangement allows estimates of transpiration to be predicted from measures of both biotic and abiotic factors, which are known to impact transpiration at the leaf level.

Aerodynamic and Eddy Correlation

The aerodynamic and eddy correlation methods attempt to account for removal of water vapor away from plant surfaces by describing the fluid motion of wind. The aerodynamic method relates windspeed, or more specifically the logarithmic wind profile, to the specific humidity gradient. The eddy correlation method is similar because it estimates the vertical transport of water vapor from instantaneous measures of vertical windspeed. This method represents an important step in theory, but it is little used in practical experiments because of difficulties with the instrumentation (Rosenberg et al., 1983).

Evaporation from a Reference Surface

Evaporation from evaporation pans and atometers often correlates well with actual evapotranspiration. Evaporation from brushes (Palland, 1979), experimental reference watersheds (Black, 1991) and soil-filled lysimeters kept at constant water level (Penman, 1948; Rosenberg et al., 1983) have also been compared to actual evapotranspiration. Penman (1948) suggests that evaporation from nearby lakes may also be used to estimate ET.

An evaporation pan is simply a container of water from which water is allowed to evaporate freely, the fall in water level equaling the water lost by evaporation. The U.S. Weather Bureau Class A type pan is most commonly used in water use experiments. Pans are cheap and relatively easy to maintain, but there are situations where they may give unreliable estimates of actual evapotranspiration. Plants are sensitive to environmental variables in ways that an evaporation pan is not. Plants will commonly close stomates when hot dry winds begin to cause stress. Under arid conditions, correlation between plant water use and evaporation pans can be quite erratic. Exposure is also important, because of the importance of sensitive heat flux in determining evaporation from the open water surface. Crop coefficients are commonly used to relate evaporation pan data to actual ET, but correlation can also depend on plant growth stage (Rosenberg, et al., 1983)

Livingston atmometers have been used to estimate evapotranspiration of containerized plants and other crops (Furta et al., 1977b; Rosenberg et al., 1983). These devices are usually made of black or white porous ceramic material which is supplied with water. Water thus evaporates freely from the surface. These devices are also relatively inexpensive, produce measurements which have correlated well with actual evapotranspiration (Furta et al., 1977b; Rosenberg, et al., 1983). Furta et al. (1977b) studied their use for containerized woody ornamentals and found that although correlation with ET was good for both black and white atmometers, correlation was better with an evaporation pan. Comparison of black and white atmometers is theoretically a measure of the importance of solar radiation to ET. As with evaporation pans, atmometers are also sensitive to exposure, with particular respect to wind. Furta (1977b) noted that under dry santana winds, white atmometers were more sensitive to increased evaporation than the experimental plant material. Atmometers may also be composed of other porous material such as paper, but these, like the other reference surfaces are less commonly used for ET estimation or prediction.

Penman Combination Equation and Derivatives

The Penman-type equations deserve special mention because of their wide acceptance and use. Penman originally proposed a model of evaporation over open water in 1948. This model is a combination of energy balance and aerodynamic theories. The base equation therefore works best calculating evaporation from a water surface. Such reference is often referred to as potential evapotranspiration because it represents the maximum evaporation expected from an unobstructed saturated surface.

Despite their complexity, the original Penman equation and it's derivatives that employ measures of air temperature, net radiation, humidity, and windrun as well as crop coefficients or other plant parameters are used successfully in many different situations. The original Penman equation and many of its derivatives have sound basis in theoretical physics. In the original Penman, only the wind function, crop coefficients and seasonal coefficients are determined by empirical means (McKenny and Rosenberg, 1993; Penman, 1948). Crop coefficients are the primary means by which the potential evapotranspiration figures are applied to some given situation. For example, bare soil may have low water availability at the surface and thus have a low coefficient, but an open tree canopy may have a leaf (evaporating) surface area which exceeds the associated land surface, and the tree may therefore have a crop coefficient greater than one.

The most commonly used derivative of the Penman equation is the Penman-Montieth equation (Rosenberg et al., 1983). This equation is able to account for moisture availability by including terms for canopy (stomatal) and enhanced aerodynamic resistance. This is a very useful equation for scientific studies where the resistances can be measured in detail, but it is not convenient for irrigation scheduling (Ben-Asher et al., 1992; Rosenberg et al., 1983). Modifications were made to use easily measured parameters to estimate resistance components instead of measuring them directly. The technique of estimating resistances from plant parameters and environmental observations can work well under well defined conditions, but this often requires species-specific crop coefficients (Ben-Asher et al., 1992).

Others have modified the Penman equation to answer some specific condition, function with the limited information or be easier to use (Allen et al., 1989; Rosenberg, et al., 1983). Some of the more common alterations were to make the basic equation more sensitive to water vapor transport (through enhanced aerodynamic description and eddy correlation methods) and soil moisture availability functions (Allen et al., 1989; Rosenberg, et al., 1983).

The modified Penman equation (Equation 1) used in our research is adapted from Jones et al. (1984) and is based on only four climatic variables; average air temperature, net radiation, wind-speed and relative humidity. Major changes include: dropping of the soil heat flux density term which is small for a single day estimate, replacing the sensible heat flux term with mathematical equation substitutions based on Bosen's equation for saturation vapor pressure (Bosen, 1960) and finally, general updating of all measurement units and coefficients to modern notation. For our own use, maximum expected cloudless sky radiation (Rso) was calculated from a simple regression equation (seen below), for latitude 35° N, using data of Jones et al. (1984) from Jensen (1974) and Doorenbos and Pruitt (1977).

Equation 1. Modified Penman Equation

PEN = (((SVP*RN)/LHV)+PC*EA)/(SVP+PC)

SVP = (33.8639*(0.05904*(0.00738*TA+0.8072)**7-0.0000342))

RN = ((1-α)*Rs –Rb)

α = ~(0.23)

Rs = (2.067*GR)

Rb = (σ*TK^4*(0.56-0.08*(sqrt(ed))*((1.42*Rs)/(Rso-0.42)))

σ = (11.71*10**-8)

TK = (TA+273)

ed = (33.8639*((0.00738*min+0.8072)**8-0.000019*(1.8*min+48)+0.001316))

Rso= (242.45*518.13*(sin(T/365*3.14159)))

LHV = (59.59-0.055*TA)

PC = (0.66) (mb / °C)

EA = (0.263*(ea-ed)*(0.5+0.0062*U2))

ea = (SVP*(RH))

SVP = (33.8639*(0.05904*(0.00738*TA+0.8072)**7-0.0000342))

ed = (33.8639*((0.00738*min+0.8072)**8-0.000019*(1.8*min+48)+0.001316))

U2 = (UZ*(2/3.66)**0.2)

UZ = (WS*(1000/(60*60*24)))

PEN = Estimated evapotranspiration. $mm \cdot day^{-1}$

SVP = Slope of the Saturation Vapor Pressure curve. $mb \cdot °C^{-1}$ (Bosen, 1960)

RN = Net Radiation. $cal \cdot cm^{-2} \cdot day^{-1}$

α = Albedo for vegetated surfaces. 0.23 (Jones et al., 1984)

Rs = Total incoming Solar radiation. $cal \cdot cm^{-2} \cdot day^{-1}$

GR = Global radiation. $MJ \cdot m^{-2} \cdot day^{-1}$

Rb = Net outgoing thermal or longwave radiation. $cal \cdot cm^{-2} \cdot day^{-1}$

σ = Stephan Boltzman Constant. $cal \cdot cm^{-2} \cdot day^{-1} \cdot °K^{-1}$

TK = Temperature. K

ed = Saturation Vapor Pressure at the dew point (minimum daily temperature). mb

Rso = Total daily cloudless sky radiation. $cal \cdot cm^{-2} \cdot day^{-1}$ (regression equation developed from Jensen, (1974) and Doorenbos and Pruitt (1977) for 35° N latitude)

T = Day of the year. Integer

LHV = Latent Heat of Vaporization. $cal \cdot cm^{-2} \cdot mm^{-1}$

PC = Psychometric constant. 0.66 mb·°C^{-1}

EA = Multiplier.

ea = Average Vapor Pressure. mb

SVP = Slope of the Saturation Vapor Pressure curve. mb·°C^{-1}

ed = Saturation Vapor Pressure at the dew point (minimum daily temperature). mb

min = Minimum daily air temperature. °C

U2 = Windrun at two meters above ground. km·day^{-1}

UZ = Windrun at height Z=(3.66 m). km·day^{-1}

WS = Windspeed. m·s^{-1}

This equation is basically the same but more refined than the one Penman originally proposed. The new equation uses daily estimated Rso instead of the monthly averages Penman used and vapor pressure equations to replace original tables and charts of vapor pressure.

Soil water content

Soil water content can be measured or estimated easily by a number of different methods including: direct sampling, neutron scattering, gamma ray attenuation, electrical capacitance, electrical conductance, heat conductance, tensiometers and pressure plates. Measuring soil moisture is not a direct means of estimating ET; but, like other environmental factors, soil moisture can be used as a predictor in more complex models. Soil moisture, or matric tension, usually is utilized as a resistance component in models like the Penman-Montieth which use this type of measurement to reflect the water status of a plant without the need for directly measuring plant water status directly.

Recent Water Use Studies of Outdoor Containerized Woody Ornamentals

Although studies of water use of containerized ornamental plants are limited in number, several models have been created. In general these models have dealt with the water use of ornamental crops in small containers (Beeson, 1993; 1997; Burger, et. al., 1987; Fitzpatric, 1980; Furta et al., 1977a; 1977b; Knox, 1989).

With the advent of microirrigation (directed water application to plant base, through spray-stakes or drip tubes), growers began to have more precise control over how much and when water is applied to their crop. With overhead irrigation it was necessary to irrigate heavily to assure that adequate moisture penetrated the canopy and was available to plants. Under this system, irrigation would be allowed to run until the foliage and containers were thoroughly wet. This was not very precise nor was it amenable to use with models of water use because models must incorporate the amount of water necessary to first saturate the foliage and then reach the container (Beeson and Knox, 1991; Beeson, 1992).

With microirrigation, a relatively precise amount of water can be delivered to the container directly, facilitating even wetting. Computer controls enable irrigation systems to deliver precise quantities of water to each plant in time increments of as little as one second. Modern studies of water use in containerized ornamentals have striven to take advantage of this precision by accurately estimating the amount of water that is needed by a given crop on a particular day.

Furta and his associates (1977a, 1977b) conducted two of the earliest studies of water use. The first study (1977a) provided only rough estimates of maximum and minimum monthly evapotranspiration. This study was based on 1-gallon containers spaced four inches apart in California. Water use differed between bed positions and between species. Evaporation from a Class A evaporation pan was compared to actual evapotranspiration data. For all 21 species tested, there was significant ($p = 0.05$) linear correlation with the evaporation pan. Correlation coefficients varied between 0.614 and 0.984, with most species exceeding 0.85. This work is important because it is the first study that indicated that environmental measurements could theoretically be used for scheduling irrigation of containerized plants in the open environment.

Furta et al. (1977b) expanded on the previous work by investigating black and white Livingston atmometers as well as an evaporation pan as predictors of water use. Again, 1-gallon potted plants in a soil substrate were used. The objective was to gather information on evapotranspiration (ET) and the influence of irrigation practices on salinity to formulate sound management practices for the use of drip or spray irrigation systems. ET correlated well with estimates from the evaporation pan and the Livingston atomometers. Although the evaporation pan had the best correlation with actual ET ($r = 0.848$ for *Callistemon citrinus* (Curtis) Stapf, selected as a typical plant), Furta et al. recommended the use of devices such as the Livingston atmometers for controlling irrigation because they might be easily used to directly control the irrigation system. Atmometers also were correlated with actual ET ($r = 0.769$ for white and $r = 0.736$ for black atomometers with *Callistemon citrinus*). The researchers noted differences in water use patterns between species, positions within a bed, plant size and shape, and unexplainable differences between plants of the same species in similar bed positions. Differences between species could not be explained merely by inherent size and shape differences, indicating that differences in water use depended upon more detailed morphological characteristics. When drip or spray irrigation was used, salts were deposited in the containers, particularly away from the central core. The salt buildup could not be controlled by continuously applying more water than was necessary but had to be periodically flushed from the container with a large volume of water. Furta et al. make three cautioning notes for growers who wish to use estimates of ET for scheduling of drip or spray irrigation: 1) Water use does not correlate well with estimates under santana winds (actual water use is lower). 2) Estimates must be adjusted for different species by using crop coefficients. 3) Salts should be periodically leached from the containers because matching ET exactly with irrigation can lead to a potentially damaging buildup of salts in the container (where irrigation water has high salt, fertility is not well managed and where rainfall will not periodically leach salts from the pots).

Fitzpatric (1980) studied actual water consumption of 15 species grown under screen shade in 1-gallon pots in southern Florida during two phases of experimentation. During the first phase the monthly water budgets of three species (*Ficus benjamina* L., *Swietenia mahogoni* (L.) Jacq. and *Chrysobalanus icaco* L.) were investigated and compared to Thornwaite, Class A evaporation pan and Bailey Moisture Index estimates of evapotranspiration. During the second phase, 12 additional species were investigated in a similar manner. In the first phase, he found the highest correlation with the Thornwaite estimates ($r = 0.94$ to 0.97). Correlation for the evaporation pan ranged from $r = 0.58$ to 0.82; however, correlation was poor for the Bailey moisture index ($r = 0.35$ to 0.38). Fitzpatric built a predictive equation based on the relationship between the Thornwaite estimate and actual water use of *Ficus benjamina* for which correlation was highest (r = 0.97). The predictive equation for *Ficus* was PF = -0.12 + 0.35x, x being the Thornwaite estimate. This estimate was then modified by using a ratio of the size index of *Ficus* with that of another species. Size index was calculated as the sum of average height and average width for each species. Fitzpatric found good agreement ranging from –33% to +27% for species which consumed more than two liters of water per month. Large differences were found for plants that used less water (range –46% to +123%). Fitzpatric (1980) realized that monthly estimates of water use would have little utility for growers until differences in container size, shade percent and seasonal variation could be accounted for within the model.

In 1983, Fitzpatric reported on a continuation of this work in which the relative water demand (average cumulative irrigation demand / potential evapotranspiration) of 12 species were studied. This time, no reference plant was used. Instead, water demand was correlated directly to the Thornwaite estimates for each month of the study. This showed that there was still good correlation with the Thornwaite estimates, but also that there was considerable variation during the production cycle. A chi-square test indicated that there was no significant difference between monthly ETp and average irrigation demand, indicating that the Thornwaite estimates could be used for general estimates of water consumption. An attempt was made to account for these differences with a measure of growth rate (change in size index) from month to month. Although there did appear to be a general trend where the faster growing plants used more water, this was not true for all species. To illustrate this difference, pigeon plum (*Cocoloba diversifolia* Jacq.) and seagrape [*Cocoloba uvifera* (L.) L.] were compared. Although both these plants had moderate growth rate and were closely related taxonomically, they had different relative water demands (353 and 124 $ml \cdot cm^{-1}$ respectively). This indicated that taxonomy and growth rate may not be consistent indicators of water use.

Burger, et al. (1987) attempted to determine the water requirement for maximum growth and aesthetic value of containerized plants in California. To this end, they developed crop coefficients to use with California Irrigation Management and Information System (CIMIS) measurements for a reference crop (healthy turf at 3 to 6 inches in height). They studied 22 species or cultivars in 1-gallon containers at two container spacings. Daily water use measurements and estimates were compared during two growing seasons. They found that crop coefficients were higher for containerized plants than for other crops, ranging from 1.1 to 5.1. This large range necessitated the division of the ornamental woody plant species into three groups: heavy, moderate and light water users. Low water users (four species) had crop coefficients between 1.1 and 2.8. Moderate water users (16 species or cultivars) had coefficients between 1.4 to 3.8. High water users (two species) had coefficients from 4.4 to 5.1. They found that the crop coefficients were higher with greater plant spacing, but that they varied little with location (4 California sites). They also found that autoporometer measurements were improved by using total leaf area, but they were still not sufficiently accurate for water use prediction. They suggest that either the CIMIS estimates or evaporation pan data could be used for on-site calculation of irrigation rate, although they caution that many factors can interact with these estimates. They note that differences between cultivars, species, developmental stage, nutrition, spacing and shading could impact actual water use. This was the first study to investigate daily water use of containerized woody ornamentals.

Knox (1989) used linear regression to investigate the correlation between pan evaporation, predicted evapotranspiration by the Thornwaite equation and growth index with water use of five species of woody plants in 1-gallon containers in central Florida. The plants were grown on tables under a sideless, acrylic roofed shelter which provided approximately 67% full sunlight. Growth index was calculated as the (height + width)/2 measured every 4 to 6 weeks. The highest R^2 values (0.78 to 0.88) were found when both pan evaporation and growth index were used as predictors. When the Thornwaite equation was used with growth index the R^2 values were slightly lower (0.26 to 0.81), but were generally good. Knox concluded that plant species and size are the primary factors that determine water use and that estimates of potential evapotranspiration could be used with plant size to determine water requirements of containerized plants.

Although Martin et al. (1989) did not study water use directly, they investigated the effects of applying 50%, 100%, 200% and 400% of Class A pan evaporation to *Acer rubrum* L. growing in three different container substrates (pine bark with 0, 20 and 40% sand) in 38-liter (#10) pots. In general they found that the best caliper (trunk diameter at 15 cm above soil-line) growth was obtained with the highest irrigation rate (400% of evaporation pan) and the highest percent sand (40%).

In 1993, Beeson presented a study from central Florida in which actual evapotranspiration of *Rhododendron* sp. 'Formosa' in 10.2-liter (#3) containers was compared to predicted evapotranspiration by the Penman equation. The Penman equation was chosen over the Thornwaite equation because it could be used at a finer time scale (daily as opposed to monthly). Another motivation for using the Penman equation was that using historical data led to inadequate irrigation during the drought years of 1990 and

1993. He found that the overall correlation between the Penman equation and actual ET was relatively poor (r = 0.67) on a daily basis, but when summed over a four-day period it became reasonable for irrigation scheduling (r = 0.88). Interestingly, he determined that the correlation was not improved by including canopy surface area or canopy volume in the model; however, he noted that this correlation might have been improved by measuring the canopy more frequently, the reasoning for this was that the correlation was poorest during periods of rapid growth. Beeson presented five equations in all: 1) based on daily values, ET_A=116.2*ET_p+36.8; 2) based on 4-day sums, ET_A=119.7*ET_p+58; 3) during quiescence (November-December), ET_A=158.3*ET_p-83.9; 4) during rapid growth (January), ET_A=199.0*ET_p-69.5; and 5) during recovery (March and April), ET_A=123.0*ET_p-20.2. The considerable difference between growth stages translated into relative water demands of 15.8, 19.9 and 12.3 $ml \cdot cm^{-1}$ ET_P as calculated by Fitzpatric (1983). Differences in relative water use throughout the season emphasize the importance of knowing the peculiarities of a crop to prevent problems whenever standard equations are used to predict water use.

In 1994, Devit et al. reported on a study which was designed to estimate the water use of three newly planted woody ornamentals (*Prosopis alba* Grisebach, *Chilopsis linearis* (Cav.) Sweet var. *linearis* and *Quercus virginiana* Mill.) in Nevada. The study investigated and modeled water use under three leaching fractions: +0.25, 0.00 and -0.25. Nursery stock in 3.8, 18.9 and 56.8-liter containers were planted into 190-liter lysimeters with artificial substrate (4:1; blow sand: forest litter-bark mix). They found that relatively good predictions of monthly water use could be obtained from equations based on estimates from the Penman equation and other variables. For oak, 79% of the variation in ET was explained by the equation:

ET = -35.31+3.63*PEN+62.64*canopy volume (upper-half spheroid method)

For mesquite, 75% was explained by

ET=-55.63+5.50*PEN+4.05*month; where

month is month of the year (1-12). For willow, 88% was explained by:

ET=-50.34+3.73*PEN+1.13*trunk diameter (in cm at 15 cm above soil level)

They noted that ET of oak was closely correlated to all measured growth parameters (height diameter and canopy volume). Plotting water use on a canopy area or stem cross-sectional area basis showed that smaller trees used disproportionately larger amounts of water, which they attributed to an 'oasis' effect. Yearly ET estimates were found to be much more accurate than monthly estimates.

Also in 1994, Reagan studied crop coefficients for 23 woody landscape plants in 3-L containers in Oregon. Though he did not present any model fit statistics, he concluded that crop coefficients could be used with the FAO Blaney-Criddle equation to predict daily irrigation needs when they were developed for a certain species, growth and developmental stage, and location. He found that crop coefficients were low during establishment, larger during shoot growth, and highest during maturity for most of the species studied. He also found that water use correlated with growth rate, slow growing species having lower Kc values than faster growing ones. Crop coefficients for containerized plants were higher than for field crops since they were artificially inflated because calculation was based on pot surface area instead of the ground surface area.

In 1997, Beeson presented a similar experiment, this time investigating the evapotranspiration of *Ligustrum japonicum* Thumb. in 10.2-liter (#3) containers at different moisture allowable deficits (MAD). The substrate was 6:3:1; pine bark:sedge peat:sand. Plants were spaced 13 cm apart in a square spacing. He found that only the control, 20 and 40% MAD treatments were economically feasible. The experiment was divided into two time periods, before and after canopy closure. Before the canopies closed actual ET was poorly correlated to Penman-predicted ET, but actual ET was well correlated to time after initiation of the experiment. The significance of the time factor was an indication of the importance of plant size as the plants grew. During the second phase of the experiment, plants had a nearly uniform evaporative surface area (top only) and were much better correlated with predicted ET in the well-watered treatments. The 60 and 80% MAD treatments still showed poor correlation due to moisture stress since moisture stress adversely affected canopy development. Correlation could be improved by normalizing the estimates of evapotranspiration by canopy surface area. Canopy surface area was estimated by regression equations based on the most recent plant growth measures. Beeson concluded that water use could be reduced without impacting product quality by implementing a 40% MAD irrigation regime, which translates to a crop coefficient of 0.50 for the Penman equation. He also noted that for maximum irrigation efficiency, canopy isolation should be minimized.

Also in 1997, Schuch and Burger studied 12 woody ornamentals in 3.0- and 15.6-L containers at two California locations (Davis and Riverside). Their objectives were to determine water use of these plants and to compare crop coefficients from the CIMIS, as calculated from nearby weather station and a modified Penman equation, with crop coefficients from on-site atmometers. Water use and the resulting crop coefficients were investigated over two years, from liner to finished product. They attempted to identify meaningful patterns in the changing Kc over time. These patterns often correlated with plant growth or stage of development, but they were also impacted by changes in microclimate. Location, species and month affected Kc. Species with high water use tended to remain high water users throughout the experiment and there was little change in the relative rankings with time. They did note that two species, *Arctostaphylos densiflora* M.S. Bak. and *Cercis occidentalis* Torr., had high water use at Davis but low-to-moderate water use at Riverside. Because crop coefficients are based on the surface area of the container rather than the amount of ground surface area covered by the canopy, crop coefficients were quite variable with a large plant in a small container. When the plants were shifted to larger containers the crop coefficients stabilized. They observed considerable differences in crop coefficients for consecutive days, which they attributed to differences between the reference plant (cropped turf) and the crop plant. At high wind conditions atmometers seemed to have more realistic estimates of ET than did the CIMIS. At low wind speeds Kc increased greatly because of different heat exchange characteristics between the crop and reference plants. Differences due to wind speed might also be an artifact caused by measuring windspeed at 2.0 m, while atmometers were placed at 0.5 m. In general, the CIMIS and atmometer estimates were closely related (R^2 = 0.96 and 0.95) for Riverside and Davis respectively, though there were differences in the regression slope caused by differing microclimate at each site. They also found that both water use estimates tended to overestimate water use during low water use periods (winter). They concluded with a rejection of the crop coefficient concept as a general irrigation tool, preferring a model that would be responsive to growth rate, stage of development, time of year and location. They did attempt to develop a model that could account for this type of fluctuation, which occurs at regular intervals, with a Fourier transformation of time (month) using sine and cosine terms. Although these curves were quite simple, they did show improvement over the estimates developed from the crop coefficients alone.

Schuch and Burger (1997) showed that there was potential to use an equation which utilizes a transformation of time to explain periodic phenomenon including growth and development. They also note the importance of accounting for species and size (height) when modeling the growth of large plants with varying canopies.

Although several useful equations have been presented, there have been no conclusive water use studies of larger plants in production containers. Substrate used in large containers is often 100% pinebark, which has much different physical characteristics than that used in smaller containers (Lea-Cox and Smith, 1997) and that used in Devit's lysimeter study (1994).

A study by Vrecenak and Herrington (1984) tested a model of transpiration with sugar (*Acer saccharum* Mill.) and Norway (*Acer platanoides* L.) maples grown in 75-L (20-gallon) lysimeters, maintained at three different soil water potentials. Their model was quite complex, requiring measurements of soil water potential, soil surface temperature, leaf temperature, air temperature, dew point temperature, short-wave radiation, photosynthetic photon flux density, wind speed, crown dimensions, leaf azimuth and inclination angle distributions, and mean and total leaf area. Their model was an energy budget equation, which solved for the mass of water lost to transpiration.

As with many others, their model appeared to function best under relatively well-watered conditions. Under these conditions, the model predictions were commonly within 30% of lysimeter measurements. Their model also dampened fluctuations in actual water use. A large part of the problem with this model was the failure to account for stomatal closure when tissue water potential dropped during the day. Adequately describing canopy characteristics appeared to be the most severe limitation of this model, as the physical submodels were deemed acceptable. Even if this model had been quite accurate, the measurements required for calculation would have been prohibitive for growers without model simplifications.

In 2000, Simpson presented a study of water use of interior Douglas-fir [*Pseudotsuga menzezii* var. *glauca* (Bessn.) Franco] in a natural environment. While there is little similarity between the natural forest and the nursery environment, he found some useful relationships which can be used for modeling water use of larger trees. He found that the rate of sap flow through these trees was not related to their size. However, the total amount of water transpired per day was related to the cross-sectional sapwood area. A mean value could therefore be used to estimate water use per cm^2 of cross-sectional sapwood area once other factors were taken into consideration. Besides cross-sectional sapwood area, water use depended on VPD and irradiance. They noted that for small trees a large portion of basal area (total cross-sectional area of stem at 1.5 m) was sapwood area. He cited work by Sellin (1991), who found by regression that approximately 95% of stem cross-sectional area inside the bark is sapwood for 10-year old dominant Norway spruce [*Picea abies* (L.) Karst.], and that it can be even higher for younger trees. Interestingly, Simpson also found a close correlation between cross-sectional sapwood area and leaf area. Further inference was made that trees that use more water usually have greater growth (stem diameter). Such trees would support greater leaf area and therefore have a greater ability to assimilate carbon. The key point is that a measure of cross-sectional sapwood area is a very good integrator of all factors impacting tree growth, and can therefore serve as a very accurate predictor of water use when daily fluctuations in environmental factors are also included in the model.

Even though several models of water use have been proposed, a model that would apply generally to a number of different species and locations has not been identified. Future modelers must use more advanced statistical techniques to identify important variables and the relationships by which they can be used to predict water use of plants in containers. Some specific problems have been identified with the combination equations and evaporation devices under specific, well-defined environmental conditions. Predictions from these sources must be modified in some way to eliminate this source of error. Predictions from these sources could be modified using other important variables to make equations which are specific to pot-in-pot production but general as to location. Differences between species or cultivars might be accommodated as a crop coefficient or as separate equations that would apply to a group of plants with similar physiology. The complexity of relationships governing water use can be a daunting problem, but starting from a good theoretical relationship (the Penman equation) or an ET device (evaporation pan or atmometer) should simplify the process. The key to success is a modeling procedure which can distinguish between normal variation between individual trees and meaningful differences in describable parameters. The same analysis must be able to handle complex non-linear relationships between predictor variables and complex data structures, which are necessary for incorporating variety and robustness into the modeling dataset. The *nlmixed* procedure of the SAS® system has the ability to handle this type of analysis (Littell et al., 1997).

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CHAPTER TWO

FREQUENT IRRIGATION INCREASES TRUNK DIAMETER GROWTH OF POT-IN-POT SUGAR AND RED MAPLE AFTER ROOTS FILL CONTAINERS

Abstract

In Virginia, pot-in-pot (P+P) production of shade trees is often accomplished by growing bareroot whips in large (≈56-L) containers for two complete growing seasons (production cycles). This work investigated the influence of irrigation frequency in a 56-L P+P system on the growth of *Acer saccharum* Marsh. 'Green Mountain' (sugar maple), a species with moderate growth rate, and *Acer rubrum* L. 'Franksred' (red maple), a species with a fast growth rate. Irrigation treatments applied an equal daily volume of water in the industry-standard once-a-day irrigation regime (1X) or in three unequal applications per day (3X). Red maples with the 3X irrigation regime had greater trunk diameter growth than trees under the 1X irrigation regime. Sugar maples had greater trunk diameter growth with 3X irrigation compared to the 1X treatment, only during the second production cycle. Height growth was greater for red maples in the first production cycle than in the second, but sugar maples had greater height growth in the second production cycle. Red maples were severely pot-bound after the second production cycle, which may have led to decreased height growth during that season. Two production cycles is therefore too long for red maple in a 56-L container, but not for sugar maple. Sap flow measurements indicate that irrigating 3 times a day modifies the daily pattern of water translocation for red maples.

Introduction

Landscape tree production in large containers is becoming increasingly common. Maximizing productivity involves the proper selection of liner stock, container size, medium, nutrient and irrigation regimes. Recently, pot-in-pot (P+P) production has become a common production technique in Virginia. Pot-in-pot production closely resembles above-ground container production, with essentially the same substrate, containers and plant material, except that the growing container itself is largely below the soil surface in P+P production. P+P production utilizes a permanent "socket pot" which remains in the ground while production containers are removed and replaced as needed. P+P offers support for the containers without close spacing (Mathers, 2000; Ruter, 1993, 1997).

The P+P system has many of the same advantages for growers as above-ground container production, including summer-long salability, fast production and suitability for mechanization (Mathers, 2000; Ruter, 1997). P+P production moderates media temperature fluctuation which decreases root loss due to hot and cold extremes. Uniform media temperature improves root distribution and often increases growth (Martin et al, 1999; Mathers, 2000; Ruter, 1993, 1997).

One method that dramatically reduces water waste if properly used is to apply water through a microirrigation system (Weatherspoon and Harrell, 1980). These systems are increasingly popular because growers can more readily control the timing and placement of irrigation water. When conventional overhead irrigation is used water not only falls between containers but is also intercepted or deflected away from containers by plant canopies. Frequent (cyclic) micro-irrigation can be used to conserve water resources (Beeson and Haydu, 1995; Beeson and Knox, 1991; Lamack and Niemiera, 1993; Weatherspoon and Harrell, 1980) and fertilizer, thereby reducing pollution concerns (Fare et al., 1996; Groves et al., 1998a, 1998b; Tyler et al., 1996). Cyclic micro-irrigation has also been observed to increase plant growth (Beeson and Haydu, 1995; Fain et al., 1998, 1999; Martin et al., 1989; Ruter, 1998). The economic advantages of cyclic micro-irrigation, compared to traditional overhead irrigation, are particularly great for production in large containers (Haydu and Beeson, 1997).

The use of relatively large high-quality liners and the increased growth obtained by improved management and technologies such as the P+P production and frequent micro-irrigation mean that larger trees can be produced faster than ever. Many landscape trees are now grown as two-season crops in Virginia.

Cell elongation is the first major physiological function impaired by low tissue water potential (Hsiao, 1973; Nilsen and Orcutt, 1996). Reducing tissue water potential (ψ) by 0.1 MPa can impact cell growth (Hanson and Hitz, 1982; Hsiao, 1973). Since daily turgor pressure commonly varies between 1 and 0.5 MPa (Nilsen and Orcutt, 1996), many plants are often under growth-limiting water stresses. Although mild water stress can make plants less sensitive to drought and less susceptible to pests (Taiz and Zeiger, 1991), it also leads to decreased growth potential (Matthews et al., 1984; Taiz and Zeiger, 1991), preventing plants from growing as fast as non-stressed plants even when the stress is removed (Matthews et al., 1984).

Beeson and Haydu (1995) noticed that the benefits of cyclic irrigation did not begin to accrue until the plants experienced some water stress, which occurred after roots had filled the container. Although tree roots filled their containers faster than shrubs, the shrubs did not show signs of water stress until nine months after planting. Plant water requirement increases as the plant grows, until at some point there is simply not enough available water in the container to maximize growth.

The objective of this experiment was to determine the effect of frequent irrigation on the growth of red maple and sugar maple during each of two seasons of P+P production. Furthermore we wanted to determine if fast growing trees could reach merchantable size in only one season in the climate of western Virginia (USDA climate zone 6a) and if daily sap flow patterns were altered by irrigation regime.

Materials and Methods

This experiment was conducted in the P+P system at Virginia Tech's Urban Horticulture Center in Blacksburg, Va. Red maple was chosen to represent a fast-growing species, while sugar maple was selected as a moderate-growing species. Twenty bare-root trees of each species were obtained from J. Frank Schmidt & Son Co. (Boring, Ore.) and potted in 56-L containers in the spring of 1996. Trees were planted into a 100% pinebark substrate amended with dolomitic lime and micronutrients. The pine bark (Summit Bark Plant, Waverly, Va.) had an initial pH of 5.1, air space = 24.3%; bulk density = 200 $kg \cdot m^{-3}$; total porosity = 79.8%; and a water holding capacity of 55.5%. Ground dolomitic limestone (18% Ca, 10% Mg; James River Limestone Co., Inc., Buchanon, VA) which had a calcium carbonate equivalence of 100% was added at a rate of 3.6 $kg \cdot m^{-3}$. The micronutrient mixture (Micromax™, The Scotts Company, Marysville, Ohio) provided the following nutrients at the indicated concentration: 12% Sulfur, 0.1% Boron (Na2B4O7), 0.5% Copper (Cu SO4), 12% Iron (FeSO4), 2.5%

Manganese ($MnSO_4$), 0.05% Molybdenum (Na_2MoO_4), and 1% Zinc ($ZnSO_4$), and was incorporated at 0.9 kg·m^{-3}. All trees were topdressed with 168 g of 18N-2.6P-9.9K Osmocote® (The Scotts Company, Marysville, Ohio), providing 37.2 g N, 4.84 g P and 18.5 g K per plant. These trees were allowed to grow under once-a-day irrigation for the first season and subjected to irrigation treatments in their second production cycle the following year.

On 14 May 1997, 20 more trees of each species were potted in the same substrate and amendments as described above. We now had 80 trees total, consisting of twenty trees of each species per production cycle. All 80 trees were topdressed with 168 g of 18N-2.6P-9.9K Osmocote®. Each irrigation treatment was applied randomly to half (5) of the 10 available rows in the P+P system. All 80 trees were then randomly assigned so each species and year combination was represented twice in each row (2 subsamples). Height and trunk diameter (measured 15 cm from substrate surface) of each tree were measured on 19 May 1997 and again at the end of the experiment (6 November 1997). Height and trunk diameter growth were calculated as the difference between initial and final measures.

The experiment was a 2 by 2 factorial (2 production cycles X 2 irrigation treatments) within a completely randomized design with subampling. Each species was analyzed as a separate experiment. The *glm* procedure of the SAS® system version 8.01 (SAS Institute Inc, Cary, N.C.) was used for data analysis.

Irrigation was applied via micro-emitters (0.85 L·min^{-1}) controlled by an electronic timer. The 3X irrigation regime applied 3/5 of the total water at 0600 hour, 1/5 at 1000 hour and 1/5 at 1400 hour. The 1X irrigation regime applied the same total volume of water at 0600 hours. Different volumes of water were applied at each of the 3X irrigation events to better manage equal fertility between irrigation treatments. If the same volume of water is applied at each irrigation, little leaching occurs for 3X containers; however, 1X containers are leached daily by applying the same volume of water. To assure both treatments were leached only once daily, sufficient water to drench both irrigation treatments was applied at 0600 hour. The two subsequent irrigation events of the 3X treatment applied approximately enough water to replace that which had transpired during the intervening period.

Sap flow was measured on non-experiment trees that were planted and grown under the same protocol as the experiment trees. Two sap-flow trees were randomly selected from 1X and 3X red and sugar maples in their second production cycle. Sap flow data were collected using eight (one per tree) Dynamax® SGB25-WS sap flow gauges (Dynamax, Inc. Huston, Texas) set up to output average sap velocity every 15 minutes. These values were recorded on a DNX10 Datalogger (Campbell Scientific, Logan, Utah) until they were uploaded to a portable computer.

Results and Discussion

Frequent irrigation (3X) was found to increase trunk diameter of red maple compared to 1X irrigation during each production cycle (Table 1) but to only increase trunk diameter of sugar maple during the second production cycle. This finding was consistent with results of Beeson and Haydu (1995) who found that slow growing shrubs did not benefit from frequent irrigation until roots had appeared to fill their containers. The increased growth of 3X plants in our experiment can probably be attributed to the relief of slight moisture stress. After a significant percentage of available water is removed by a large plant during the day, water becomes harder for the plant to obtain because of rising substrate moisture tensions (Brady, 1990). At this time plant tissue water content may drop to such an extent due to high environmental water demand that a mid-day wilt is observed, even though the medium appears to contain sufficient moisture. Red maples in our experiment commonly exhibited a wilted appearance under high vapor pressure deficits. 2-yr sugar maples and red maples in both production cycles commonly used more water than 1-yr sugar maples (Chapter 4) which indicates that they may be more likely to encounter moisture stress.

Sugar maples in our study showed average trunk diameter growth of 0.79 cm and 0.81 cm for the 3X and 1X irrigation treatments in the first production cycle, respectively (Table 1). It is not surprising that 1-yr sugar maples should show no significant growth response to irrigation frequency since their small size dictates relatively small amounts of water being removed from the large containers. Because they do not withdraw much water from the containers, water availability remains high and little drought stress develops. Once the trees are established in the second production cycle, increased trunk diameter growth can be expected, particularly if no drought stress develops. During the second production cycle trunk diameter growth of 1.14 and 0.83 cm was observed for trees under 3X and 1X irrigation treatments, respectively.

Height growth and trunk diameter growth did not respond similarly to irrigation treatments for trees of either species (Table 1). However, shoot elongation is commonly less responsive to environmental stresses than is trunk diameter growth (Kramer and Kozlowski, 1979), which may explain these differences.

Growth of most trees is very limited the first year after transplanting (Harris et al., 1998). This was the case for sugar maples, which put on significantly more height growth during the second production than during the first. However, height growth was significantly less for red maples during the second production cycle than during the first production cycle regardless of irrigation treatment.

Unlike sugar maples, red maples had virtually no period of slowed growth after transplanting into containers. The fast growth of red maples resulted in their roots quickly filling the pots during the first growing season and probably induced water limitations of trees irrigated only once per day. Visual inspection of the roots of trees at the start of the second production cycle revealed that red maple roots had already filled the pots, and were circling the containers. Numerous roots competing for the same water resources likely exacerbated water availability problems which could not be completely dissipated by 3X irrigation for red maples.

Sap flow of eight trees was measured during mid summer, revealing a different pattern of water use for red and sugar maples (Figure 1). The 18th of July was selected to represent a typical mid-summer day (Figure 2). On this day the average daytime temperature was 27.4 °C while the maximum was 31.2 °C. The average daytime relative humidity was 60.7%. Hourly average windspeed ranged from 0.02 to 3.22 $m \cdot s^{-1}$. Due to relatively constant environmental conditions, global radiation was well correlated with Penman-Van Bavel predicted evapotranspiration (van Bavel and van Bavel, 1990) throughout the day, including at 1400 hour when clouds were present. Due to the cloud cover at zenith, maximum global radiation peaked during the 1500 hour at 955 $MJ \cdot m^{-2} \cdot s^{-1}$.

Sap flow measurements (Figure 1), did not mirror Penman-Van Bavel predicted evapotranspiration (Figure 2), except during the early morning rise and again through the evening decline. Sap flow of red maples peaked during mid morning and was followed by a dramatic drop through the rest of the day. 3X irrigation slowed the decline of sap flow through the day for red maples indicating that sap flow must be tied to substrate water availability for that species. Sugar maples showed a relatively constant pattern of sap flow throughout the middle of the day regardless of irrigation treatment. The plateau trend of sugar maples is consistent with the theory of optimal variation presented by Cowan (1977, 1982) and Cowan and Farquar (1977) who theorize that plants close stomates during periods of high environmental water demand as an evolutionary strategy to conserve water.

The early peak sap flow rate of red maples may be supported by the use of water stored in the bole of the tree. The work of Simonneau et al. (1993) and Goldstein et al. (1997) indicate that a significant portion of daily transpiration may be initially derived from stem and trunk storage. Sap flow rate of red maples may have declined through the day because water was becoming increasingly harder to obtain, not only from the container media but also from the internal trunk storage. Water limitation may occur rapidly in the P+P system because trees are allowed sufficient space to have nearly isolated crowns, and water availability is limited to that which can be held in a relatively small container. These containers are filled with substrate having low water holding capacity. Even when water is applied to the roots with frequent irrigation, the trunk storage portion has already become somewhat depleted by the time supplemental irrigation is applied.

Tree water use can be divided into three parts: 1) environmental demand (which is not always met), 2) internal storage (which recharges only when transpiration is relatively low), and 3) availability at the root (which decreases as water is removed). Because water movement is buffered and regulated, a change in source availability does not always translate to a noticeable change in delivery. This explains why frequent irrigation does not have more impact on observed sap flow. The complexity of this system makes explanation of species differences in diurnal sap flow difficult. However, the diurnal pattern of red maple sap flow is consistent with that of trees adapted to wet sites (Cowan, 1977; Cowan and Farquhar, 1977). Although Red Sunset® is a horticultural derivative, and its ecological adaptation can not be inferred, studies have shown that it is among the most flood tolerant red maple cultivars (Anella and Whitlow, 1999; Zwack et al., 1999).

Root growth of random trees was visually inspected periodically throughout the growing season and assessed for all 3X trees in the spring of 1998. Red maples had overgrown their containers by the end of the second production cycle. Despite frequent irrigation, these trees most likely suffered from resource limitations, as roots could be seen to overlap and circle the container. This limitation may have been responsible for much less height growth during the second production cycle. Height growth was observed to be 69.7 cm in the first production cycle, but only 34.2 cm in the second production cycle.

The results of this study are in close agreement with those of Martin et al. (1989) and Fain et al. (1998). Martin et al. (1989) studied the effect of irrigation rate on seedling red maples in 38-L containers, finding greater irrigation volume improved caliper, but not height growth during both years of the study. Fain et al. (1998) studied the effect of cyclic irrigation and substrate in P+P of Red Sunset® red maple, finding that frequent irrigation improved both trunk diameter growth, and shoot height growth regardless of three common media mixes. This work adds to these reports with growth information from two species, and with a study of daily sap flow patterns which indicates that trees of different species and irrigation regimes have differing diurnal patterns under the same environmental conditions. In our study, we found that the daily pattern of sap-flow for red maples differs between 1X and 3X irrigation regimes. Frequent irrigation appears to be most critical when plant water use is high, particularly for larger trees during conditions of high vapor pressure deficit. Slower growing sugar maples do not appear to experience growth limiting water stress in their first production cycle.

Conclusions

Frequent irrigation increases trunk diameter growth when trees have grown enough to tax container water resources. Beeson and Haydu (1995) roughly identified the initiation of mild water stress as the time when roots fill the containers. Although precise measurements were not made in our experiment, roots of sugar maples had just begun to duplicate function, overlap each other and circle the container wall by the end of the first production cycle. Periodic visual inspections of red maple root systems revealed that roots had begun to circle the container wall by mid-summer of the first production cycle. Height growth was not affected by the irrigation treatments used in this experiment.

Growers should not keep red maple in the 56-L pots through a second production cycle, due to decreased height growth potential. This reduction in height growth is probably a result of a root limitation (pot bound) which apparently affected growth independent of irrigation treatment. If red maples must be kept in the same containers for the second production cycle, improved trunk diameter growth can be expected if the trees are irrigated three times a day.

For sugar maple, irrigation treatment did not affect growth in the first production cycle. The benefits of frequent irrigation appeared in the second production cycle as increased trunk diameter growth. This indicates that there is little need for more frequent irrigation in the first production cycle for the moderate grower, sugar maple.

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Table 1. Effects of irrigation frequency on trunk diameter growth and height growth of red and sugar maples in each of two production cycles (n=10 for each group).

Production cycle and irrigation treatment[z]	Trunk diameter[y] increase (cm)	Height increase (cm)
Red maple		
First production cycle 3X	1.19	67.1
First production cycle 1X	1.01	72.3
Second production cycle 3X	1.21	38.1
Second production cycle 1X	0.94	30.4
Sugar maple		
First production cycle 3X	0.79	14.4
First production cycle 1X	0.81	14.0
Second production cycle 3X	1.14	43.9
Second production cycle 1X	0.83	31.5
Significance		
Red maple		
Production cycle	0.6996	0.0001
Irrigation frequency	0.0026	0.8246
Production cycle x irrigation frequency	0.4412	0.1953
Sugar maple		
Production cycle	0.0200	0.0001
Irrigation frequency	0.0526	0.1003
Production cycle x irrigation frequency	0.0339	0.1215
Contrasts		
Sugar maple, 1st production cycle, 1X vs. 3X	0.8746	---[x]
Sugar maple, 2nd production cycle, 1X vs. 3X	0.0066	---

[z] Production cycle indicates first or second year in P+P production. Irrigation treatments were: all water applied in morning (1X) or the same amount of water applied in three unequal allotments per day (see text).

[y] Measured 15 cm above substrate surface.

[x] Contrast not tested due to nonsignificant interaction.

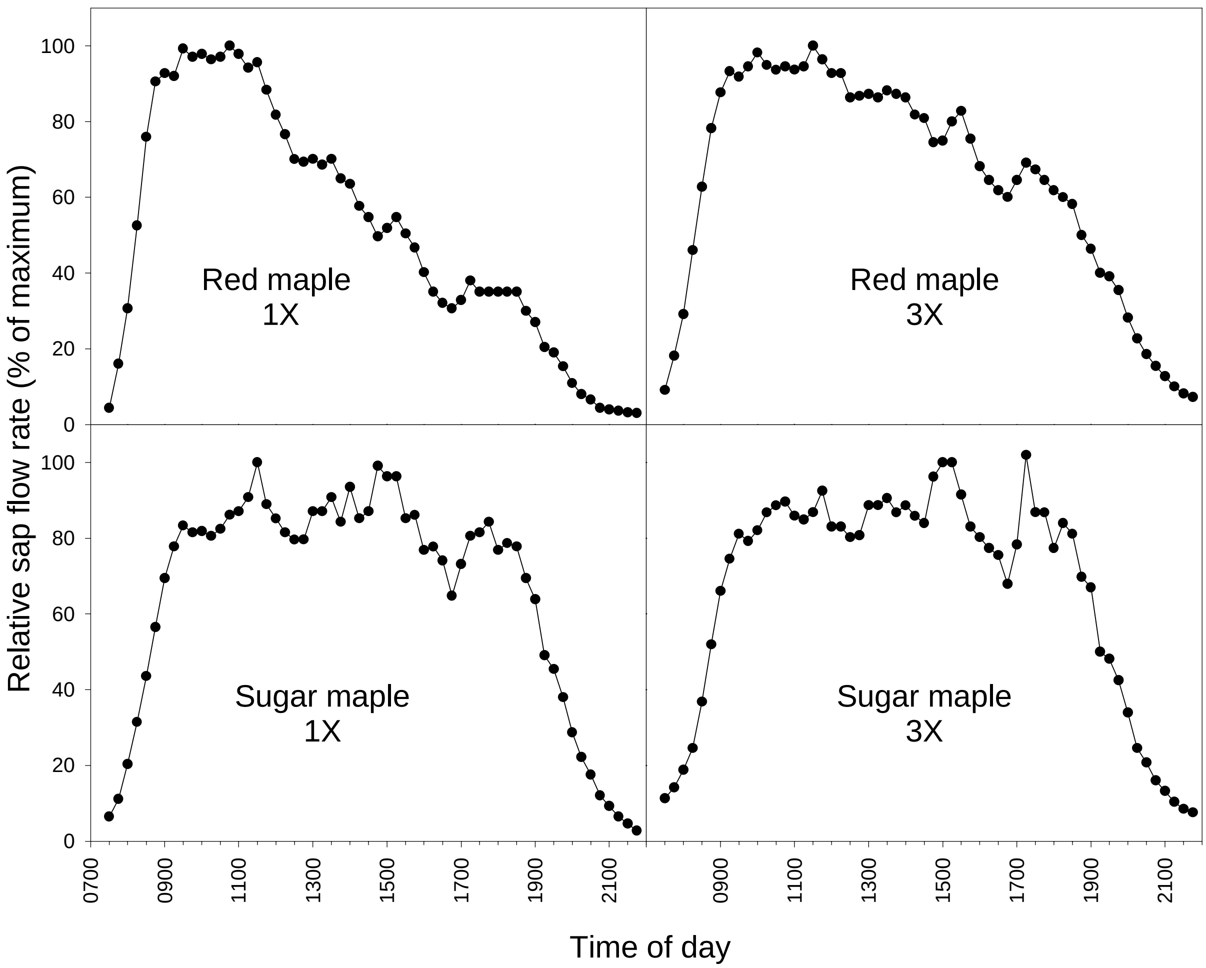

Figure 1. Relative pattern of sap flow during 18 July 1997. Graph shows the pattern of water use of red (top) and sugar (bottom) maple in their second production cycle when irrigated once (1X) (left) or three times (3X) (right) a day (n=2 for each graph).

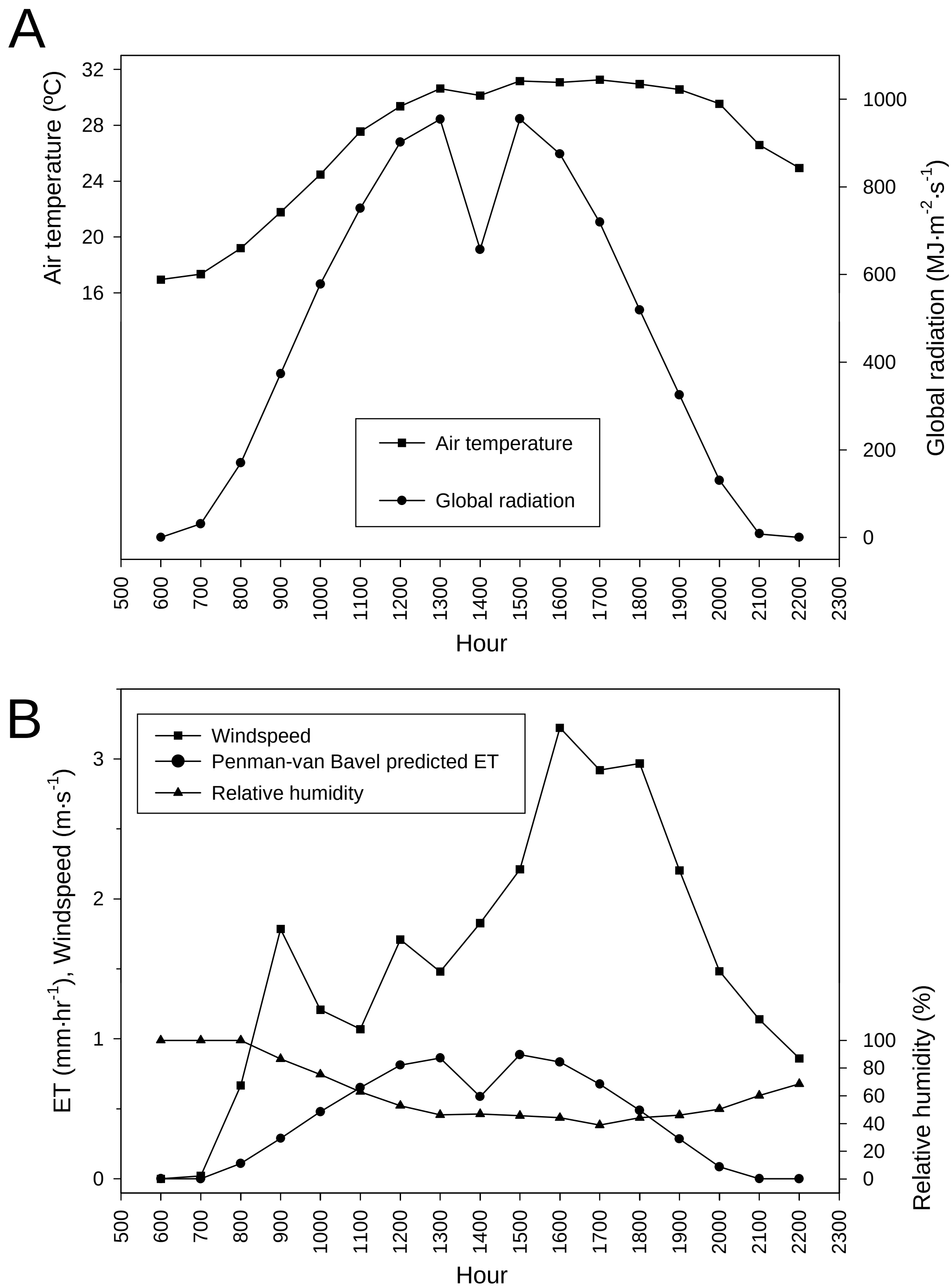

Figure 2. Environmental conditions on 18 July, 1997, when sap flow observations were recorded. Graph A shows air temperature on the left axis and global radiation on the right axis. Graph B shows Penman-van Bavel potential evapotranspiration and windspeed on the left axis and relative humidity on the right axis.

CHAPTER THREE

GROWTH AND IRRIGATION REQUIREMENT OF TRANSPLANTED POT-IN-POT RED AND SUGAR MAPLES

Abstract

Red maple (*Acer rubrum* L. 'Franksred') and sugar maple (*Acer saccharum* Marsh. 'Green Mountain') trees were grown in a 56-L pot-in-pot production system (P+P) for 1 (1-yr) or 2 (2-yr) years and then transplanted to field soil to study growth and irrigation frequency requirement. Transplanted trees were monitored over three growing seasons to determine: 1) irrigation frequency required to maintain root zones at low moisture-stress levels, and 2) growth differences between 1-yr and 2-yr trees. Irrigation frequency requirement depended on four factors. 1) Higher frequency requirement correlated with high environmental water demand (vapor pressure deficit). 2) Soil surrounding large trees initially dried quicker than soil surrounding smaller trees. 3) Drying was delayed by approximately one day when the source of saturating moisture was rainfall rather than irrigation. 4) Sugar maples eventually required less frequent irrigation than red maples. Average irrigation frequency for all trees for periods without rain was 4.9, 5.5, and 6.6 days in the first, second and third seasons following transplanting, respectively. During the first year after transplanting 1-yr red maples grew to the same trunk diameter as 2-yr trees. Sugar maples maintained pre-existing height and trunk diameter differences between 1-yr and 2-yr plants throughout the experiment. All 4 groups had the least trunk diameter growth in the first year (0.29 cm), the greatest in the second (0.89 cm) and intermediate growth in the third (0.60 cm). The same pattern

was expressed as average height growth of 1.12, 2.22 and 1.68 m, recorded in years one to three, respectively.

Introduction

Container-grown (CG) trees are relatively lightweight and easily handled, and they can be planted more successfully throughout a longer season than bare-root (BR) or balled and burlaped (B&B) trees. These advantages make them popular among both growers and landscapers. However, container substrates are prone to rapid drying when planted in the landscape (Costello and Paul, 1975; Nelms and Spomer, 1983; Spomer, 1980), and poor establishment and survival of CG plants have frequently been attributed to inadequate irrigation following planting (Blessing and Dana, 1987; Gilman et al. 1998; Gilman and Beeson, 1996; Harris and Gilman, 1993; Matheny et al., 1979; Nelms and Spomer, 1983).

Much of the water that trees use in their first year after transplanting is thought to be taken up from within the original rootball (Gilman et al., 1998; Sivyer et al., 1997). Because the rootballs of CG trees are excessively drained when planted in free draining field soils, there is a need for frequent irrigation (Costello and Paul, 1975; Nelms and Spomer, 1983; Spomer, 1980), and CG trees may require more frequent irrigation than B&B trees (Gilman, et al., 1998).

The need for precise irrigation guidelines is acute for arborists and urban foresters because many of these managers have limited capability to irrigate newly planted trees, and they must rely on nearby homeowners. Other caretakers have the ability to transport water, but they are hindered because of a lack of precise information about how much and how frequently they need to irrigate. In either case, irrigation recommendations often generalize to "irrigate frequently when dry" (Sivyer, et al., 1997). This type of generalization is not adequate for efficiency nor public relations concerns of today's arborists or urban foresters.

Accurate estimates of water use of transplanted trees are critical to develop specific irrigation recommendations. Sivyer et al. (1997) studied the water use of 7.2-cm trunk diameter B&B *Pyrus calleryana* 'Redspire' (pear) and *Betula nigra* 'Heritage' (river birch) trees. Trees were irrigated according to the Lindsey-Bassuk model which is based on tree size and average evaporation from a class A evaporation pan (Lindsey and Bassuk, 1991) or as needed (when soil moisture tension rose above 0.055 MPa). The experiment compared the growth, total water application, and number of applications needed when irrigation was applied as needed (control) or according to the model (34 L every three days). By using estimates and average values, a daily transpiration rate of 10 L was calculated. Estimating the amount of water available in a saturated rootball as 33 L, rootballs were estimated to contain a 3.6-day water supply. This estimate was rounded down to a 3-day irrigation interval and 34 L of water per irrigation event to insure adequate wetting of the rootball. Control trees were irrigated with 34 L of water whenever soil moisture tensions reached 0.055 MPa. The irrigation interval for control trees ranged from 2.6 to 3.3 and 2.3 to 3.3 days for pear and birch, respectively, which was very similar to the model regime. Using revised estimates Sivyer calculated that 19 L of water applied every 2.6 days would keep the average soil moisture tension from dropping below 0.055 MPa.

Although Sivyer's study gives some good information about the average water requirements of newly planted B&B trees, it does not specifically address the subject of container-grown trees. Gilman, et al. (1998) compared the irrigation needs of both CG and field-grown live oak (*Quercus virginiana* Mill.) trees of various sizes. Specifically, they found that infrequently irrigated CG trees grew less than trees from other production methods and irrigation regimes, due to water stress. They found that that at 2 weeks after transplant (WAT) container rootballs contained only enough water to supply the tree's water needs for one day. At 21 WAT infrequently irrigated CG trees were still more stressed than trees grown by other methods. These differences were absent by 55 WAT, presumably because all trees had rooted into the surrounding soil. They concluded that: 1) Transplanted trees do not need to be irrigated outside the rootball to establish quickly, which confirms work by Sivyer, et al., (1997). 2) A large volume of irrigation does not compensate for infrequent irrigation. 3) No more than 1.2 L irrigation per cm of trunk diameter per irrigation is required for good growth of live oaks in sandy soil after transplant. 4) Frequent irrigation during the first growing season is critical for establishment and survival. 5) Container-grown trees are generally more sensitive to desiccating conditions than B&B trees that are sufficiently hardened-off before transplanting. 6) Small trees grow faster and establish sooner than large trees.

Beeson (1994a) suggested that irrigation of newly planted CG plants in Florida sand should be more frequent than that which is required in the nursery. Beeson (1992) noted that once-a-day irrigation was insufficient to support maximum growth of four ornamental species in 10.4-L containers . This observation has been confirmed by the work of many others (Beeson and Haydu, 1995; Fain et al., 1998, 1999; Ruter, 1998; Witmer et al., 1998). Certainly this level of irrigation is beyond the capability of most arborists.

If a CG rootball is planted properly, many roots at the edge of the rootball are in contact with surrounding soil. As long as the backfill soil remains reasonably moist, the tree should not suffer life-threatening water stress, and rooting into the surrounding soil will be encouraged. Most landscapers want simple guidelines that will get trees established with a minimum number of site visits. An efficient and adequate irrigation strategy might be to keep the soil surrounding a CG rootball wet enough to prevent severe stress. Although Gilman et al. (1998) and Sivyer et al. (1997) concluded that transplanted trees do not need to be irrigated outside the original rootball to establish quickly, all of Gilman's infrequently irrigated trees survived and became established within 9 months, despite growth limiting water stress which was probably worsened by the native sandy soil. Sivyer was working with B&B trees, which hold more water than CG rootballs.

The objectives of this study were to determine 1) irrigation frequency required to maintain root zones at a low moisture-stress level, and 2) growth differences between 1-yr and 2-yr trees.

Materials and Methods

On 29 April 1998, 20 each of pot-in-pot (P+P) grown red and sugar maple were transplanted into a Groseclosse silty clay loam (clayey, mixed, typic Hapludult with a pH = 6.5) at the Virginia Tech Urban Horticulture Center near Blacksburg, Va. to study their growth and irrigation requirement during establishment. Ten trees of each species had been grown in the P+P system for the previous two years while the remaining 10 of each species had been grown for one year. All trees were originally obtained as 1.5 m–tall whips (J. Frank Schmidt & Son Co., Boring, Ore.) and were randomized during production. All trees were transplanted into a completely random design and planted 2 m apart in 0.6 m-diameter, auger-dug holes. At planting, all rootballs were cut from top to bottom using four equally spaced vertical cuts (approximately 5 to 8 cm into the side of the rootball), administered with a sharpened spade. Planting holes were then backfilled with native soil and a thin layer of soil was placed over the rootball. All P+P trees were originally grown in a pinebark substrate amended with dolomitic lime and micronutrients. The pine bark substrate (Summit Bark Plant, Waverly, Va.) had an initial pH of 5.1, air space = 24.3%; bulk density = 200 kg/m^3; total porosity = 79.8%; and a water holding capacity of 55.5%.

At planting and during each following spring all trees were topdressed with 168 g of 18N-2.6P-9.9K Osmocote® (The Scotts Company, Marysville, Ohio), providing 37.2 g N, 4.84 g P and 18.5 g K per plant. Plant height and trunk diameter at planting are presented in Table 1.

An irrigation system applied water to trees of one group with little influence on the others by using four separate irrigation lines. Each tree was supplied with water from two micro-emitters, adjusted to collectively wet an area approximately 1.2 m in diameter around each tree. Special care was taken so that water was not applied under adjacent trees. Uniform application was assured by using a pressure regulator and timing irrigation. Irrigation need was assessed by daily monitoring of 16 electrical-resistance moisture sensors (Model 200, Irrometer Company, Inc., Riverside Calif.) placed on the east side of four randomly selected trees per group. The sensors were located just outside the rootballs, 18 cm below the surface (half-way down the rootballs). When the average of the four sensors reached 0.055 MPa, the entire group was irrigated, applying approximately 40 L of water per irrigation event. A tension of 0.055 MPa was selected as the irrigation point because it is within the range recommended in the device manual (Irrometer Company, Inc., n.d.), and prevented visible stress in another study (Sivyer, et al., 1997.).

The dry-down and irrigation history of sample trees was compared to rainfall data from an on-site DYNAMET® weather station (Dynamax, Inc., Houston, Texas) which recorded hourly rainfall and other environmental parameters. Periods without significant rainfall were identified from the weather data and were used to calculate the mean number of days between irrigation events for each group of trees.

At the end of each growing season, mean irrigation intervals were calculated and height and trunk diameter were recorded. Height and trunk diameter data were subjected to analysis of variance using the general linear model procedure of the SAS® system, version 8.00 (SAS Institute Inc, Cary, N.C.), and contrasts were conducted between 1-yr and 2-yr trees of each species where appropriate [with significant ($\alpha < 0.05$) interaction].

Results and Discussion

Four factors clearly impacted the time required for the backfill soil to dry to 0.055 MPa tension. Environmental conditions were important, as the shortest dry-down periods correlated well with conditions producing high evaporative demand (data not shown). Secondly, tree size was a clear indicator of drying rate; soil near the larger trees dried fastest. Third, more time was required to dry to 0.055 MPa after rainfall than after irrigation, even though both events saturated the soil near the tree. Finally, differences between species became apparent in the second and third growing season.

Although moisture sensors were installed just after the trees were planted (May), the first simultaneous dry-down of all four groups which was not interrupted by rain occurred in July. Rainfall on and before 8 July 1998 had brought three of the groups to near zero soil moisture tension (Figure 1). The 1-yr sugar maples (C) were brought to near zero soil moisture tension by irrigation on the same day the others were beginning the drying cycle (9 July). On this first complete dry-down, soil near the 1-yr red maples (A) dried faster than the other three groups, taking five days to reach 0.055 MPa, whereas the three other groups took six days.

In the second dry-down, the 2-yr trees of both species (B, D) dried backfill soil to 0.055 MPa in only four days. Cloudy weather on 19 July prevented the 1-yr sugar maples from reaching the threshold until the fifth day. The third dry-down was similar to the second for both groups of red maples and the 2-yr sugar maples (A, B, D). This time these groups took five days to reach the threshold due largely to the cloudy weather of 19 July.

A series of days with low evaporative demand slowed the drying of all treatments considerably during the next period (drying cycle three for 1-yr sugar maples, cycle four for the others). The red maples (A, B) took six days to dry. The 2-yr sugar maples (D) would have taken seven days to reach the threshold, but were mistakenly irrigated on day six. The 1-yr sugar maples (C) took eight days to dry during this period.

The same general pattern of drying continued throughout the first growing season after transplant (data not shown). In 1998 irrigation frequency ranged from two to nine days for periods without rain (Table 2). The 1-yr sugar maples had the longest interval (nine days) although the 1-yr red maples and the 2-yr sugar maples both had 8-day intervals. The longest interval for 2-yr red maples was seven days. The shortest interval was two days for the 2-yr red maples and the 2-yr sugar maples. The shortest interval was five days for 1-yr sugar maples and three days for 1-yr red maples.

In 1999, both groups of red maples had long intervals at the end of the season, 10 days for 2-yr red maples and 15 days for 1-yr red maples (Table 2). These intervals for red maples were longer than those for sugar maples because the sugar maples did not complete a dry-down during these periods due to rain. Excluding these long intervals, red maples had intervals of six and five days for 1-yr and 2-yr trees, respectively. Two-yr sugar maples had a long interval of eight days, while the 1-yr trees had an interval of twelve days. Two-yr trees of both species recorded short intervals of two days. One-yr trees had short intervals of three and five days for red and sugar maples, respectively.

In 2000, increasing dry-down intervals were the rule (Table 2), which combined with a wetter than normal summer resulted in fewer irrigation events than were required in the previous years. Nevertheless, three groups appeared to be well established in the landscape. One-yr red maples had an average irrigation frequency requirement of 7 days with a range of 4 to 10 days. Both groups of sugar maple were similar, having a range of 6 to 9 days and an average irrigation frequency requirement of 7.2 to 7.8 days for 1-yr and 2-yr trees respectively. Two-yr red maples had a range of 3 to 9 days and an average irrigation frequency requirement of only 5.4 days, which was similar to the previous year. This suggests that these trees were still getting much of their moisture from sources near the rootball, which may indicate that they had not completely grown out of their pot-bound condition.

Environmental effects

Much of the variation in irrigation frequency was probably attributable to environmental effects. Few long intervals were registered in mid-summer, although the longest intervals were recorded at the end of the 1999 and during an uncharacteristic chill in mid summer 1998. All groups recorded dry-down periods during the first spring. Many of these were longer than the summer intervals. Relatively long intervals were frequently cut short by rainfall during the spring. During the spring, moderate rainfalls frequently failed to completely rehydrate the backfill soil of a treatment registering relatively high soil moisture tension. This group would then be the next to require irrigation following the rain. Only those intervals for which a clearly wet starting time could be determined were used for interval calculation. This requirement, along with frequent moderate rains led to a scarcity of data during the first spring. Small differences in the water use patterns were largely due to chance, as the 0.055 MPa target was an artificial value selected to ensure that trees were not severely drought stressed. Very small differences in actual soil moisture tension may have decided whether a group was irrigated on one day or the next.

Frequently, natural rains did not seem to modify the pattern of dry-down. Sensors were located just outside the rootball within the rain shadow of most trees. During light rains, canopies of large trees appeared to intercept much of the rain that would have reached the root system. Besides the rain shadow effect, water may have moved around the bark medium because of natural capillary forces (Brady, 1990; Brutsaert, 1963; Spomer, 1980). In the first year, roots were probably concentrated within the bark media and not far into the surrounding soil (Arnold,1996; Blessing and Dana, 1987; Harris and

Gilman, 1993; Beeson, 1994a, 1994b). The area just outside the bark media where sensors were located would be expected to quickly return to pre-rain dryness because with little moisture available within the rootball, the newly formed roots take nearly all of the needed water from this zone.

Size

Differences between age classes were likely due to size, since older trees had larger canopies (Chapter 4). The average irrigation interval for days without rain in 1998 was 6.4 days for 1-yr sugar maples (Table 2) which was considerably longer than 4.5 days for 2-yr sugar maples. Red maples of each age group were closer in size (Table 1) and were also close in average irrigation interval, 4.2 days for 2-yr, 4.6 days for 1-yr trees. Minimum drydown time was also lower for the larger 2-yr trees than the smaller 1-yr trees (Table 2). Maximum drydown days do not make good comparisons because the longest drydown periods were frequently ended by rain before soil tension reached 0.055 MPa. In 1999, 1-yr and 2-yr red maples were nearly identical in height and caliper (Table 1) and in irrigation frequency requirement of 5.5 and 5.2 days, respectively. Sugar maples maintained a large difference in size and in irrigation frequency requirement (Table 1, Table 2). In 2000, most groups appeared to have established well, having average irrigation intervals between 7 and 8 days. Only the 2-yr red maples had a more frequent irrigation requirement, which may have been a result of slowed establishment due to potbound condition at planting.

Trees with larger trunk diameters initially required more frequent irrigation, probably due to larger canopy areas. Longer frequencies during the second year (Table 2) are an indication that the root system was expanding beyond the backfill where sensors were placed. During the third year only the 2-yr red maples showed short irrigation intervals, suggesting that they were not fully established. Slower establishment of large trees is consistent with other studies (Gilman, et al., 1998; Lauderdale et al., 1995; Watson, 1985). In general this is because smaller trees more quickly regain a balance of root:shoot. Although restoring this balance is normally considered a B&B problem, large CG trees usually have circling roots which may be cut at planting in an attempt to avoid potential girdling root problems (Laiche et al., 1983). The 2-yr red maples had the largest trunk diameter at planting and were severely rootbound, resulting in a larger portion of the root system being lost when roots were cut at planting. Arnold and Struve (1989) found that up to 37% of root dry weight was removed from ash seedlings in 2.2-L containers when pruned in a similar manner. The dense nature of the cut roots in the current study may also have hindered root growth out of the rootball. Although not measured quantitatively, smaller trees appeared to loose proportionally fewer roots at planting, which may have helped them avoid moisture stress and speed establishment.

Irrigation versus rain

Irrigation intervals were often shorter following an irrigation event than after rains (data not shown). Although competition was controlled in the immediate vicinity of the trees, water could be lost from the surrounding soil because of evaporation, deep drainage or by lateral movement away from the trees (Black, 1991). As the surrounding soil became drier, a greater percentage of applied water was probably lost because this water was drawn to the drier areas away from the well watered zone near the tree (Kramer, 1969). After rainfall the soil was uniformly moist, likely resulting in little net lateral water movement. In the second or third season, when roots had grown outside the nursery row, trees competed directly for water with nearby turf. Therefore, some applied water was not available for tree use.

Another factor that accentuated the difference between tree response to rain vs. irrigation were the dry atmospheric conditions. Conditions associated with no rainfall were also conditions of low relative humidity, and thus high vapor pressure deficit. As less water was available to surrounding vegetation, the microclimate around the trees became drier. Although there are few clear replications by which to assess this phenomenon statistically, the difference in irrigation interval was quite clear when a saturating rainfall was followed by successive days without rain. For example, on 12 July, a rainfall of 4.4 cm fell on ground which was already moistened from two days of light rain (Figure 2.). This rain thoroughly saturated the soil and dropped soil moisture tension to near zero. A subsequent 15-day dry period was interrupted by a minor rainfall of 0.12 cm on 24 July. Despite the rain which came during the second or third dry-down, all groups except the 2-yr sugar maples (D) had shorter irrigation intervals after irrigation than after rain. The 2-yr sugar maples would also have shown this pattern if it were not for the minor rain which lowered soil moisture tension just before the irrigation threshold would have been reached on day six. Both groups of red maples (A, B) reached 0.055 MPa tension six days after rain, but took only four days on the next two dry-downs. As noted earlier, the 1-yr sugar maples (A) took longer to dry than the other groups. In this case they took eight days to dry to 0.055 MPa tension after the rain, but seven days after irrigation.

Species

Figure 2 illustrates the difference between species. Although the 2-yr sugar maples (D) were similar in size to the red maples at planting (Table 1), by the middle of 1999 they had developed a dry-down pattern that was similar to the 1-yr sugar maples (C, Figure 2) even though they were significant differences in both height and trunk diameter between the groups of sugar maples (Table 1). This is probably a genetic expression of differing water-use efficiency between the two maple species. Red Sunset® is among the most flood tolerant red maple cultivars (Anella and Whitlow, 1999; Zwack et al., 1999). Sugar maple is generally considered flood intolerant, being rarely if ever found in swamps (Burns and Honkala, 1990). Canham et al. (1996) found that red maple had reduced biomass allocation to roots when soil resources were plentiful, although sugar maple had a more conservative allocation to the root system which did not vary with availability of soil resources.

Growth

One-yr and 2-yr red maples had similar height at planting, and after only one summer in the field, also had similar trunk diameter (Table 1). During the summer of 1998 height growth of 1-yr sugar maples was greater than 2-yr sugar maples (Table 3). In 1999, 2-yr red maples had significantly more height growth than 1-yr red maples even though 1-yr red maples grew more in trunk diameter than the 2-yr red maples. These growth differences did not result in significant differences in height or trunk diameter between 1-yr and 2-yr trees after 1, 2 or 3 years in the field (Table 1). In 2000 there were no differences in growth of any group (Table 3).

One-yr Sugar maples had significantly greater height growth than 2-yr trees in 1998 (Table 3). Despite this growth difference, the 2-yr sugar maples were always larger in height and trunk diameter than the 1-yr trees (Table 1).

Conclusions

Red and sugar maples had different growth rates (Table 3) and patterns of water use (Figure 2). After one season of growth in the field there were no significant differences between red maples which had spent one or two seasons in P+P production. Landscapers therefore can plant 1-yr red maples instead of 2-yr trees and have similar sized trees one year after planting. One-yr sugar maples, however, will remain smaller than 2-yr trees, at least for three growing seasons.

After transplanting, supplemental irrigation requirement was controlled by four factors other than the occurrence of rainfall. Environmental variables were responsible for most of the observed variation in irrigation frequency. For example, the largest range (3 to 15 days), that was recorded for 1-yr red maples in the second season was primarily the result of varying environmental conditions. The smallest trees (1-yr sugar maples) initially had the longest interval between irrigation events, probably due to their smaller canopy area; however, the largest trees (2-yr red maples) did not establish as well as other trees and required more frequent irrigation three years after transplanting. Soil drying occurred approximately one day sooner if the source of water was irrigation versus natural rainfall. Finally, sugar maples appeared to require slightly less frequent irrigation than red maples after establishment.

Because environmental conditions are usually less stressful during the spring than in mid summer, newly planted trees may need more frequent irrigation in the summer.

However, prevention of rootball desiccation is critical for newly planted trees, although we did not directly assess rootball dryness in this study. As a general rule, 40 L of water every four days was sufficient under most conditions for P+P trees during the first season after planting. In light of other studies (Gilman et al. 1998; Sivyer et al., 1997), this irrigation volume may be excessive at times. Irrigation every three days should be appropriate during dry periods when irrigation has been the only source of water. Less frequent irrigation appears to be acceptable under lower environmental demand.

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Table 1. Mean height and trunk diameter at planting (spring 1998), after one (fall 1998), two (fall 1999) and three (fall 2000) growing seasons in the field (n=10).

	Spring 1998	Fall 1998	Fall 1999	Fall 2000
Treatments	Height (m)			
1-yr red maples	2.60	2.90	3.85	4.43
2-yr red maples	2.54	2.85	4.01	4.69
1-yr sugar maples	1.81	2.18	2.96	3.51
2-yr sugar maples	2.56	2.73	3.40	3.97
	Trunk diameter[z] (cm)			
1-yr red maples	3.35	4.63	7.28	8.98
2-yr red maples	3.77	4.88	7.30	9.11
1-yr sugar maples	2.36	3.43	5.23	6.95
2-yr sugar maples	3.36	4.35	6.30	7.87
Significance[y]	Height			
Species	<0.0001	<0.0001	<0.0001	<0.0001
Production cycle	<0.0001	0.0004	0.0027	0.0017
Species x Production cycle	<0.0001	<0.0001	0.1621	0.3722
	Trunk diameter			
Species	<0.0001	<0.0001	<0.0001	<0.0001
Production cycle	<0.0001	<0.0001	<0.0001	0.0002
Species x Production cycle	<0.0001	0.0013	0.0001	0.0034
Preplanned contrasts	Height			
Red maple 1-yr vs. 2yr	0.4488	0.5423	0.2118	0.0865
Sugar maple 1-yr vs. 2yr	<0.0001	<0.0001	0.0022	0.0044
	Trunk diameter			
Red maple 1-yr vs. 2yr	<0.0001	0.0645	0.8736	0.4660
Sugar maple 1-yr vs. 2yr	<0.0001	<0.0001	<0.0001	<0.0001

[z] Measured 15 cm from substrate surface.

[y] P > F from analysis of variance.

Table 2. Mean and range of number of days required for backfill to dry to 0.055 MPa tension after saturating rain or irrigation during each year in the field (n = 4).

	1998		1999		2000	
	Mean	Range	Mean	Range	Mean	Range
1-yr red maples	4.6	3 to 7	5.2	3 to 15	7.0	4 to 10
2-yr red maples	4.2	2 to 8	5.5	2 to 10	5.4	3 to 9
1-yr sugar maples	6.4	5 to 9	7.2	5 to 12	7.2	6 to 9
2-yr sugar maples	4.5	2 to 8	4.9	2 to 8	7.8	6 to 9

Table 3. Height and trunk diameter growth during each year in the field (n=10).

	1998	1999	2000
Treatments		Height increase (m)	
1-yr red maples	0.299	0.946	0.581
2-yr red maples	0.306	1.166	0.678
1-yr sugar maples	0.373	0.779	0.555
2-yr sugar maples	0.170	0.657	0.580
		Trunk diameter increase[z] (cm)	
1-yr red maples	1.28	2.65	1.70
2-yr red maples	1.12	2.42	1.80
1-yr sugar maples	1.07	1.86	1.65
2-yr sugar maples	0.99	1.95	1.57
Significance[y]		Height increase	
Species	0.4385	<0.0001	0.4033
Production cycle	0.0181	0.04959	0.4108
Species x Production cycle	0.0118	0.0217	0.6263
		Trunk diameter increase	
Species	0.0088	<0.0001	0.0826
Production cycle	0.0585	0.2289	0.8697
Species x Production cycle	0.5402	0.0160	0.2521
Preplanned contrasts		Height increase	
Red maple 1-yr vs. 2yr	0.9012	0.0356	0.3557
Sugar maple 1-yr vs. 2yr	0.0009	0.2338	0.8108
		Trunk diameter increase	
Red maple 1-yr vs. 2yr	0.0772	0.0118	0.3536
Sugar maple 1-yr vs. 2yr	0.3512	0.3623	0.4846

[z] Measured 15 cm from substrate surface.
[y] P > F from analysis of variance.

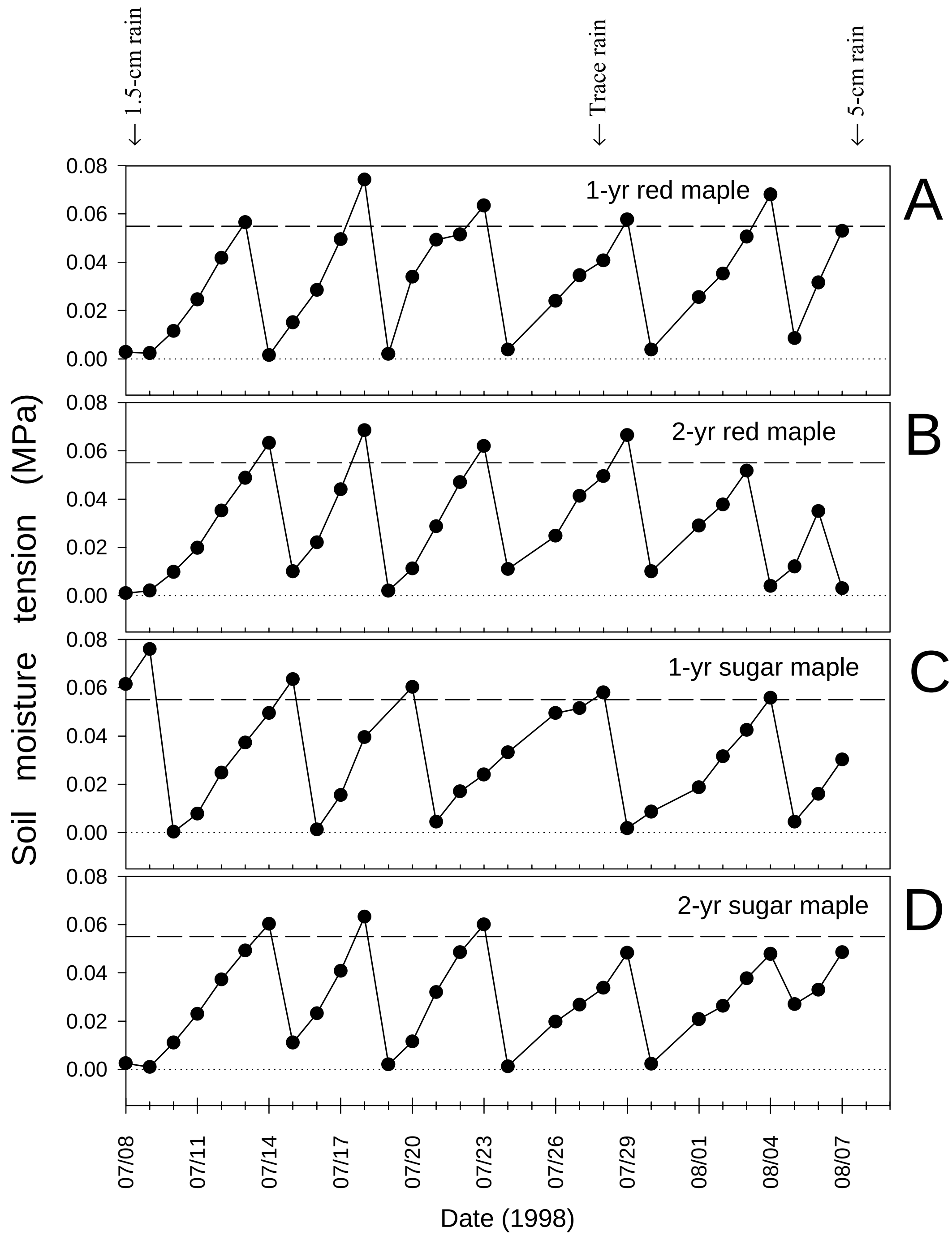

Figure 1. First uninterrupted dry-down of the experiment. Graphs show average soil moisture tension adjacent to the rootball for trees of each group (A = 1-yr red maple, B = 2-yr red maple, C = 1-yr sugar maple, D = 2-yr sugar maple). The dashed line marks 0.055 MPa, the irrigation threshold (n=4).

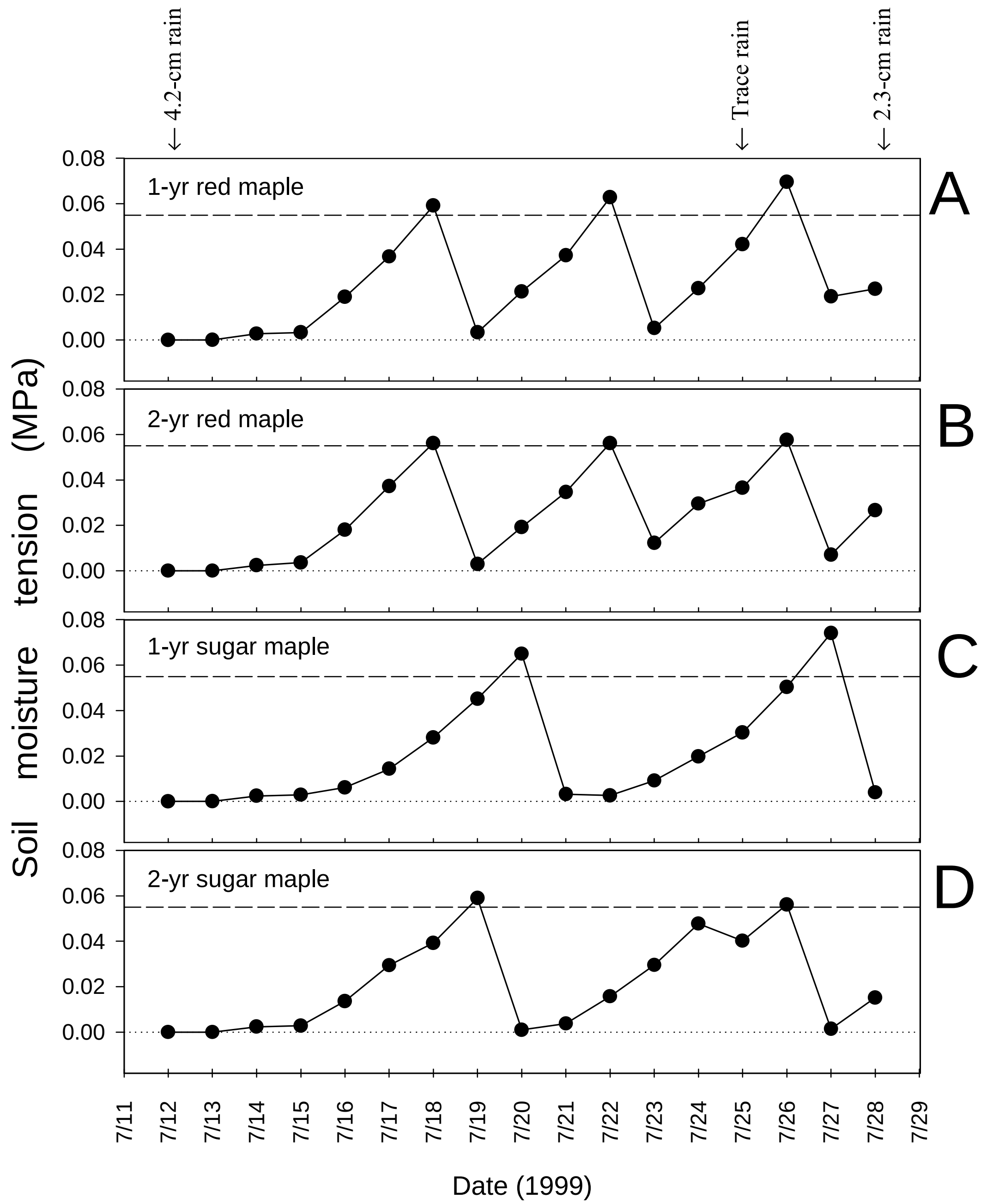

Figure 2. Dry-down pattern after natural saturating rainfall, and irrigation. Graphs show average soil moisture tension adjacent to the rootball for trees of each group (A = 1-yr red maple, B = 2-yr red maple, C = 1-yr sugar maple, D = 2-yr sugar maple). The dashed line marks 0.055 MPa, the irrigation threshold (n=4).

CHAPTER FOUR

PREDICTING WATER USE OF TREES DURING POT-IN-POT PRODUCTION

Abstract

Irrigation management during plant production is becoming increasingly critical as water resources dwindle and the public becomes concerned that nurseries may pollute the environment by the intensive use of water and fertilizer. Models of water-use developed for above-ground container production are unsuitable for pot-in-pot (P+P) production due to considerably different environmental conditions and plant growth rates. Water use therefore was modeled for red maple (*Acer rubrum* L. ‘Franksred’) and sugar maple (*Acer saccharum* Marsh. ‘Green Mountain’), produced in either 1-yr or 2-yr P+P production cycles. Comparing tree growth and environmental measurements with individual tree water use yielded equations that predicted water use. Three prediction equations were developed. 1) A simple model, dependent only on tree size and air temperature, was determined to be acceptable for general use. 2) An environmental-based model modified the Penman-van Bavel equation by the addition of other environmental observations and tree descriptive variables. 3) A complex model utilized sine and cosine functions of day-of-the-year to further improve water use predictions. The environmental and complex models are probably not suitable for the general use of most growers, as they require considerable equipment and environmental measurements. The statistical analyses used to develop these models represent an improvement over traditional correlation or multiple linear regression methods.

Introduction

Water availability is crucial to the growth and development of woody plants. For example, community productivity in natural ecosystems has been positively correlated with increasing rainfall (Lieth, 1973). Many plant physiological processes are closely tied to water availability. Cell elongation is the first major physiological function to be impaired by low tissue water potential (Hsiao, 1973; Nilsen and Orcutt, 1996). A reduction in tissue water potential (ψ) of only 0.1 MPa can impact cell growth (Hsiao, 1973; Hanson and Hitz, 1982). Since turgor pressure commonly varies between 0.5 and 1 MPa (Nilsen and Orcutt, 1996), plants are often under growth-limiting water stresses. This growth-limiting water stress may be expressed as midday wilt or stomatal closure (Schulze, 1986). Whitlow et al. (1992) found that ψ fell below –2.0 MPa near midday daily for trees in New York City, even though the trees were able to quickly recover to predawn water potentials. Partial midday stomatal closure was observed during the study, particularly under the most extreme water potential reductions. Even when plants are irrigated daily, water stress during the latter part of the day led to reduced growth in pot-in-pot production (Witmer et al., 1998).

Pot-in-pot (P+P) production closely resembles conventional above-ground container production, except that most of the P+P growing container is below the soil surface. This is accomplished by placing a permanent “socket” pot in the ground. The socket pot remains in the ground while production containers are removed and replaced as needed. The in-ground placement of the production containers prevents extreme fluctuation of rootball temperature, thus allowing increased root growth and better root distribution, and it also prevents container blowover without close spacing (Ruter, 1993; 1997b; Mathers, 2000).

Plants produced in P+P production systems often have increased growth (Martin et al., 1999; Ruter, 1997a) and are grown at greater spacings than above-ground container production, both of which may increase irrigation demand. Increased growth with cyclic irrigation (Fain et al., 1998, 1999; Ruter, 1997a; Witmer et al., 1998) suggests that P+P trees do undergo low-level water stress when irrigated only once a day. Growers can potentially reduce this low-level water stress by properly using improved irrigation technologies; however, plants may still experience mid-day water stress, not because water is lacking in the substrate but because water use exceeds the capacity of the plants hydraulic system (Schulze 1986).

Inexpensive electronic timers may be used to accurately control microirrigation systems. These systems can provide as much or as little water as is desired, offering computer-controlled precision for irrigation scheduling. Recent studies have shown that although water use may increase with cyclic irrigation, the leached fraction is less, which leads to water and fertilizer savings (Beeson and Haydu, 1995; Karam and Niemiera, 1994; Ruter, 1998).

Unfortunately, the full benefit of computer-controlled microirrigation systems is not being realized because of insufficient knowledge about the water needs of plants in P+P production. The P+P production system has a significantly different environment from either above-ground container or field production. In particular, substrate temperatures are buffered from extreme heat or cold (Young and Bachman, 1996). Since substrate temperature affects growth (Cooper, 1973; Graves et al., 1989; Lyr, 1996; Lyr and Garbe, 1995), buffering of temperatures may help explain the increased growth observed in P+P production as compared to above-ground container production (Ruter, 1993; 1996; Martin, et al., 1999). Because of the altered microclimate induced by P+P production, standards developed for irrigation of above-ground container plants may be inadequate for P+P production. Many growers find it difficult to adapt water regimes to P+P production (Ruter, 1997a).

Numerous water use models have been created for outdoor container production of ornamental crops in small containers (Burger, et al., 1987; Beeson, 1993; 1997; Fitzpatric, 1980; Furta et al., 1977a; 1997b; Knox, 1989). In an early quantitative experiment, Furta et al. (1977b) reported that monthly water use patterns for plants in 3-L containers were significantly (r = 0.61 to 0.98) correlated with evaporation from a Class A evaporation pan. He presented maximum and minimum water use (for a single day) during each month and ploted these figures on a graph connecting the points with smooth sine-like curves.

As a continuation of this work, Furta et al. (1977a) studied the daily water use patterns of 3-L containerized plants under drip irrigation in California and again found good correlation between a Class A evaporation pan and white and black Livingston atmometers. Typical correlation coefficients (r) were 0.848 to 0.736 but were influenced by a number of factors. They found that evapotranspiration varied with species, position within a bed, wind, plant size and shape, and time of year. Solar radiation inconsistently influenced evapotranspiration, leading to the assumption that other factors were more important. Differences in evapotranspiration between species could not be explained by plant size and shape characteristics alone. Individual plants, within species and microenvironment exhibited significant variation.

Fitzpatric, (1980) studied actual water consumption of 15 species grown under screen shade in 3-L pots in Florida. He compared the monthly water use patterns with the Bailey moisture index, a Class A evaporation pan, and the Thornwaite equation and found the highest correlation with the Thornwaite estimates (r = 0.94 to 0.97). Fitzpatric started with the size (height and width) of a reference plant (*Ficus benjamina* L.) for which water use could be predicted accurately (r = 0.97). A ratio of size between another species and the reference plant was used to modify the regression equation (y = -0.12 + 0.35x) for *Ficus benjamina* to predict monthly water use. A good correlation ranging from –33% to +27% for species that consumed more than 2 L of water per month was found. Large differences were reported for plants that used less water (range = –46% to +123%). The Thornwaite equation ($E_t = 1.6(10Ta/I)^a$) is based upon the monthly mean air temperature (Ta) and the annual heat index (I) = $\sum_{i=1}^{12} 1.6\left(\frac{Tai}{5}\right)^{1.5}$, a = $4.9 \times 10^{-1} + 1.79 \times 10^{-2} I - 7.71 \times 10^{-5} I^2 + 6.75 \times 10^{-7} I^3$ (Fitzpatric, 1980). The evaporation pan had correlations of r = 0.58 to 0.82 with the three test species, while the Bailey moisture index had correlations of only r = 0.35 to 0.38 for these plants.

In 1983, Fitzpatric reported on a continuation of this work in which the relative water demand of 12 species was studied. This time, no reference plant was used; instead, water demand was correlated directly with the Thornwaite estimates for each month of the study. This showed that there was still a good correlation with the Thornwaite estimates, but also that there was considerable monthly variation during the production cycle. This study did not focus on the utility of the Thornwaite predictions, but focused on the relative differences between species, which were considerable.

Burger, et al. (1987) attempted to determine how much water was required for maximum growth and aesthetic value of containerized plants in California. To this end, they developed crop coefficients for use with CIMIS (California Irrigation Management and Information System) measurements for a reference crop (healthy turf at 7.5 to 15 cm in height). They found that crop coefficients were higher for containerized plants than for other crops, ranging from 1.1 to 5.1. This large range necessitated the division of these 22 ornamental woody plant species into three groups: heavy, moderate and light water users. They found that the crop coefficients depended on plant spacing but varied little with location (4 California sites). They also found that autoporometer-based estimates were improved by using total leaf area, but they were still not sufficiently accurate for predicting water use.

Knox (1989) used linear regression to investigate the relationship between pan evaporation, predicted evapotranspiration by the Thornwaite equation and growth index with water use of five species of woody plants in 3-L containers in Florida. The plants were grown on tables under a sideless, acrylic-roofed shelter providing approximately 67% full sunlight. Growth index was calculated as (height + width)/2 and measured every 4 to 6 weeks. The highest R^2 values (0.78 to 0.88) were obtained when both evaporation pan and growth index were used as predictors. When the Thornwaite equation was used with growth index, the R^2 values were lower (0.26 to 0.81), but were generally considered good. He concluded that plant species and size are the primary factors influencing water use and that estimates of potential evapotranspiration could be used with plant size to determine water requirements of containerized plants.

Beeson (1993) presented a Florida study where actual evapotranspiration of *Rhododendron* sp. ‘Formosa’ in 12 L containers was compared to evapotranspiration predicted with the Penman equation. The Penman equation was chosen over the Thornwaite equation because it could be used at a finer time scale (daily as opposed to monthly). He found that the overall correlation was relatively poor (r = 0.67) on a daily basis, but when summed over a four-day period became reasonable for irrigation scheduling (r = 0.88). Interestingly, he determined that the correlation was not improved by including plant canopy characteristics in the model. He also determined that the 95% confidence interval for the crop coefficient ranged from 0.50 to 0.65 for the four-day summed Penman prediction. Beeson also noted that the Penman equation was particularly inefficient during the period of shoot growth, but he also indicated that this might be improved by frequently measuring the canopy during this period.

In 1997 Beeson performed a similar experiment to investigate the evapotranspiration of *Ligustrum japonicum* Thumb. at different moisture allowable deficits (MAD). He found that only the control, 20% MAD and 40% MAD treatments were economically feasible. Correlation with predicted evapotranspiration was best after the canopy had closed in the high irrigation treatments. Correlation could be improved by normalizing the estimates of evapotranspiration by canopy surface area. The canopy surface area was estimated by regression equations based on the most recent plant growth measures.

Early researchers of water use in containerized plants recognized the importance of environmental factors and plant characteristics (Beeson, 1993 and 1997; Burger, et al., 1987; Fitzpatric, 1980; Furta et al., 1977a; 1977b; Hales, 1727; Knox, 1989). The first quantitative studies identified expected maximum and minimum water use values for each month (Furta et al., 1977b). Later, researchers tried to model water use with various instruments and prediction equations, with mixed success. Recent research has utilized the Penman equation because it provides water use predictions for time scales as short as one day, which is quite practical for irrigation scheduling. Unfortunately, although plant characteristics can be used to refine the precision of the models, the models still are not able to predict to the desired precision level.

A model of water use in the P+P system which accounts for the major determining factors, both environmental and plant, will be useful for future development of precise irrigation regimes. With this in mind, the objectives of this study were: 1) to determine which environmental and descriptive variables which most influence water use, 2) to determine how these variables interact to determine water use in P+P production, 3) to develop a pragmatic model which can be used for irrigation scheduling by growers, and 4) to develop a more complete model which describes theoretical interrelationships that will be beneficial for further study.

Materials and Methods

On 10 May 1996, 1.5 m-tall bare root whips of red maple and sugar maple were planted into 56-L pots. The pine bark substrate (Summit Bark Plant, Waverly, Va.) had an initial pH of 5.1, air space = 24.3%; bulk density = 200 kg/m^3; total porosity = 79.8%; and a water holding capacity of 55.5%. Ground dolomitic limestone (18% Ca, 10% Mg; James River Limestone Co., Inc., Buchanon, Va.), with a calcium carbonate equivalence of 100%, was added at a rate of 3.6 $kg{\cdot}m^{-3}$. A micronutrient mixture (Micromax™, The

Scotts Company, Marysville, Ohio) provided the following nutrients at the indicated concentration: 12% Sulfur, 0.1% Boron ($Na_2B_4O_7$), 0.5% Copper ($Cu\ SO_4$), 12% Iron ($FeSO_4$), 2.5% Manganese ($MnSO_4$), 0.05% Molybdenum (Na_2MoO_4), and 1% Zinc ($ZnSO_4$), and was incorporated at 0.9 kg/m^3. All trees were topdressed at the beginning of each growing season with 168 g of 18N-2.6P-9.9K Osmocote® (The Scotts Company, Marysville, Ohio). These trees were allowed to grow in the P+P system with daily irrigation for one year before being used in the experiment. The P+P system had socket pots alternately spaced 1.36 m apart within rows and 1.18 m apart between rows which allowed 2.5 m^2 per tree.

On 15 May 1997, trees of four groups were arranged as a randomized complete block experiment. The groups consisted of: 1) 10 newly potted bare-root, red maples 2) 10 newly planted sugar maples (3) 10 previously grown red maples, and 4) 10 previously grown sugar maples. The trees were potted 22 April 1997 and 10 May 1996 for the newly planted and previously grown groups, respectively. All trees were originally obtained as 1.5 m - tall whips from J. Frank Schmidt & Son Co., Boring, Ore. The newly planted trees were potted in the same substrate and manner as the previously grown trees. Liners were pruned back to approximately 1.8-m height. All trees were topdressed with Osmocote® as described above. Data were collected during the growing seasons of 1997 and 1998.

In the spring of 1998 the trees which had been planted in 1996 were removed from the experiment and the trees which were potted in 1997 were then identified as being in their second production cycle. Newly potted (3 April 1998) liners of red and sugar maple replaced these trees as the first production cycle measurement units. A new randomization of the same experimental design was put into effect when the trees were measured on 5 May 1998. At the beginning of the second growing season (1998) the desired liner material was not available. Red maple liners used in the second year were therefore smaller than in the previous year; average trunk diameter was 1.30 cm compared to 2.13 cm the year before (Table 1). *Acer saccharum* ‘Green Mountain’ liners were not available, so *Acer saccharum* ‘Commemoration’ liners were used. The replacements were similar trees with approximately the same growth rate and foliage characteristics. The same substrate, amendments and fertilizer as previously described were used. Liners were pruned to 1.8 m tall when planted.

In Virginia it is common for both of these species to be placed in P+P production for two growing seasons (production cycles). The experiment therefore included trees in each production cycle during each of the two years.

All trees were brought to container capacity (full water holding capacity after drainage) at 0600 daily with a computer controlled microirrigation system with one 360° spray-stake placed near the center of each pot. Container capacity was assured by irrigating until runoff. Leachate was collected periodically to determine if the plants were receiving sufficient water and to monitor electrical conductivity (EC) of the substrate solution. Frequently checking the position of the spray stake assured good surface coverage and thorough wetting of the substrate. Water use for the previous day was determined as the difference in weight just before, and one hour after irrigation. Both were measured by early morning to minimize the risk of transpiration between measurements. A preliminary study (data not presented) showed no significant difference between the weight of trees at container capacity from one day to the next.

In addition to water use, tree-size was also recorded on each measurement day. Trunk diameter was measured twice at 90° angles 15 cm above the substrate surface, and the lengths of three previously selected, randomly selected shoots were recorded. Trunk cross-sectional area (basal area) was calculated from the average trunk diameter using the formula for the area of a circle. As an estimate of canopy size, two profile pictures were taken with a 35-mm camera, scanned into a computer with Adobe® Photoshop® version 4.0.1 (Adobe Systems Incorporated, San Jose, Calif.), and brightness and contrast adjusted to clarify pot dimensions and canopy area. The pictures were then transferred to SigmaScan/Image™ Version 1.02.09 (SPSS Science, Chicago, Ill.). When calibrated with the known pot height, the flood-fill measurement tool estimated projected canopy area (CAN) in cm^2.

Environmental observations were recorded continuously with a DYNAMET® weather station (Dynamax, Inc., Houston, Texas) equipped to measure air temperature (TA in ºC), global radiation (GR in w·m-2), wind speed (WS in m·s-1), relative humidity (RH in %), and precipitation (mm). The weather station was modified to measure wind and radiation at 3.8 m above ground (just above the highest canopies), relative humidity and temperature were at mid canopy level, while rainfall was measured over adjacent cropped turf. Data were recorded hourly with a data logger and periodically uploaded to a portable computer. The environmental data were partitioned so that daytime (prefix D), nighttime (prefix N), and whole day totals or averages could be obtained for the study days. The values for complex predictive relationships: vapor pressure deficit (VPD) (see Equation 1 below), vapor pressure deficit over windspeed (VPDOWS), the Penman estimate of evapotranspiration (PEN) (see Equation 2 below), and the Penman-van Bavel estimate of evapotranspiration (ET) (see Equation 3 below) were also calculated from the data. The Penman-van Bavel equation is a modification of the Penman equation using hourly average values instead of daily observations. The Penman-van Bavel equation depends on the elevation and the height of wind observations and was adjusted accordingly for our 610-m elevation and 3.8-m measurements. The environmental data set thus consists of four measures of primary environmental parameters and four calculated values; all except the Penman estimate were then divided into daytime and nighttime averages for each study day.

Equation 1. Vapor pressure deficit

VPD=(SATA*RH)/SATA

SATA = 33.8639((0.00738TA+0.8073)8-0.000019(1.8TA+48)+0.001316)

SATA = Saturated Vapor pressure. mb (Bosen, 1960)

Equation 2. Standard Penman Equation

PEN = (((SVP*RN)/LHV)+PC*EA)/(SVP+PC)

SVP = (33.8639*(0.05904*(0.00738*TA+0.8072)**7-0.0000342))
RN = ((1-α)*Rs –Rb)
α = ~(0.23)
Rs = (2.067*GR)
Rb = (σ*TK^4*(0.56-0.08*(sqrt(ed))*((1.42*Rs)/(Rso-0.42)))
σ = (11.71*10**-8)
TK = (TA+273)
ed = (33.8639*((0.00738*min+0.8072)**8-0.000019*(1.8*min+48)+0.001316))
Rso= (242.45*518.13*(sin(T/365*3.14159)))
LHV = (59.59-0.055*TA)
PC = (0.66) (mb / °C)
EA = (0.263*(ea-ed)*(0.5+0.0062*U2))
ea = (SVP*(RH))
SVP = (33.8639*(0.05904*(0.00738*TA+0.8072)**7-0.0000342))
ed = (33.8639*((0.00738*min+0.8072)**8-0.000019*(1.8*min+48)+0.001316))
U2 = (UZ*(2/3.66)**0.2)
UZ = (WS*(1000/(60*60*24)))

PEN = Estimated evapotranspiration ($mm \cdot day^{-1}$)
SVP = Slope of the Saturation Vapor Pressure curve ($mb \cdot °C^{-1}$) (Bosen, 1960)
RN = Net Radiation ($cal \cdot cm^{-2} \cdot day^{-1}$)
α = Albedo for vegetated surfaces (0.23) (Jones et al., 1984)
Rs = Total incoming Solar radiation ($cal \cdot cm^{-2} \cdot day^{-1}$)
GR = Global radiation ($MJ \cdot m^{-2} \cdot day^{-1}$)
Rb = Net outgoing thermal or longwave radiation ($cal \cdot cm^{-2} \cdot day^{-1}$)
σ = Stephan Boltzman Constant ($cal \cdot cm^{-2} \cdot day^{-1} \cdot K^{-1}$)
TK = Temperature (K)
ed = Saturation Vapor Pressure at the dew point (minimum daily temperature) (mb)
Rso = Total daily cloudless sky radiation ($cal \cdot cm^{-2} \cdot day^{-1}$) (regression equation developed from Jensen, (1974) and Doorenbos and Pruitt (1977) for 35° N latitude)
T = Day of the year (Integer)
LHV = Latent Heat of Vaporization ($cal \cdot cm^{-2} \cdot mm^{-1}$)
PC = Psychometric constant (0.66 $mb \cdot °C^{-1}$)
EA = Multiplier.
ea = Average Vapor Pressure (mb)
SVP = Slope of the Saturation Vapor Pressure curve ($mb \cdot °C^{-1}$)
ed = Saturation Vapor Pressure at the dew point (minimum daily temperature) (mb)
min = Minimum daily air temperature (°C)
U2 = Windrun at two meters above ground ($km \cdot day^{-1}$)
UZ = Windrun at height Z, (3.66 m); ($km \cdot day^{-1}$)
WS = Windspeed ($m \cdot s^{-1}$)

Equation 3. Penman-van Bavel Equation

ET = (X+(X^2)^0.5)/2

X = ((eps*rnt/LHV)+(def/ras))/(eps+1)
Eps = (1013/abp)*(0.921-0.002632*TA+0.003075*TA*TA)
abp = 1013*EXP(-elf*0.00003817)
elf = 2000
Rnt = (0.8*3600*GR)+nlw
nlw = -0.00020142*((TA+273)^4)+skl
skl = 0.00020142*((TA+273)^4)*(0.7+0.08241*hum*EXP(1500/(TA+273)))
hum = def*rh/(1-rh)
def = (1-RH)*1.323*EXP(17.27*TA/(TA+237))/(TA+273)
LHV = 2.44e6 = latent heat of vaporization ($cal \cdot cm^{-2} \cdot mm^{-1}$)
Ras = (LN(zom/zot)^2)/(0.16*wsm+1)
wsm = WS*3600
zom = 3.8 = height of windspeed measure (m)
zot = 0.0005 = surface roughness parameter

Actual water use data were collected approximately every five days during the summers of 1997 and 1998 as conditions permitted. Because rainfall was not excluded from the containers, water use could only be determined on rain-free days. There were 26 measurement days in 1997 and 16 measurement days in 1998. In 1997 the measurement days spanned 10 June to 20 Oct. In 1998 the measurement days spanned from 13 May to 11 Oct. This provided data during the later part of leaf emergence for the trees through the summer, and to fall leaf drop.

The objectives of model building was threefold: 1) investigate and identify the most important factors affecting water use in the P+P system, 2) evaluate the potential of using environmentally based models for irrigation, and 3) identify or develop a simple model which growers could use in P+P production. Having two years of data allowed testing differences between years. Although the most robust model can be obtained by combining all the data and developing a single model, including years in the model can help determine how much variation can be expected from year to year. The importance of year in the model is inversely an indicator of robustness for prediction.

Model fitting was an involved process in which the strength of multivariate relationships was assessed within the repeated measures structure of the experiment. The *mixed* and *nlmixed* procedures of The SAS® System versions 8.00 and 8.01 (SAS Institute Inc., Cary, N.C.) were used for model fitting and assessing all final models. Both procedures work well for multivariate data. The *mixed* procedure helps to identify the best model by explaining the variation which is due to individual units as a function of time (e.g., individuals with high water use at one time will likely also have high water use, compared to their compatriots, at the next time). In model fitting the exponential temporal/spatial covariance structure was used to describe inter-relations of the repeated measurements and to obtain reliable estimates of the precision of model coefficients and to make reliable inferences. The *nlmixed* procedure does not have the capability to fit complex data structures, however, correlation between observations from an individual can be accounted for by including random effects in the model (Appendix A). The *mixed* and *nlmixed* procedures are both based on maximum likelihood estimation in which the Gauss-Marquardt algorithm is used to maximize the log likelihood (SAS online help documentation). I used the exponential spatial (temporal) covariance structure which defines the (i,j)th element as $\sigma^2[\exp(-d_{ij}/\theta)]$. This is simply a way of describing the stochastic dependency between points in time, in which the expected correlation between two observations of the same experimental unit decreases exponentially with the distance (time) between observations.

Throughout the analysis I used Akaike's Information Criterion (AIC higher is better) and the –2 log likelihood (-2LL) to assess the quality of the various models. The AIC can not be used directly for probability tests, but it can be used to compare non-nested models, the better model has the higher AIC. This statistic is calculated as (log likelihood) – (# of covariance parameters). The -2 log likelihood is similar to the error term in ANOVA tests, and can be used to perform statistical tests between two models. R^2 measures are not appropriate with these analyses, but significance can be tested for the entire model and each of the component terms (used for nested models). Hypotheses may be tested simply as a Chi-squared test of the difference in the –2LL between the two models with degrees of freedom equal to the difference in the number of terms in the compared models.

Results and Discussion

Initial investigation showed two factors [tree size (trunk diameter) and energy available for evaporation (temperature)] to be of primary importance for determining water use (Figures Figure 1 and Figure 2). This was not surprising because researchers dating back to Hales (1727) have noticed that these factors impact water use. Because many different environmental variables have been observed to impact water use, it was surprising to find that a simple model comprised of only these two factors could be used to explain and predict water use accurately.

Development of a simple model

The objective of this analysis was to develop a model based on easily obtained, reasonably accurate, and simple values.

In other studies trunk diameter was often closely correlated with other measures of tree size and leaf area (Martin et al., 1998; Simpson, 2000; Vertessy et al., 1995), while leaf area was correlated with water use for a given set of environmental conditions (Beeson, 1997; McDermitt, 1990; Teskey and Sheriff, 1996; Vertessy et al., 1995). Leaf area and cross-sectional sapwood area were related in balsam fir (*Abies balsamea* (L.) Mill.) (Coyea and Margolis, 1992), mountain ash (*Eucalyptus regnans* F.J. Muell.), silver wattle (*Acacia dealbata* Link.) (Vertessy et al., 1995) and Monterey pine (*Pinus radiata* D. Don) (Teskey and Sheriff, 1996). Because leaf area and sapwood area are closely related, sapwood area should also serve as a predictor of water use for individual trees, either as a direct predictor or when used to estimate leaf area. Not only is sapwood area easier to measure than leaf area, it might also be a more reliable estimator of water use making it a desirable substitute. Wullschleger et al. (1998) observed that total hydraulic conductance only varied between 3.4 and 5.5 $mmol \cdot m^{-2} \cdot s^{-1} \cdot MPa^{-1}$ when expressed per unit sapwood area but varied from 0.30 to 9.9 $mmol \cdot m^{-2} \cdot s^{-1} \cdot MPa^{-1}$ when expressed per unit leaf area. St-Clair (1994) observed that foliage efficiency (stem increment per unit leaf area) was strongly correlated with harvest index (trunk volume) and other measures of tree size for Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) but varied from tree to tree, concluding that partitioning traits were under genetic control.

Trees in this experiment were clones (budded on seedling rootstock) and therefore genetically similar, and according to St. Clair's work (1994) a high degree of precision may be expected when tree size or water use is estimated from trunk diameter. It was soon noted that while water use was related to trunk diameter the relationship was nonlinear (Figure 1A). Although the scatter of this graph appears relatively large, species and age differences explain much of the variation. Because almost the entire xylem of a young stem is recently produced sapwood, it may be assumed to conduct of water and nutrients (Greenridge, 1954; Kramer and Kozlowski, 1979). Thus, stem cross-sectional area should serve as a useful (and easily measured) estimate of leaf area and therefore water use. Water use is linearly related to trunk basal area (BA) (Figure 1B).

BA alone is a relatively good indicator of maximum potential water use for individual trees; however, other factors also determine actual water use for a plant on a given day. For example, many different environmental factors impact water use. In fact, the topic has been extensively studied with little universal understanding. Different factors appear to be good predictors of water use, depending on the environment in which the studies were conducted (Jarvis and McNaughton, 1986). The interaction between a plant and its environment is too varied and complex to be completely explained by one simple universal equation; yet, some simple equations may prove useful in a limited setting, and more complex models (e.g., Penman equation) are useful for almost universal application. As an illustration of complexity, there can be little water loss without a vapor pressure difference between the internal leaf environment and the external environment, although some water may be lost through gutation (Campbell, 1990; Kramer and Boyer, 1995). Vapor pressure deficit provides the driving force for transpiration, but it is linked not only to absolute humidity but also to air temperature by physical laws (Penman, 1948; Kramer and Boyer, 1995). Temperature also affects transpiration because it provides energy used for evaporation. Because temperature is correlated with sunlight, it is difficult to separate the effects of each environmental variable. This is aspect is especially complex because increased radiation affects leaf physiology independent of the associated rise in surface temperature. Although it may appear that any model of water use should include measures of sunlight and relative humidity, this is not necessarily the case. A simplification may be made because under most common circumstances, temperature is positively correlated with water use. This generalization proved useful in the simple model that follows. Although variation is inherent in the data, a linear trend can be identified (Figure 2). This correlation is primarily due to the service of temperature as the energy source for evaporation.

After further investigation, I found that the product of TA and basal area provided an estimate of water use which was much improved over the use of the independent simple effects TA and BA (Table 2). This relationship is useful because it is a shortcut, predicting water use under typical conditions without description of all the factors and complex interactions which act together to determine actual water use. A descriptive model would require that the simple effects remain in the model to properly describe the relationship between the two variables; however, we want a stochastic predictive model, so it is appropriate to drop simple effects for simplicity when they are relatively unimportant.

Components of the simple model were selected by inspecting simple linear correlation coefficients to identify variables and interaction terms that were correlated with water use. The *mixed* procedure was then used to evaluate and select potential model components. This analysis confirmed that the interaction term TABA was the best single predictor of water use (*1 in Table 2.). Next, the importance of the categorical variables: species (S), production cycle (A) and year (Y) was investigated. Only S was important in the model (*2 in Table 2.). Utilizing the interaction term necessitated investigation of the importance of the simple effects TA and BA. Adding both simple effects did not significantly improve the fit of the model ($p = 0.626$), so each simple effect was tested alone. Adding only TA did not improve the fit; however, adding BA alone did create a significantly better model ($p = 0.0006$). The effect of the categorical variables was again assessed and only S was required in the model.

The simple model (see Equation 4 below) is based on the product of basal area and TA and the simple effect of BA for each species, and provides a good estimate of water use. This model is very robust since it is insensitive to differences between production cycles and between years, and is also relatively consistent with changes in other environmental variables.

Equation 4. The simple model is species specific and is based on basal area and the product of air temperature (TA) and basal area (BA).

Red Maple:

$$WU = 0.863 + 0.0767*BA + 0.00832*TA*BA$$

Sugar Maple:

$$WU = 0.702 – 0.0232*BA + 0.0121*TA*BA$$

The simple model has an AIC of –1098.7 and a –2LL of 2193.4. The inclusion of the categorical variables A and Y failed to improve the simple model based on the increase in –2LL of each model (Table 2). This means that the simple model is little influenced by differences between production cycles or years. Taking species out of the model raised the –2LL, indicating that species was required in the model. Using the –2LL to select the best model allowed a way to determine whether having separate models for each level of the categorical variables or a universal model would be preferable.

The negative coefficient for BA in the sugar maple model is reasonable because this model does not rely on an underlying theory to predict water use, rather it is the simplest model which gives reasonable predictions. Through much of their range, TA and BA vary colinearily so coefficients for this term actually reflect the importance of each component for times when they are not perfectly colinear. Similar coefficients of the interaction term TA*BA indicate that both species have similar general trends. Although the interaction terms alone would seem to indicate that sugar maples have higher water use than red maples, this is not the case. The negative coefficient of BA for sugar maples takes away some of the influence of BA, lowering the prediction and leaving a greater percentage of variability explained by TA. In the same manner, the large positive coefficient of red maple BA increases the estimate and the percentage of variation explained by BA. The final predictions show that expected water use of sugar maples is lower than for red maples of a given BA and TA. If not for the coefficients of BA, the interaction term would be locked into an equal split as to the importance of the two estimators. This flexibility is important because the species have different physiological and growth characteristics. Red maples are fast-growing and therefore had a wider range of BA values that dwarfed differences related to TA. Sugar maples were slower-growing and therefore temperature was the major source of variation in water use for those trees.

Both coefficients also reflect the physiological differences between the two species. When the trees were in full leaf (day 170 to 250) each cultivar had a different ratio of BA to CAN, 0.00125 for red maple and 0.00136 for sugar maple. Hydraulic conductance or other physiological differences could also be responsible for species specific variation (Vertessy et al., 1995; Wullschleger et al., 1998)

The model can be statistically improved by the addition of more terms, but the benefit gained is much less substantial than with the initial parameters. It was very important to select a simple model that was not sensitive to differences that could not be easily controlled or measured. For example, water use might be accurately estimated with a series of humidity sensors which could measure the difference between upwind and downwind humidity at various heights, but this is not practical because it is not easily measured or controlled in the field. Species differences are another matter. A species-dependent model does present some questions as to its applicability to any unmodeled species. The idea of grouping similar species into three water use categories is common for ornamental crops (Burger et al., 1987; Fitzpatric, 1983), even though many researchers found considerable differences in the yearly patterns of water use which appeared to be species or even cultivar dependent (Fitzpatric, 1983; Schuch and Burger, 1997; Stanley and Harbaugh, 1994). Specifically, Roberts and Schnipke (1987) found significant differences in relative water demand between red and sugar maple (among other *Acer* species). My investigation confirms that there are relatively small but important differences in the water use pattern of red and sugar maple.

As the species specific traits which control water use can not identified and explained with certainty, selecting a model to use with a new species is problematic. Both models predict reasonably similar water use (0.44 L predicted difference at the highest commonly observed TA and BA values) even though the models are statistically different. This similarity between models is encouraging, because it indicates that growth rate may be used to estimate water use. More research will be needed to determine if water use estimates may be based on growth rates alone. For example, a species-specific stem conductance index might be used to modify BA for predicting water use. Under well-watered conditions, such a measurement could be used to scale BA and a standard interaction with temperature to predict water use. Further testing will be required to determine if the similarities observed in the current models will be sufficient for irrigation prediction of a wide range of species.

In summary, the simple model is an effective shortcut to predicting maximum potential water use of individual trees in the P+P system under normal conditions. The model utilizes the covariation of temperature with water use and the absolute indicator of maximum potential water use for each individual BA to predict water use. This combination allows predictions to be responsive to an integrated measure of tree size and to a general measure of environmental conditions. Unfortunately, the model is not responsive to complex changes in other environmental variables, as is the environmental model that follows; nor is it sensitive to seasonal patterns of water use, as in the complex model.

The simple model is superior to other models of equal complexity. Table 2 contains the fit statistics for other relatively simple models, which are based on the Penman and Penman-van Bavel estimates of water use. These models were expected to provide better predictions of water use because they are utilize more environmental information which is combined based on theoretical models of evaporation. However, the Penman and Penman-van Bavel prediction-based models do not perform as well as a model containing temperature alone or with BA. The combination models do have an advantage over the untransformed environmental measurements. They are based on theoretical relationships which can be teased apart to advance our understanding of water use in the P+P system. The Penman-van Bavel model can be modified to perform even better than any linear combination of the raw or transformed environmental observations, as will be seen in the discussion to follow.

The Environmental Model

The simple model is a good basic estimator of water use of plants in the P+P system, but it is not directly sensitive to changes in environmental variables other than temperature. However, other environmental factors do not significantly improve the model when added as linear or transformed terms. This might be because there is a more complicated interrelationship than can be emulated with the linear combination. Several equations have been created which predict potential evaporation or evapotranspiration based on environmental measurements.

The Penman, and Penman-van Bavel equations are known as combination models because they combine energy availability and turbulent transfer theories to calculate evapotranspiration (Rosenberg et al., 1983; van Bavel and van Bavel, 1990). These models did show some utility for predicting water use, even though their initial performance, when used alone or with BA, was not as good as the simple model using TABA (Table 2). This is probably because some aspect of the P+P microclimate impacts water use in a manner that is not explained by the model, within either energy availability and/or turbulent transfer.

The Penman equation was originally developed to predict evaporation over open water, but it was also found to be useful for bare soil and turf with slight modifications (seasonal and crop coefficient terms, and albedo adjustment) (Penman, 1948). Other researchers found that the underlying relationship was reliable and useful for prediction of water flux in a wide range of situations and environments, particularly in agricultural and hydrologic studies (Black, 1991; Rosenberg et al., 1983). One condition for which the Penman equation is clearly inadequate is under the condition of advective heat removal (Rosenberg et al., 1983). Plant and soil parameters are often successfully used to modify the Penman equation (Rosenberg et al., 1983). In this case, the Penman equation is used as an estimate of potential evapotranspiration, with measures of moisture availability and stomatal conductance acting as resistance terms to reduce the estimate of predicted evapotranspiration.

The van Bavel modifications to the Penman equation include substituting a theoretical wind relationship and a surface roughness parameter for the empirical windrun relationship of the original Penman equation. The van Bavel equation also can be used on a short time scale (usually 1 hour), whereas the Penman equation can only be used for daily evapotranspiration estimates (Rosenberg et al., 1983; van Bavel and van Bavel, 1990).

The extreme differences between the altered microenvironment of the P+P system and the natural environment for which the Penman equation has been commonly used explain why it does not perform as well as was hoped. The P+P system provides each tree with sufficient space for an essentially open canopy, unlike the cropped turf or bare soil to which Penman compared his models. The space between our trees was covered with black landscape fabric and plastic that absorbed heat and did not allow moisture to exchange between soil and air. Finally, the substrate in which P+P plants are grown has low bulk density and limited volume, and it is maintained at relatively high moisture availability levels unlike natural soils. The impact of these differences are difficult to explain theoretically, especially when dealing with an already complex relationship, but modern statistical techniques allow us to investigate these changes and to determine with a fair degree of certainty which aspects of the altered microclimate have the greatest influence on water use. With these empirical-based modifications, the combination equations may still have some utility for modeling water use in the P+P system.

One experimental goal was to identify the situations and conditions under which the combination models were not efficient predictors of water use. However, before the environmental models could be studied in detail much of the variation due to individual tree characteristics needed to be explained. To do this, a model-building base program was constructed. This was accomplished by using the *mixed* procedure of SAS® to create four separate models, one for each species and production cycle combination, under a single analysis (see SAS® programming statements in Appendix A). This analysis also incorporated repeated measures as in the simple model.

A single analysis that encompassed four separate models simultaneously allowed for quick and efficient model selection. The combination models provided a logical place to begin building because they are used universaly in evapotranspiration estimation and prediction and are based on theoretical relationships. The Penman-van Bavel equation provided better estimates than the Penman equation because it responds to hourly changes in predictive data. Only the model building process for the Penman-van Bavel based equations will be discussed, as these equations were more accurate than the Penman based equations with the same number of predictor terms.

The first model consisted of an intercept term (mean) for each combination of species and production cycle. This model had an –2LL of 2680.1 (Table 3). Other factors were then added to help explain individual differences. Basal area was the logical choice, as it had proved useful in the simple model. However, whenever species and production cycle were both included in the model, trunk diameter (CAL) proved to be a better predictor of water use. Although the utility of trunk diameter was compared to basal area at each step during model building, trunk diameter was consistently the most useful measure of tree size. As in the simple model, only one measure of tree size was selected to avoid problems of overspecification. The model for water use for each species and production cycle combination with trunk diameter as the only predictor gave an –2LL of 2538.2. Species, production cycle and trunk diameter remained in the model during the building process and were only re-evaluated at the end of the process.

The importance of including shoot length (SHT) was investigated at each step and was quite erratic. A combination of environmental variables explained the same variation that SHT explained. This is probably because shoot growth functions better as an indicator of physiological development than as a measure of tree size. When shoots were small and immature there was little water use. However there was great variation in the growth of selected shoots, negating their value as a measure of tree size. As environmental variables were added to the model they explained the same variation that SHT had explained in the early models. Finally, SHT was not significantly important in the final environmental model. Shoot length is also time consuming for growers to measure, and it is probably unrealistic to include in a grower's model. Shoot length is dependent on species and age. Had these terms not been included in the model it is very likely SHT would not have appeared important in any model.

Penman potential evapotranspiration and Penman-van Bavel potential evapotranspiration were evaluated next, and as indicated earlier, the Penman-van Bavel values were consistently more useful. The Penman-van Bavel estimate was added to the model both as a linear term and as an interaction with trunk diameter. This improved the fit of the model to a –2LL of 2297.8 and an AIC of –1150.9 (*1 in Table 3), which was still not improved over the simple model presented above.

At this point it is important to review some basic model building theory. A model attempts to explain variation in the dependent variable, or in the case of a predictive model, variation in future observations of the predicted variable. Identifying and describing a relationship between the dependent variable and one-to-many predictor variables does this. The relationship may be a simple linear function of a single variable (linear regression), a more complex description involving many factors which impact the dependent variable in a linear manner (multiple linear regression), or it may be a much more complex relationship in which the predictor variables combine in complex functions to describe the relationship with the dependent variable (non-linear regression). Because non-linear regression is quite complicated and time consuming, variables may be transformed in some manner to approximate the true curvilinear relationship. Once transformed they may be analyzed as linear models. In the following analysis, log and squared transformations were applied to environmental variables to detect areas of the

Penman-van Bavel equation which could be modified to provide better prediction of water use in the P+P system.

The environmental model is based on the Penman-van Bavel combination equation, which acts as a complex transformation. Because of its complexity identifying precisely the location of any mis-specification within this variable is difficult. At best, the gross areas where there appear to be problems can be identified. To do this, inclusion of simple weather observations were evaluated after ET was included in the model. Transformations of the weather data were applied after the important environmental variables were selected.

Adding the daily average environmental measures: TA, global radiation, relative humidity and windspeed to the model improved the –2LL to 2108.5 and the AIC to –1056.3 (*2 in Table 3). The AIC indicated that this model was better than the simple model, but it is much more complex and still needed further adjustment. The drop in –2LL gained by adding these variables was highly significant ($p < 0.0001$), although model fixed effects analysis showed that global radiation was not important. Removing the radiation term gave a model for which all terms were significant at $p < 0.05$. Although this model had an improved fit, it was not sufficient to warrant removal of the radiation term before evaluation of environmental measurements with a complete set of alternatives.

The Penman-van Bavel equation predicts zero water loss when there is no incoming global radiation (unlike the Penman equation); it also does not account for moisture deposited as dew. For these reasons the effect of specifying day versus night environmental conditions was evaluated. Weather data were separated into three measures: overall average, daytime average and nighttime average. When these ten terms were included in the model the –2LL was improved to 1998.7 which was highly significant (*3 in Table 3). However, not all of the individual terms added were significant.

The best model should have only as many terms as needed to describe a relationship adequately. If fewer terms are included, the model is under-specified; if more terms are included it is over-specified. This time, a modified backwards selection procedure was conducted to remove unnecessary terms from the model. The environmental term with the lowest Type III main effect F-value (the greatest probability of a greater F) was removed until the –2LL could not be reduced further. When the backwards selection was complete, nighttime air temperature, overall average relative humidity, daytime relative humidity, nighttime relative humidity and overall average wind-speed remained in the model. An –2LL of 1930.9 was attained by this method (*4 in Table 3). This selection decreased both the –2LL and the complexity of the model.

Inspection of deviation plots revealed that log, squared and inverse transformations of the five selected environmental variables might be more accurate predictors. By replacing a term with its transformation and assessing the fit of the entire model, four terms were improved by transformation: WS became log windspeed (LWS), RH became log relative humidity (LRH), DRH was replaced by daytime relative humidity squared (DRHXX2), NRH remained unchanged, while NTA was replaced by log nighttime air temperature (LNTA). These transformations improved the fit of the model to a –2LL of 1830.5 (*5 in Table 3).

The model was now nearly complete. Upon checking other potential components, the –2LL could be significantly ($p = 0.039$) lowered to 1820.4 by the adding daily average vapor pressure deficit (*6 in Table 3). At this point the addition of no other environmental or tree size variable could improve the fit of the model. However, further simplifications were made.

Close inspection of the coefficients for each equation revealed that only three terms, ET, CAL*ET and LWS were significantly important in all four equations. Two of these terms, LWS and CAL*ET had coefficients similar enough to share a single estimate. When this step was complete the final environmental model had an AIC of –903.9 and a –2LL of 1803.8 (*7 and *8 in Table 3). Although the simplification of CAL*ET was not a significant ($P = 0.165$) improvement to the model it allowed for simplification. At this point all main effects in the model had p-values less than 0.0001, although not every coefficient was important in each of the four prediction equations. The full list of model coefficients and the significance of each component in their respective equations can be found in Table 4. Figure 4 illustrates the fit of the environmental model to average water use.

Further investigation revealed that both species ($p < 0.0001$) and production cycle ($p < 0.0001$) were required in the model. The –2LL improved to 1648.7 when year was included in the analysis. This indicated that there were significant ($p < 0.0001$) differences in this model with respect to years. This difference was probably a result of inconsistent plant material from year to year, although other factors could also be involved. Without knowing the true cause of these differences there is no utility to having separate equations for each year. Significant differences between years indicate that considerable variation is still unexplained by this model. Further research should be conducted to determine if differences in water use are indeed due to describable differences in plant material or other factors. This model is designed as a test of the utility of the Penman-van Bavel estimate of evapotranspiration rather than a model for field use. The environmental model is not recommended for irrigation scheduling, primarily because with nearly the same information a more precise prediction will be obtained with the complex model.

The interaction of TA and BA which was so crucial in the simple model is absent from the environmental model. This is probably because the chosen combination of environmental variables could explain more variation when many terms were allowed in the model. Furthermore, these terms explained the same variation in a much more direct manner than the simple interaction was capable of explaining (colinearity).

Shoot length, CAN and BA were also not included in the model. As indicated above SHT was not retained in the final model because it did not explain more variation than the environmental variables. Even though the environmental variables did not reflect physiological development in the same way as SHT, their coincidental covariation makes SHT unnecessary as a predictor of water use. Basal area is also missing from the model because when species and age are specified relative differences in size are more important than the actual ability of the plant to transport moisture. The methods used to obtain CAN were not precise enough to make this variable valuable. Day-to-day variation in sunlight direction and intensity, wind and camera position created anomalies in the measurements of this variable. If this technique is to be used in the future, it must be under tightly controlled (indoor) conditions. If these technical difficulties can be resolved, this method should prove useful in future studies, as the general trend in these data was quite good. Estimates of CAN might be used in conjunction with developmental stage to describe how the factors of developmental stage and tree canopy area combine to determine water use. Trunk diameter was more important than basal area as a measure of relative tree size, than as an absolute predictor of ability to translocate water. Trees of the same species and production cycle had similar canopy areas and similar responses to environmental conditions. Trunk diameter changed less dramatically than basal area throughout the season, preserving its usefulness by describing relative differences in size between trees in a particular group.

Of those terms that remained in the final model, ET was one of the most important. The Type III F-value of the interaction between CAL and ET was 83.92 with 1 and 1521 df, indicating this interaction was very important and was a highly significant ($p < 0.0001$) component of each equation. However, many additional environmental terms were needed to fully describe the relationship between environmental conditions and water use in the P+P system. All of the main environmental measures except global radiation are used to modify the Penman-van Bavel estimate. GR may be missing, not because its importance is well modeled by the combination equation, but because the experimental protocol limited the range of observations (data were collected only from days without rain which generally correlated with high GR).

Of the environmental factors that did appear in the environmental model, RH showed up most frequently, being in four of the modifying terms (Table 4). Relative humidity's presence as both daytime, and nighttime values and in VPD indicated that RH can be used more efficiently than it is in the Penman-van Bavel equation. The significance of so many similar terms hints at the complexity inherent in both the model and in the needed modifications. Although relative humidity is clearly important, the complexity of the model adjustments and the complexity inherent in the Penman-van Bavel model indicate that making clear inferences is very difficult. The impermeable black surface of the P+P system causes large differences in humidity of the air above. Whenever this surface is wet and energy is available, water is released rapidly to the air above; however, when the surface is dry and energy is available, the surface heats quickly, releasing heat to the air and dropping relative humidity. The combination equations are not able to model both the vegetated and unvegetated surfaces simultaneously. The energetics of the non-vegetated surface of the P+P likely interacts with the vegetated surfaces in ways that were unintended in the original models. These interactions may be influenced by solar radiation angle, eddy correlation, advection, and other difficult to describe and complex factors rather than the normal measures of environmental parameters, which explains why they would manifest themselves as functions of relative humidity rather than as functions of global radiation or daytime air temperature.

Nighttime air temperature was the only temperature-related modification. One of the prime differences between P+P and other production methods is the substrate temperature. Nighttime air temperature may reflect the average substrate temperatures in the P+P system. As substrate temperatures were not studied during the experiment, we can not test this theory directly. However, near earth air temperatures are surely related to soil temperatures (Lowry and Lowry, 1989; Rosenberg, et al., 1983), and soil temperatures impacted growth and water relations (Graves, et al., 1989). Several species of plants had greater growth at higher soil temperatures than are typical in their native environment (Lyr and Garbe, 1995). Differences in tolerance to high soil temperature appear to be species specific with minimal clinal variation (Graves and Aiello, 1997), although tolerance can be altered by preconditioning (Ruter, 1996). The P+P system typically maintains rootball temperatures that are more moderate than in above-ground containers, yet warmer than nursery beds (Martin et al., 1999; Ruter, 1993, 1997b). The moderate temperature maintained in P+P production as opposed to above-ground container production is commonly credited with producing differences in growth of many species (Martin et al., 1999; Ruter, 1993, 1997a, 1997b, 1998). Spring substrate temperature in the P+P system also tends to be as much as 5°C (2 to 3°C is typical) warmer than adjacent field beds whenever a large portion of the black surface is exposed to solar radiation, as is the case before leaf emergence or with a large percentage of small trees (Harris and Fanelli, 1999). Although nighttime air temperature surely affects respiration and growth, the impact of this factor on daily water use should be of minor consequence. The ability to absorb and translocate water to the leaves is also impacted by substrate temperature, and might be of more immediate relation to daily water consumption. Monitoring substrate temperatures in further studies would enable confirmation of this hypothesis.

Overall average windspeed was also a correction factor in the environmental model. This likely reflects an incorrect specification of the roughness parameter within the Penman-van Bavel equation. The impact of wind on evapotranspiration is both important and complicated. The simple wind function used in the Penman equation is probably adequate for turf and other short, uniform plants, though more descriptive measures are needed for complex plant structures (Holbrook and Lund, 1995). The default value for surface roughness was used in the Penman-van Bavel equation because information regarding the proper coefficient for an almost closed canopy of small trees was lacking. Later attempts to identify the correct surface roughness parameter using nonlinear analysis failed, presumably due to the relatively small dataset.

Although different factors were important for each group, all main effects were significant at $p < 0.0001$. All predictors were also important ($p < 0.0001$) for 2-yr red maples, presumably because these trees were the largest, and therefore the most exposed to differences in environmental variables. All coefficients in this equation are quite large; indicating that applying this equation when conditions are outside the observed range has the potential to produce some serious errors. One-yr red maples were profoundly sensitive to fewer factors; however, significance was greater than $p = 0.05$ for CAL and VPD. Only three descriptive terms: ET, the interaction of ET and CAL, and LWS, were significant components in both production cycles for sugar maple. In addition, 1-yr sugar maples were sensitive ($p < 0.05$) to CAL and VPD, while 2-yr sugar maples were sensitive ($p < 0.05$) to the transformed variables: DRHXX2, NRH and LNTA. The differences in sensitivity to various environmental factors could reflect the disengagement of the smaller plants, which were more thoroughly enveloped in the modified microclimate.

Overall, the environmental model provides a good estimate of water use in the P+P system; however, the theoretical relationships that are the strength of the combination equations are negated by the addition of numerous other environmental measurements. Still, the Penman-van Bavel equation remains the core of this model. No other combination of environmental variables can equal the precision obtained with this estimate. Yet if this estimate is so strong, the environmental variables must be explaining some other source of variation.

Examining the predictions of this model made it clear that some descriptor of physiological stage was needed in the model. Correlation was good during the spring and early summer, but was poor during the late summer, when trees were attaining their maximum trunk diameter but simultaneously loosing responsiveness to environmental variables because of leaf senescence. The environmental variables measured were unable to completely account for this source of variation, even though there was some coincidental variation during this period.

The Complex Model

A more complex model was needed because of the importance of seasonal development to transpiration. The environmental model handles weather factors admirably, but it is not sufficiently responsive to tree physiology. Trees have low water use in the spring due to their small canopy size, even though individual newly formed leaves may have low water use efficiency. Likewise, water use of trees that are loosing their leaves in the fall is not as responsive to changes in environment as it is during the summer when trees are in full canopy. This developmental cycle apparently impacted water use of red and sugar maples in a periodic and predictable pattern, perhaps explaining some of the inconsistencies observed in the earlier models.

Schuch and Burger (1997) suggested that a Fourier curve based on months could be used to describe the seasonal pattern of water use. They concluded that crop coefficients may be useful for low water users even though they tend to inflate estimates when water use is actually low, particularly during the winter. High water users needed to have water use estimates adjusted for growth stage and location. In either case, the Fourier curve could be used to adjust the estimates of water use to the cyclical pattern of yearly water use.

A repeating function (sine-cosine curve) was therefore used to describe the general pattern of water use at a particular time. A transformation similar to a Fourier curve was used, but it estimated the general trend with the sum of only two equations rather than 12. This was possible because of the non-linear statistical approach, and because the model did not need to predict water use during the winter months.

The key to identifying the proper transformation was to look for conditions under which other models performed poorly and to then find a transformation that fit the trend of average water use during the entire time period. The simple model seemed to miss-predict or to break down entirely during the late summer and fall when the leaves were senescing (Figure 3). At this time temperatures and basal area were relatively high, yet water use was falling quickly. Further investigation confirmed that this pattern could also be detected with the environmental model (Figure 4). The resulting predictions of both models cut through the middle of the data, predicting lower than actual in the late summer to avoid predicting too high at the end of the season, but still predicting higher water use than was observed during this period. The multiplicative relationship that was used for both the simple and environmental models produced a good fit to the data, but it did not take into account the fact that the leaves had started to senesce. An objective measure of senescence, called canopy quality (CQ = percent of crown area which is colored or missing) was recorded the first year and did help to alleviate some of the problem. However, the data showed a reduction in water use that began before visible signs of senescence.

A function which repeats periodically works well for this type of estimation because water use can be expected to return yearly to some base level and can be modified to respond to tree size or age variables to modify summer water use estimates. Growth rate and senescence follow a general pattern from year to year based on light, temperature, and water and nutrient availability. Because water and nutrient levels are kept relatively consistent from year to year in the P+P system, large differences should not be expected in the periodic cycle of leaf emergence, growth, maturity and senescence as they affect water use. When light and temperature patterns are viewed on a yearly scale, their general patterns are also quite predictable. This means water use should be predictable as a function of day-of-the-year if the proper form of the relationship describing changing water use through the growing season could be determined.

After scanning many potential models and comparing them to water use patterns of individual trees and mean values, one relationship appeared to be appropriate because it grows slowly to a peak and falls rapidly at the end. The general form of the transformation follows in Equation 5:

Equation 5. The general form of the time transformation

$$Y = \sin(2*X)+5*\cos(X)$$

This equation describes a repeating curve, which has a peak at X=0.3214 and repeats every $2*\pi$ (see Figure 5). The location of the peak can be adjusted by adding a value (α) to both X values in the equation such that the amount of the adjustment equals

$(2*\pi)/365.25$ days so that for each day forward a value of 0.017202 is added to X. The new form of the equation follows in Equation 6:

Equation 6. Foundation equation modified to fit peak to time α

$$Y = \sin(2*(X+\alpha))+5*\cos(X+\alpha)$$

The timing of the peak expected water use can be calculated precisely as: $(((2*\pi) - \alpha) / 0.017202) + (0.3214/0.017202)$ days after the start of the year ex. for $\alpha = 2.9$ the peak would fall on day 215 (3, August) in late summer.

Including a multiplier can control the magnitude of the curve (β) which modifies the entire expression to the form seen in Equation 7:

Equation 7. Form of the foundation equation modified for amplitude β and peak timing α

$$Y = \beta*(\sin(2*(X+\alpha))+5*\cos(X+\alpha))$$

This multiplier controls how much the model appears to curve through the data when it is combined with an intercept term (χ) as seen below in Equation 8:

Equation 8. Final foundation equation with α, β and χ adjustments.

$$Y = \chi+\beta*(\sin(2*(X+\alpha))+5*\cos(X+\alpha))$$

The intercept term controls the placement of the curve on the Y-axis. The range of our data covers 160 days, from day 133 to day 293, or about 43% of the year. This means that there is little need for much vertical adjustment of the curve to properly fit the data while maintaining an overall positive assumed water use.

Because this is a non-linear model, a new analysis procedure must be used. The *nlmixed* procedure of SAS® allows investigation of non-linear models. This allows inclusion of repeated measures, categorical, continuous and random effects. The only drawback is that it does not handle the repeated measures data in the same way as the *mixed* procedure. To compensate for this, a random term may be added which modifies the β term for each individual. This is an indirect way of accounting for correlation among the measurements. Because a different modeling procedure was used for this analysis the AIC is not comparable to the earlier models.

The transformation using only three terms (α, β and χ) provides a tight fit to the observed data. Such a simple model explains more variation in water use than any other single environmental parameter or equation. No further adjustment of the curve due to time is needed to fit water use during the growing season. Adding a parameter which would multiply the X or time measurement (T) would allow the curve to stretch or compress to fit the data even better, but it would make the model unnecessarily complex. Further modifications could also be added to prevent negative water use predictions during the winter, but because plants are not irrigated during the winter in this climate these terms were not needed.

Using time alone to estimate water use yields the following foundation model (Equation 9):

Equation 9. Water use as predicted by the foundation equation

$$EWU = 0.9846+0.3412(\sin(2*(T/365*2*3.14159+2.5666))+5*\cos(T/365*2*3.14159+2.5666))$$

This equation fits the average daily water use data very well (Figure 6), with a –2LL of 2548.1 (*1 in Table 5).

Although this model explains much of the variation between days, it does not explain any of the variation between trees of different sizes, production cycles or species. This model fits the basic pattern of changes in average BA throughout the year because these changes follow a relatively predictable growth pattern as a function of time. However, the model is not responsive to the differences between individuals. Much of this variation can be explained by adding species and production cycle as categorical variables. A measure of tree size would also help identify individuals which were not of typical size for their production cycle and species group. Finally, the general trend may be modified by adding environmental variables, which allows the model to respond to days which do not fit the general pattern for that time of year. There is still a great deal of variation between both days and individuals, which may be accounted for with a more complex model.

The same basic reasoning was used as in the development of the base environmental model. A base model, with separate foundation equations for each species and production cycle was used to evaluate additional terms (model programming in Appendix A). The base model was better than models separated by species or production cycle only, having a –2LL of 1960.3 (see *2 in Table 5). After entering species and production cycle into the model, it was possible to investigate the importance of plant size and weather observations. The complex base model revealed not only the importance of specifying species and production cycle, but also the difference in yearly water use patterns between the groups.

Of particular interest is the timing of peak water use. Although further modifications will be made to the model, I would like to diverge on this topic while the model is less complex and the relationships are clear. The base model predicts a different pattern of water use for each species and age combination (Figure 7.). Interestingly, red maples are predicted to use more water later in the season having their peak water use on 2 September in the first production cycle and 27 August in the second production cycle. The pattern for sugar maples appears less dependent on production cycle as their expected days of maximum water use are 8 and 11 August for the first and second production cycles, respectively. As more factors are added to the models the α values reflect the unexplained pattern of water use. For example, when basal area is added to the model, it explains much of the same variation as the time transformation. However, its presence in the model means that the estimated parameters for the time transformation will change to best take advantage of the new information. In short, we know that day of the year and basal area are related. Therefore, when basal area is added to the model we expect that this systematic modification will be expressed as a change in the coefficients of the time transformation. Indeed this is the case since when BA was added to the model, the estimates of peak water use time were 1 to 5 days earlier than in the model without BA. This resulted from BA remaining high at the end of the season, which forced the transformation equation to peak at an earlier time to allow estimates to fall properly at the end of the season. This adjustment in transformation peak does not mean that the actual time of highest water use has changed, as the estimates of peak water use continue to increase past the time of peak in the transformation because basal area was increasing.

Model building is more difficult and time consuming with nonlinear models. Analyses will not converge unless starting values of coefficients are chosen carefully. Even then they may not converge. Therefore, it is not possible to conduct the same type of backwards regression used for the environmental model. Instead, residuals from the base model were subjected to multiple linear analysis using the *mixed* procedure to select terms for further investigation. These terms were then entered as linear modifiers in the nonlinear analysis, to confirm their value as regressors. The utility of these regressors was tested using the likelihood ratio test described earlier. This analysis showed that BA, ET, BA*ET, TA, TA*BA, RH and GR were likely candidates for inclusion in the model. As these additional terms were added to the model, the χ coefficient became the intercept term for each model, instead of the intercept for the time relationship alone. Likewise, α looses its meaning as a precise measure of predicted peak water use and becomes another coefficient for accurate estimation.

Good equations were identified during development of the simple and environmental models, and this information was used while developing the complex model. In the simple model it was found that the interaction TA*BA was very important. In the environmental model CAL*ET was important. Because of their similarity and the complexity these terms introduce to the model, only one interaction of this type is desired in the complex model. The linear analysis indicated that both TA*BA and BA*ET were candidate terms in the complex model, so both interactions were fully investigated.

A test of the model components TA, BA and TA*BA indicated that these terms were valuable (-2LL = 1763.8, AIC = -910.9), even though much of the same variation was explained by the time transformation. This model requires only easily measured variables to provide good estimates of water use, so it is important even though not selected as the complex model (Appendix A). Although the simple model components were valuable regressors, the Penman-van Bavel estimate of evapotranspiration formed a better base from which to develop more complex models.

As indicated above, basal area was added to the model as a linear term and was important (*3 and *5 in Table 5), both alone ($p < 0.0001$) and with ET ($p < 0.0001$). Penman-van Bavel ET was also valuable (*4 and *5 in Table 5) alone ($p < 0.0001$) and with BA ($p < 0.0001$). The interaction of BA and ET also significantly ($p < 0.0001$) improved the model (*6 in Table 5). This model now had a –2LL of 1795.8 and an AIC of –926.9. Although these regressors do not fit the water use data as tightly as the model above, this model can be improved to a greater extent in subsequent steps than the alternative. During complex model building, BA was equal to or better than, trunk diameter and SHT for explaining variation in water use. Using BA as a multiplicative modifier of the time function was attempted, but made the relationship too complicated to converge. This would have allowed the time function to be directly responsive to differences in basal area instead of being modified later.

This model is now more responsive to differences in BA and daily differences; however, there are still further modifications that will help to adjust the model to day-specific conditions. As in the environmental model, weather observations were added as linear terms in the model. Air temperature, RH, GR and WS all improved the model when added alone as linear terms. Air temperature and RH were the terms that decreased the –2LL most. Air temperature was the single most important term significantly improving the fit of the model ($p < 0.0001$). RH was the next most valuable regressor, but did not significantly improve the fit of the model ($p = 0.289$), so it was not included in the final model. Transforming these variables did not improve model fit.

The final complex model had an AIC of –895.6 and a –2LL of 1725.2 (*7 in Table 5). The coefficients for this model are presented in Table 6, while the full results are included in Appendix A. All coefficients are significant terms for at least one group of plants. The α and β terms are highly significant for all four groups which confirms the need for a time dependent transformation.

This model appears considerably better for prediction than either of the previous models. Because of the change in model specification with the non-linear model, the AIC does not fully reflect the ability of this model to predict accurately. Comparing predicted values to the observed average water use in Figure 8, we can see that the predicted values follow the actual observations better than either of the previous models (Figure 3 and Figure 4).

Reduction tests were conducted to determine whether species and production cycle remained important in the final model. Both species ($p < 0.0001$) and production cycle ($p < 0.0001$) were important in the final model (Table 5).

As in the environmental model, years differed significantly ($p < 0.0001$), but the cause of this effect is not clear, although the difference in plant material was a likely factor. The environmental model should have been fairly robust and insensitive to differences in years because many of these differences are included as terms in the model. However, possibly the most important difference between years was in the size of the plants used. The considerable difference in plant material from year to year was important because the equation was not flexible enough to accommodate a large range of basal area and still hold the proper shape for transformation of time. This is a direct result of not being able to include a term for the interaction of basal area and the time transformation as was desired. This interaction would have allowed basal area to be more influential during times of the year with high water use, but less influential when water use was low in the spring and fall. Unfortunately, as mentioned earlier, the model would not converge with this arrangement resulting in a complex model that was sensitive to differences in years. The comparatively late start of data collection in the first year could also have allowed the transformation curve to fit in a slightly different way, contributing to the differences between years. In any case, the effect of these differences is quite small. Although the model parameters for some terms are considerably different, the actual predictions of water use are quite similar for a given set of conditions. This is because the model accounted for the uniformity in the yearly pattern of water use for groups of individuals to accurately predict water use.

The complex model responded to most environmental variables similar to the actual data, although not as strongly. The complex model predicts the same general trend as its base model, but it is responsive to environmental variables responsible for day to day differences in water use (Figure 8). Some of the fluctuation in Figure 8 is due to differences in basal area between years which create variation in the general trend of water use for both the actual observations and the predicted values on this graph.

The complex model is very sensitive to differences in time. Second production cycle trees were exposed to the natural environment and therefore responded to environmental cues, whereas the smaller trees did not respond to the same cues because they were kept refrigerated until planting time. The difference in planting date from one year to the next was considerable (19 days), resulting in a difference in developmental stage that contributed to the different yearly water use patterns. These differences probably contributed to the greater degree of uncertainty associated with plants in the first production cycle. Although these plants were more uniform in overall size than the second production cycle trees, there was a greater uncertainty about model coefficients for the younger trees. One solution might be to tie the timing of peak water use to the planting date for first production cycle trees rather than to day-of-the-year. This solution requires much more data about the relationship of planting date to water use. These differences mean that there is greater uncertainty about predictions for the first production cycle, although the complex model presented should prove acceptable for prediction purposes.

The large differences between species indicate that there are unexplained physiological differences between even closely related species, making it problematic to use these models for other species without first knowing the cause.

Conclusions

Several models were presented which may be used by growers to predict water use. It is important to note that like any model, these are best used only under conditions similar to those for which they were developed. With this in mind, these equations represent approximate maximum water use for rain-free days.

Growers are often interested in maximum growth, or in maximum water use efficiency. One benefit of pine bark substrate is that when unamended with sand, peat or other materials it is very difficult to over-irrigate plants. A very small reduction in water availability may reduce growth (Hsiao, 1973; Hanson and Hitz, 1982). Growers must balance the desire for maximum growth with the cost of applying more water, wasting fertilizer, and potentially polluting the environment. Applying water at the same rate it is being used for growth is ideal for maximum efficiency, although irrigating to this standard may facilitate a buildup of salts in the container (Furta et al., 1977b). One-hundred percent pinebark substrate worked well for experimentation, although growers should be able to choose a different mix with little change in the expected water use as long as water is readily available to the plant.

The equations developed for this study are the result of water use measurements for rain-free days. This procedure may cause the model to overestimate water use on days when water use is not high, particularly on rainy days. Growers must always investigate model effectiveness by in-field inspections, even with the most sophisticated models. Because differences between individual plants were significant, some plants will receive more or less water than is required. Growers may feel the need to apply slightly more water than the models predict to allow for this variation. On the other hand, reducing the amount of water applied below that predicted could be used as a strategy to conserve water under drought restrictions or other water limitations, yet to supply adequate water to maintain high quality plants. Periodic leaching may be particularly important when this irrigation strategy is used.

Most growers will probably find that the simple model best suits their irrigation scheduling needs. It is insensitive to differences in production cycle and year of experiment, yet still performs sufficiently well to be used for prediction. The simple model can be implemented with a thermometer, calculator and knowledge of average trunk diameter. Because the simple model does not require production cycle information, it may be used to obtain adequate estimates of water use across a wide range of trunk diameters. This could be quite beneficial when growers start with plant material differing in size from that used for our models. The more general nature of this model might make it the better choice for predicting water use of different species. New species might be irrigated by the most appropriate equation; the red maple equation would be most appropriate for fast growing species and sugar maple equation most appropriate for more moderate growers. Or, crop coefficients could be developed to modify the base equations.

The simple model is a good predictor of water use; however, it should be used with caution as the graphs indicate that it may be prone to underprediction during mid to late summer, and to overprediction at the beginning and end of the season. This model should provide adequate estimates of water consumption even with blocks of mixed species (but similar trunk diameter). Chronic underprediction may be a problem during the late summer because of salt buildup in the containers. During the experiment, salt buildup was not a problem because of the high rate of water application needed to determine water use. Although the simple model does not predict water use as precisely as the environmental and complex models, it does have the advantage of being very robust. Only temperature and basal area are needed to reasonably estimate water use.

The environmental model is intended as a base from which researchers may expand investigation. The environmental model identifies some problems with the way the combination equations predict water use for the P+P system. Since additional environmental terms besides the Penman-van Bavel estimate of ET were significant, it is evident that there is some important relationship that is miss-specified for use in the P+P system. The problem may be something as simple as an improper surface roughness parameter, or albedo, but it is probably more complex. Another possibility is that the assumption of zero sensible heat conductance to the soil is incorrect. If further studies are attempted in the P+P system, a record of substrate temperatures should be kept. Further study of the wind patterns through eddy correlation might also be informative. Even with these problems, the Penman and Penman-van Bavel equations do appear to have potential for predicting water use in the P+P system. There is no doubt that these equations provided a much more precise estimate of water use than was obtained with the simple model; however, that greater level of precision was only obtained by the addition of correction environmental terms. The necessity for specification of species and production cycle within the model also limits its general application.

The complex model has perhaps the greatest potential for accurately predicting water use in the P+P system. The sine-cosine transformation is unique for it's simplicity, functionality and fit to yearly water use data. Although our data were not collected the entire year, the shape of the curve is such that it could be used for predicting water use for the entire year. With a larger data set, the same basic curve could be modified to also be a function of basal area or tree age, making it an even more powerful tool. Preliminary tests of this technique showed promise, although it could not be incorporated in the present analysis. The strength of the sine-cosine relationship indicates that it, or something similar, should be a component in any model of this type.

Implementing the complex model would require the installation of a weather station and would work best with computer controlled irrigation. Growers may also want to derive coefficients for their own complex model locally because microclimate factors may be more or less important at another site than they were in Blacksburg, as was found to be the case in California (Burger, et al., 1987).

The complex model also uses the Penman-van Bavel estimate of evapotranspiration as the most influential environmental predictor. Although the complex equation is quite data intensive, it does predict more precisely than a simpler model.

A combination of the foundation equation and the simple model components performed quite well (Appendix A). This combination was insensitive to differences between years, but it indicated that both species and production cycle parameters were needed. When species and production cycle information are included in this model, a very good model (AIC = -910.9 and –2LL = 1787.2) is created. Although using these components as a base did not work as well as using the Penman-van Bavel equation, it did represent a viable and less data intensive alternative for water use prediction. Even though this model provides better estimates of water use than the simple model, growers may find it is more limited in scope. Because this model identifies the production cycle, it also limits the range of basal areas for which it is compatible. For extrapolating the water use of trees outside the typical size for that production cycle, the simple model may provide better estimates.

The simple effect of BA dropped in importance when the time transformation was inserted into models that included species and production cycle. This indicates that the time transformation explained tree growth as it impacted water use more effectively than BA alone. In effect, the transformation is a model of both typical growth and typical environmental conditions at any point in the season as they impact water use.

What is needed most in this type of model is a method of identifying which days and/or plants do not fit the general trend. Identifying which days should have more or less evapotranspiration from predicted ET would seem to be an easy task. However, because of the strength of the time transformation, a day that appears to have high evapotranspiration at either end of the season may appear to have lower than expected water use in the middle of the growing season. An interaction term between time and ET would probably be effective at describing the desired relationship, but its inclusion made the model too complex to converge under the current analysis. A larger data set with a single species might help alleviate this complexity and allow a better description to be obtained.

The linear term used in the complex model is the best useful identifier of atypical observations under the current analysis. The significance of the simple ET testifies to its general utility. The interaction between BA and ET is even more complicated. Although BA alone is not significant in the models and ET is only slightly effective, when combined they are much more efficient at identifying those trees which may have extreme water use at any particular time. Again, this interaction could probably be best utilized as an interaction with the time transformation, but it can only be analyzed as a simple interaction of BA and ET.

Beeson (1997) found that irrigating at a 40% moisture allowable deficit yielded acceptable plants and water conservation. Though his calculations were based on daily measurements, the current models could be employed on an hourly basis. This fine control of irrigation timing may be desirable, especially since large trees in pinebark substrate can dry quickly. Irrigating three times a day, compared to once a day, improved growth of red and sugar maples in pure pinebark substrate (Chapter 2).

Water use of plants grown P+P differs from that of similar-sized plants in other methods of production. This study provides three equations that help us to understand water use patterns in the P+P system. Certainly, tree species, tree size and air temperature are the three most influential parameters governing water use in the P+P system as indicated by the simple model. More precise estimates can be obtained by utilizing the Penman-van Bavel equation for potential evapotranspiration, although it does not appear to be perfectly suited to this use. Some complex aspect of P+P microclimate impacts water use in a manner that is not fully described by the relationships included in the Penman-van Bavel equation. Finally, water use follows a general pattern based on growth and environmental conditions, which can be described by a sine-cosine function of day-of-the-year. When modified by tree size and environmental variables, this relationship can provide precise predictions of water use.

The tool that enables this complex analysis, is the repeated measures capability of *mixed* and *nlmixed* procedures of SAS®. These procedures remove variation associated with individual experimental units so truly important relationships can be identified. I expect that this form of analysis will become standard for all studies of this nature.

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Table 1. Trunk diameter and height at beginning of each growing season of the study (N = 10 for each group)

1997	**Mean**	**Standard deviation**	**Maximum**	**Minimum**
Trunk diameter (cm)[z]				
'Franksred' red maple, first cycle	2.13	0.13	2.38	1.99
'Franksred'red maple, second cycle	2.89	0.17	3.09	2.57
'Green Mountain' sugar maple, first cycle	1.68	0.15	1.89	1.42
'Green Mountain' sugar maple, second cycle	2.41	0.29	2.72	1.94
Height (m)				
'Franksred' red maple, first cycle	2.01	0.10	2.13	1.86
'Franksred'red maple, second cycle	2.30	0.12	2.46	2.13
'Green Mountain' sugar maple, first cycle	1.77	0.17	2.09	1.53
'Green Mountain' sugar maple, second cycle	2.16	0.12	2.35	1.89
1998				
Trunk diameter (cm)				
'Franksred' red maple, first cycle	1.30	0.18	1.46	0.88
'Franksred'red maple, second cycle	3.17	0.18	3.44	2.96
'Commemoration' sugar maple, first cycle	0.95	0.20	1.43	0.76
'Green Mountain' sugar maple, second cycle	2.45	0.27	2.84	1.98
Height (m)				
'Franksred' red maple, first cycle	0.88	0.37	1.60	0.65
'Franksred'red maple, second cycle	2.03	0.06	2.11	1.93
'Commemoration' sugar, maple first cycle	1.27	0.35	1.66	0.70
'Green Mountain' sugar, maple second cycle	1.71	0.17	2.10	1.45

[z] Measured 15 cm from substrate surface

Table 2. Comparison of fit statistics: simple model. Akaike's Information Criterion (AIC) and –2LL, for potential simple models. The table details the model selection process which included investigation of models for each categorical variable: species (S) production cycle (A) and year (Y), the combination models: Penman (PEN), Penman-van Bavel (ET) the environmental observation, air temperature (TA) and tree size measure, basal area (BA). A lone intercept is indicated by (I). *# indicates order in which progressively better models were selected.

Model components **Term**	**Intercept**	**AIC**	**-2LL**	**Comments**
TA	I	-1270.6	2541.2	Simple effect of TA
BA	I	-1283.9	2563.8	Simple effect of BA
TA*BA	I	-1116.6	2229.2 *1	Interaction of TA and BA
TA*BA*A	A	-1122.9	2241.8	Production cycle not needed (> -2LL)
TA*BA*Y	Y	-1124.6	2245.3	Year not needed (> -2LL)
TA*BA*SBA*S	S	-1106.2	2208.4 *2	Species is needed (p = 0.0000304)
TA*BA*SBA*STA*S	S	-1104.9	2205.8	Add both simple effects (p = 0.626)
TA*BA*STA*S	S	-1107.4	2214.9	Add simple TA (> -2LL)
TA*BA*S	S	-1098.7	2193.4 *3	Add simple BA (p = 0.000553)
TA*BA*S*A BA*S*A	S*A	-1108.6	2213.7	Production cycle not needed (> -2LL)
TA*BA*S*Y BA*S*Y	S*Y	-1099.2	2194.7	Year not needed (> -2LL)
TA*BABA	I	-1110.2	2216.4	Species is needed (> -2LL)
Alternate models for comparison				
PEN	I	-1341.6	2679.2	Simple effect of PEN
ET	I	-1323.4	2642.8	Simple effect of ET
PEN*S BA*S PEN*BA*S	S	-1205.8	2407.6	Interaction and simple effects by S
ET*S BA*S ET*BA*S	S	-1198.7	2393.5	Interaction and simple effects by S
BA*S PEN*BA*S	S	-1162.0	2320.1	Removed nonsignidicant effect of PEN
BA*S ET*BA*S	S	-1157.1	2310.2	Removed nonsignidicant effect of ET

Table 3. Comparison of fit statistics: environmental model. Akaike's Information Criterion (AIC) and –2LL, for potential environmental models. The table details the model selection process which included investigation of potential model components of both tree size and environmental factors as well as complex environmental equations from the basis of a species and production cycle dependent model structure. *# indicates order in which progressively better models were selected. Terms include: species (S), production cycle (A), year (Y), Penman-van Bavel evapotranspiration (ET), basal area (BA), trunk diameter (CAL), air temperature (TA), global radiation (GR), relative humidity (RH), windspeed (WS), vapor pressure deficit (VPD), Prefix D = daytime average, N = nighttime average, L = log transformation. Suffix XX2 = squared transformation.

Model components **Terms**	**Intercept**	**AIC**	**-2LL**	**Comments**
	S*A	-1342.1	2680.1	Means only
S*A*ET	S*A	-1274.4	2544.8	With ET estimate
S*A*BA	S*A	-1281.0	2557.9	With BA
S*A*CAL	S*A	-1271.2	2538.2	With CAL
S*A*ET S*A*BA S*A*ET*BA	S*A	-1158.5	2312.9	
S*A*ET S*A*CAL S*A*ET*CAL	S*A	-1150.9	2297.8 *1	Base for environmental tests
Environmental variables (TA GR RH WS) entered as interaction of S*A	S*A	-1056.3	2108.5 *2	Main effect of GR term was not significant
All day and night divisions of environmental variables added as interaction of S*A	S*A	-1001.3	1998.7 *3	Main effects of all wind terms not significant
WS RH DRH NRH NTA retained as needed terms	S*A	-967.5	1930.9 *4	After backwards selection
LWS LRH DRHXX2 NRH LNTA transformations	S*A	-917.3	1830.5 *5	Selected transformations
VPD*S*A added	S*A	-912.2	1820.4 *6	Coefficients found similar for LWS, CAL*ET and ET
Shared coefficient for LWS	S*A	-906.4	1808.9 *7	
Shared coefficient for CAL*ET and LWS	S*A	-903.9	1803.8 *8	Best environmental model
Best model*y	S*A*Y	-826.4	1648.7	is sensitive to years
Best model without *A (*S only)	S	-993.6	1983.2	needs production cycle
Best model without *S (*A only)	A	-978.1	1952.2	needs species

Table 4. Coefficients and p-values for t-tests of the importance of each in the environmental model. Separate models for each combination of species and production cycle. Terms include: species (S), production cycle (A), year (Y), Penman-van Bavel evapotranspiration (ET), trunk diameter (CAL), air temperature (TA), relative humidity (RH), windspeed (WS), vapor pressure deficit (VPD), Prefix D = daytime average, N = nighttime average, L = log transformation. Suffix XX2 = squared transformation.

	S=1 and A=1		**S=1 and A=2**		**S=2 and A=1**		**S=2 and A=2**	
Term	**Coefficient**	**p (>t)**	**Coefficient**	**p (>t)**	**Coefficient**	**p (>t)**	**Coefficient**	**p (>t)**
Intercept	3.858	0.0148	9.129	0.0001	1.539	0.2818	0.175	0.8698
CAL	-0.181	0.1202	1.039	0.0001	-0.375	0.0306	0.226	0.1053
ET	-0.325	0.0001	-0.508	0.0001	-0.242	0.0001	-0.342	0.0001
CAL*ET	0.150	0.0001	0.150	0.0001	0.150	0.0001	0.150	0.0001
LWS	-0.139	0.0001	-0.139	0.0001	-0.139	0.0001	-0.139	0.0001
LRH	3.08	0.0347	10.158	0.0001	0.733	0.5740	1.082	0.3235
DRHXX2	-2.366	0.0007	-7.406	0.0001	-0.079	0.8958	-1.193	0.0164
NRH	-1.872	0.0327	-8.027	0.0001	-0.292	0.7059	-1.410	0.0229
LNTA	0.762	0.0001	1.628	0.0001	0.179	0.1475	1.180	0.0001
VPD	0.008	0.7606	-0.163	0.0001	0.058	0.0428	-0.031	0.2794

Table 5. Summary of fit statistics for selection of the complex model. Terms include: the sine-cosine transformation of day-of-the-year (SC), species (S), production cycle (A), year (Y), Penman-van Bavel evapotranspiration (ET), basal area (BA), air temperature (TA), relative humidity (RH).

Model components	AIC	-2LL	Comments
SC transformation only	-1279.0	2548.1 *1	Fits average data well (1 equation)
SC S*A	-965.2	1960.3 *2	Fit much improved (p < 0.0001) by group (4 equations)
SC S*A BA	-956.6	1913.1 *3	Basal area improves model (p < 0.0001)
SC S*A ET	-951.7	1861.4 *4	Penman-van Bavel ET also improves fit (p < 0.0001)
SC S*A BA ET	-944.5	1838.9 *5	BA and ET are independently important (p < 0.0001)
SC S*A BA ET BAET	-926.9	1795.8 *6	Interaction of basal area and ET is needed (p < 0.0001)
SC S*A BA ET BAET TA	-895.6	1725.2 *7	Linear effect of TA improves fit (p < 0.0001)
SC S*A BA ET BAET TA RH	-859.9	1719.8	Linear effect of RH does not improve fit (p = 0.249)
SC A BA ET BAET TA RH	-1067.1	2100.2	Species is needed (p < 0.0001)
SC S BA ET BAET TA RH	-936.2	1838.3	Production cycle is needed (p < 0.0001)
SC S*A*Y BA ET BAET TA RH	-858.7	1587.4	Year is important (p < 0.0001)

An equation with TA BA and TABA was better (-2LL = 1763.8, AIC = -910.9) than the equation based on ET BA and BAET at this point, but could not be improved to the same extent to which the latter equation was in subsequent steps.

Table 6. Coefficients and p-values for t-tests of the importance of each in the complex model. Separate models for each combination of species and production cycle. Terms include; Intercept (χ) sine-cosine transformation components (β and α) species (S), production cycle (A), Penman-van Bavel evapotranspiration (ET), basal area (BA), air temperature (TA), relative humidity (RH).

	S=1 and A=1		**S=1 and A=2**		**S=2 and A=1**		**S=2 and A=2**	
Term	**Coefficient**	**Pr > t**	**Coefficient**	**Pr > t**	**Coefficient**	**Pr > t**	**Coefficient**	**Pr > t**
Intercept (χ)	0.8430	<0.0001	0.7426	0.0013	1.9110	0.0034	-0.3728	0.2034
β	0.2863	<0.0001	0.0964	<0.0001	0.4558	<0.0001	0.1949	<.0001
α	2.1932	<0.0001	2.7979	<0.0001	2.4522	<0.0001	2.8196	<.0001
ET	-0.1674	0.0038	-0.1699	0.0115	-0.0877	0.1977	0.06098	0.1299
BA	-0.0952	0.0075	-0.0830	0.0427	-0.1936	0.0228	-0.01646	0.7629
BA*ET	0.0352	<0.0001	0.0557	<0.0001	0.0249	0.0082	0.01298	0.1214
TA	0.0264	0.0020	0.0144	0.0806	0.0185	0.0242	0.05945	<.0001

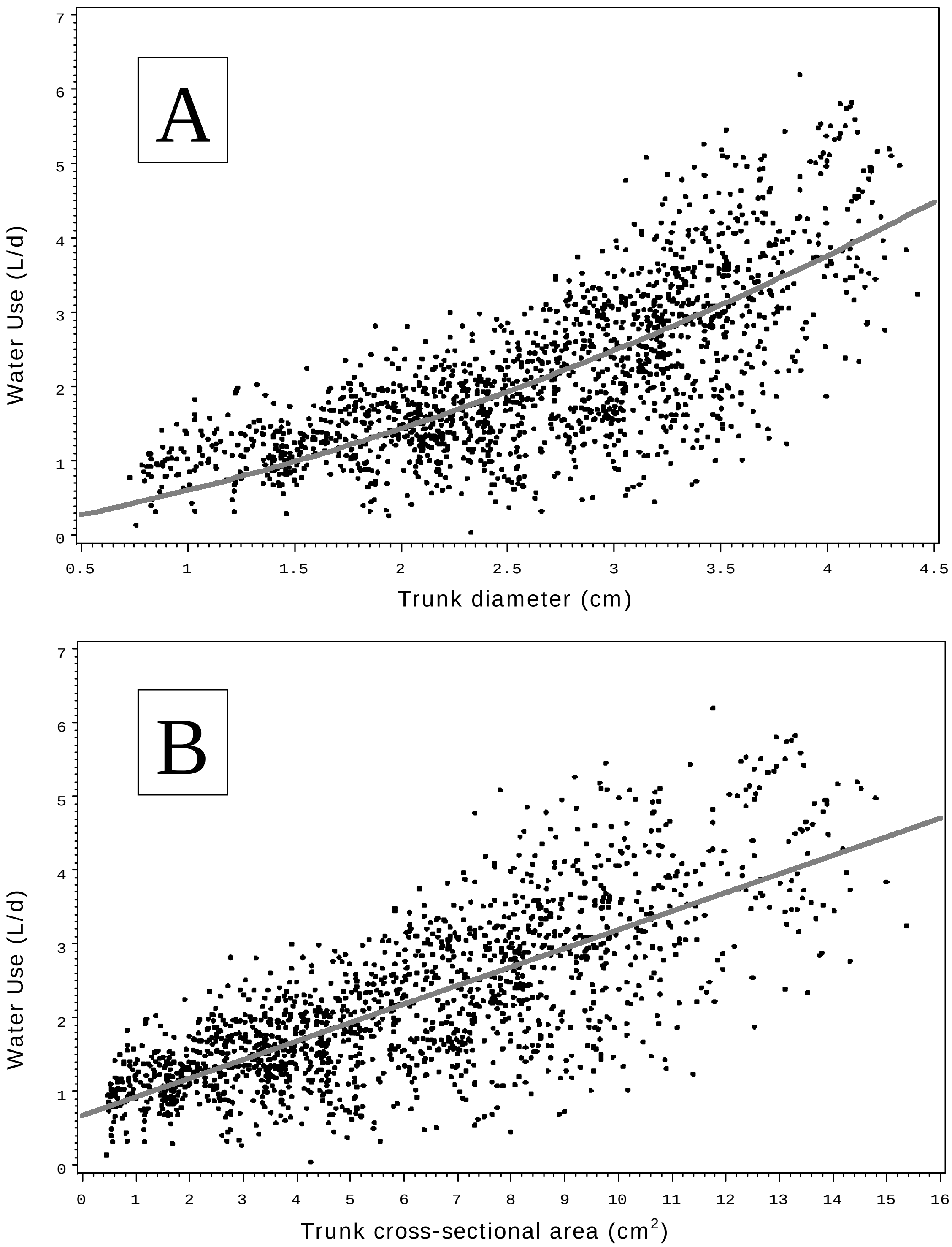

Figure 1. Plot of water use against trunk diameter (A) and water use against trunk cross-sectional area (B) for all data points combined. The gray line describes the simple quadratic relationship with diameter: wu = 0.496*CAL + 0.112*CAL^2, or the simple linear relationship with cross-sectional area wu = 0.337*ba.

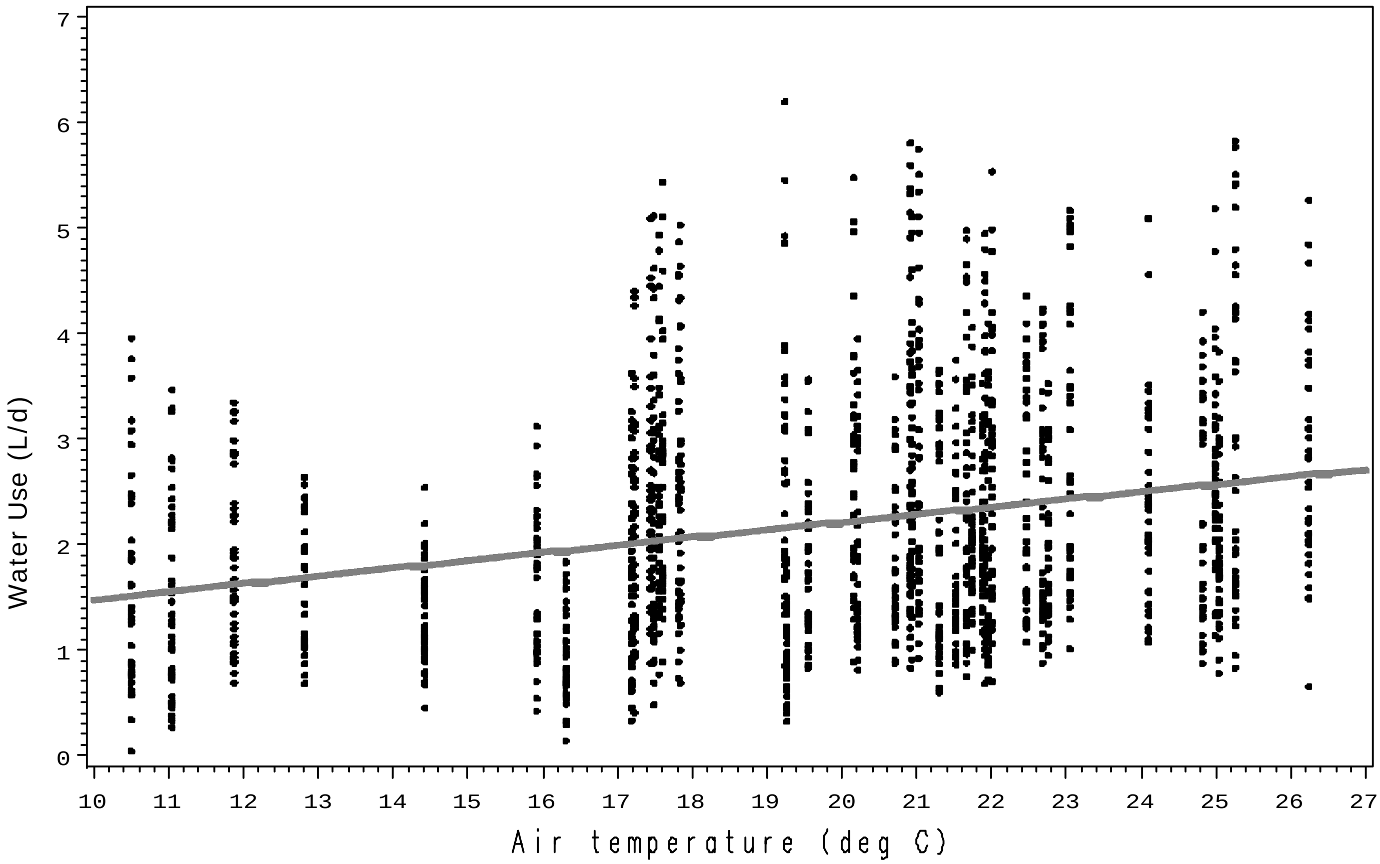

Figure 2. Plot of water use against air temperature for all data points. The gray line describes the simple linear relationship: wu = 0.758 + 0.0727*ta.

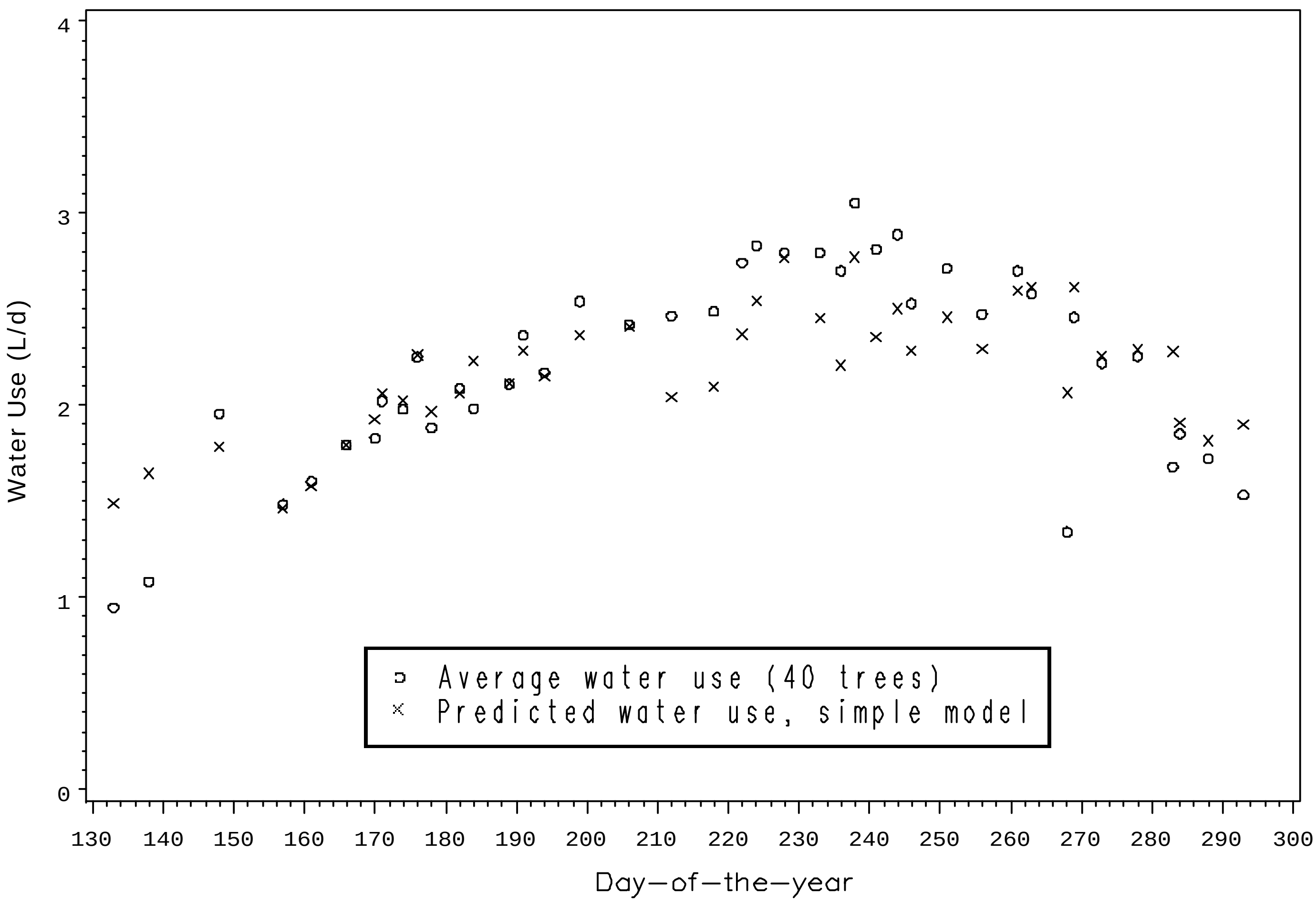

Figure 3. Observed average daily water use (○) and corresponding predictions from the simple model ( ).

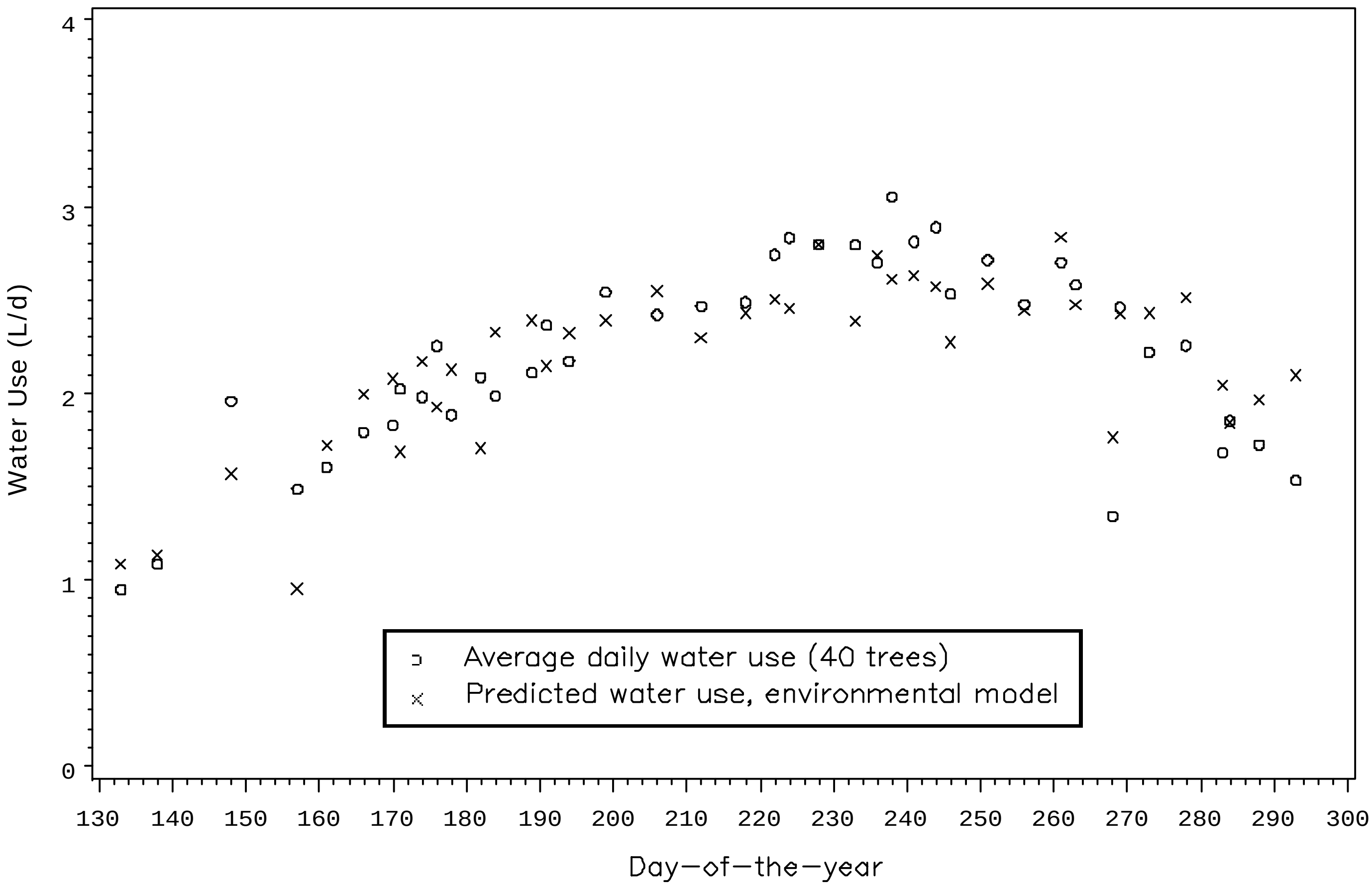

Figure 4. Observed average daily water use (O) and corresponding predictions from the environmental model ( ).

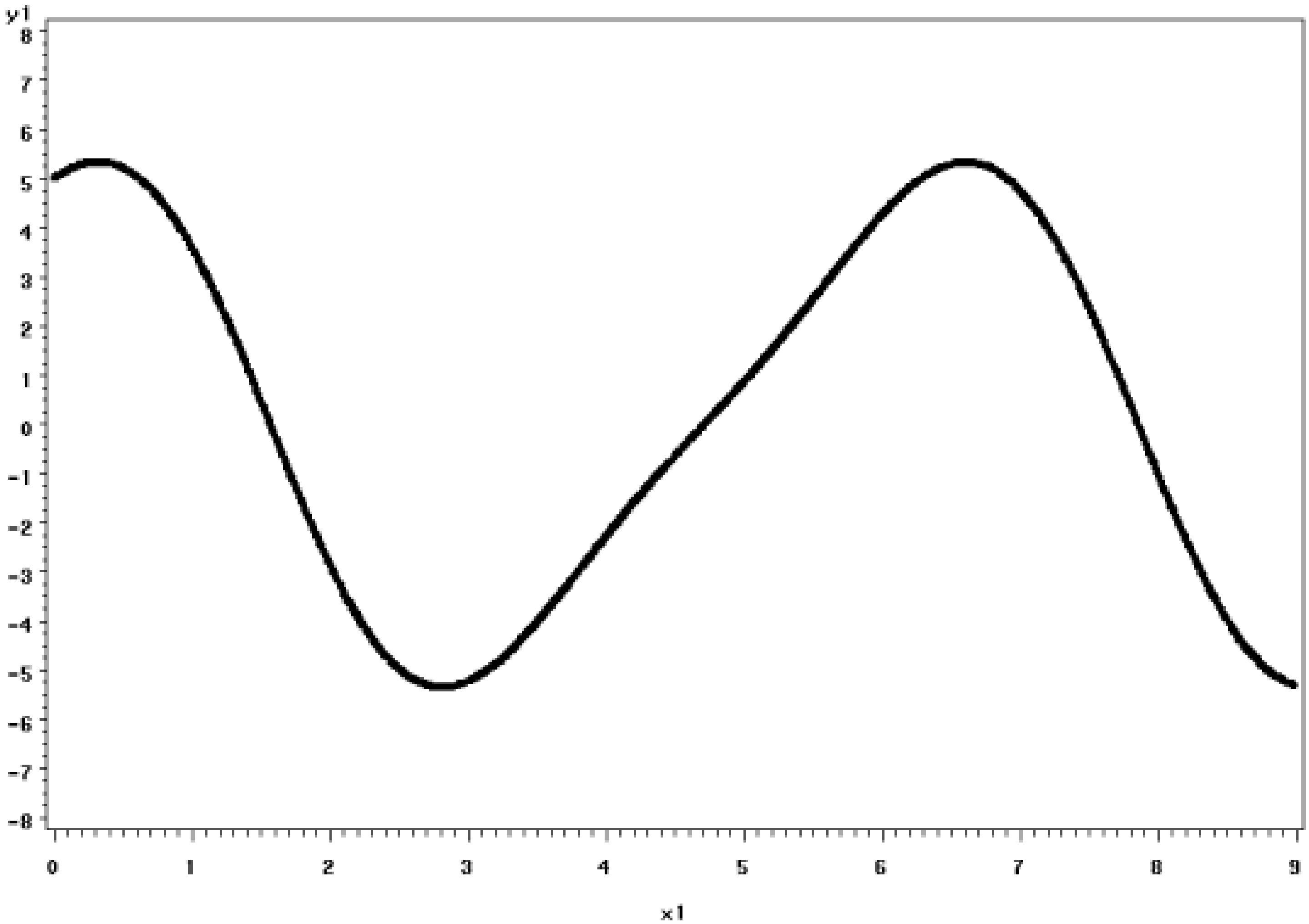

Figure 5. General form of the sine-cosine equation for the transformation of time.

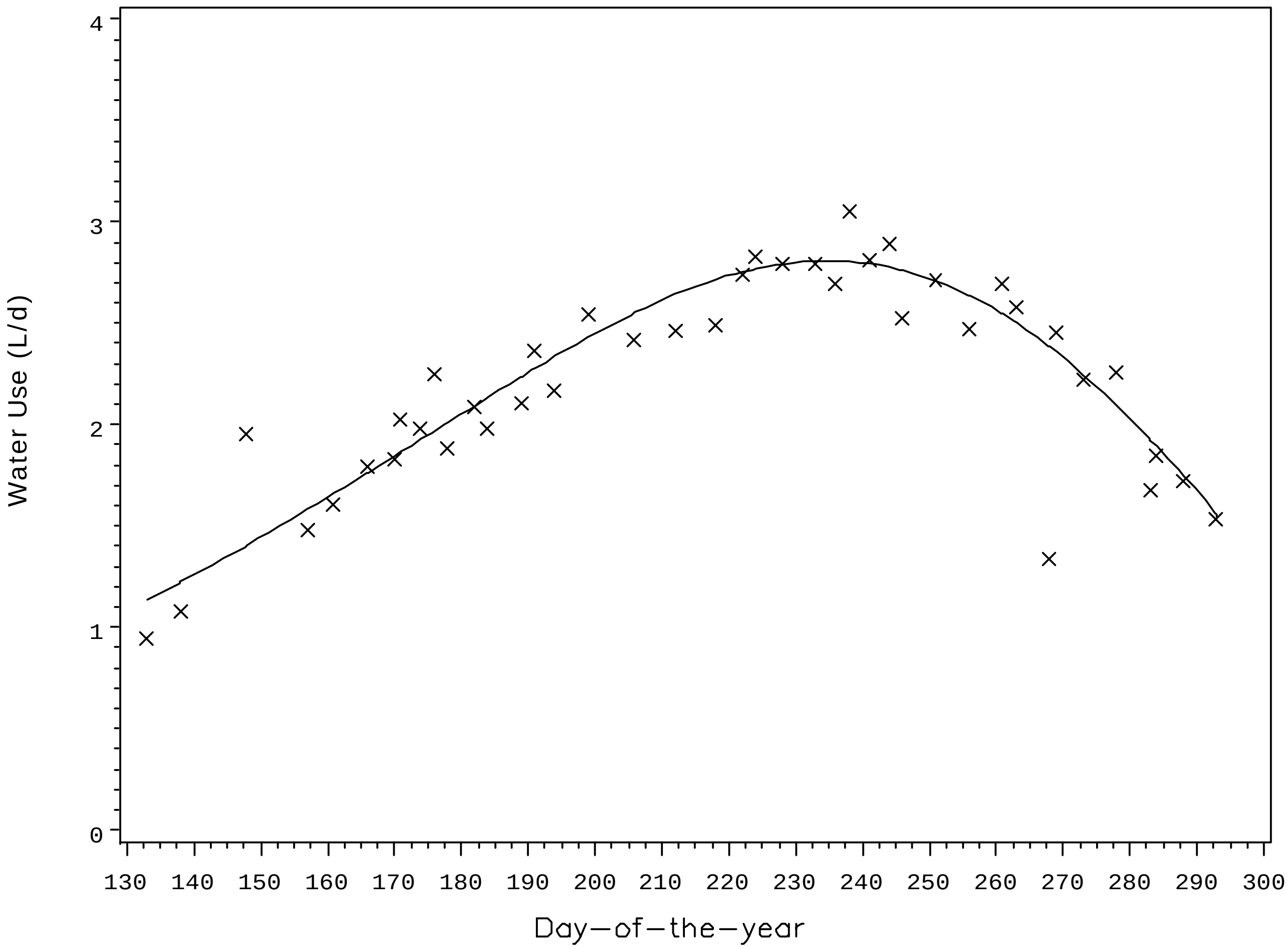

Figure 6. Fit of the foundation model (line is prediction) to daily average water use of all 40 trees (X) for both years data.

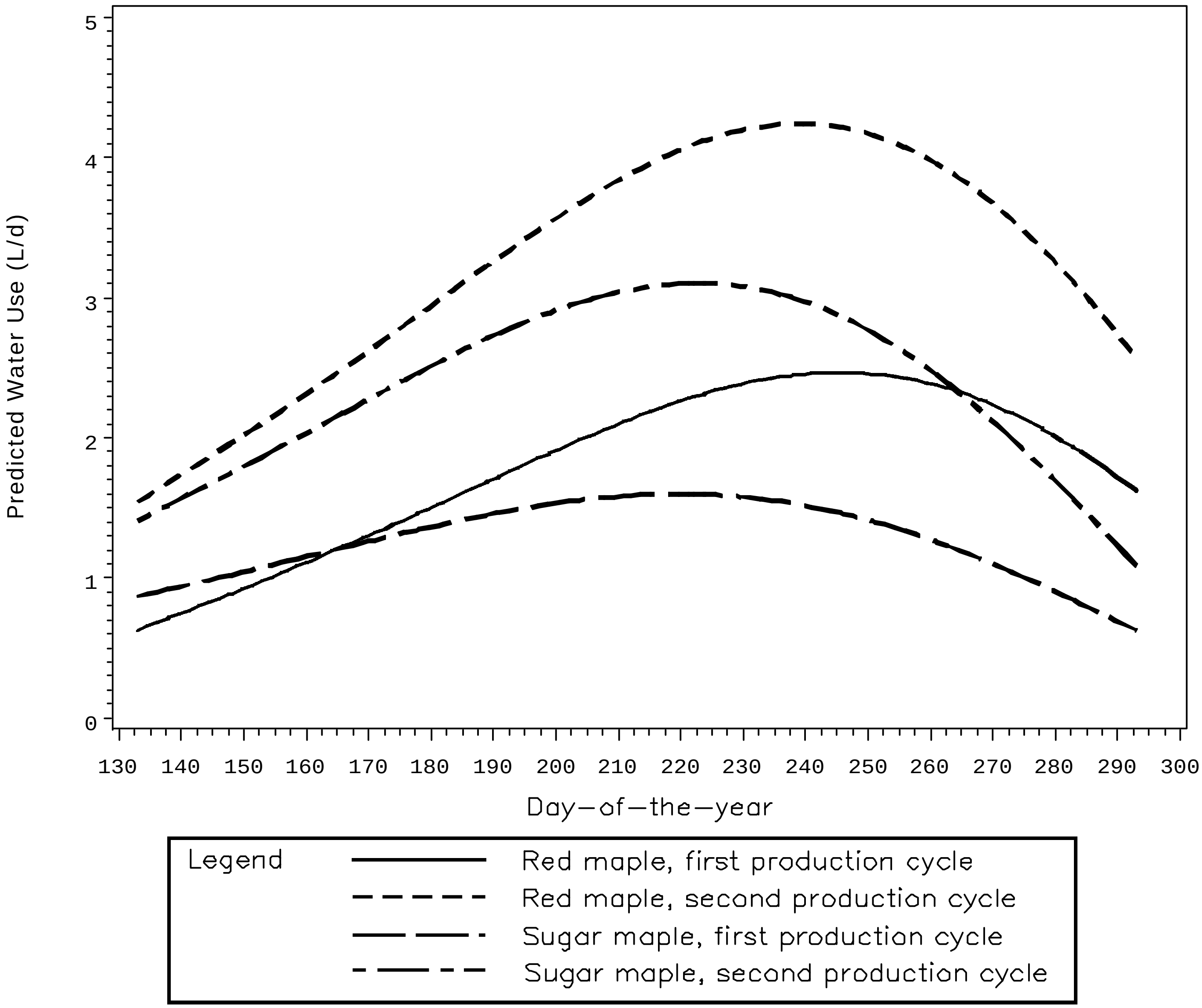

Figure 7. Seasonal pattern of water use varies with species and production cycle. Sugar maples peak sooner than red maples. Red maples in their first production cycle have peak water use on day 245 (2 September) in late summer, presumably due to their continued growth.

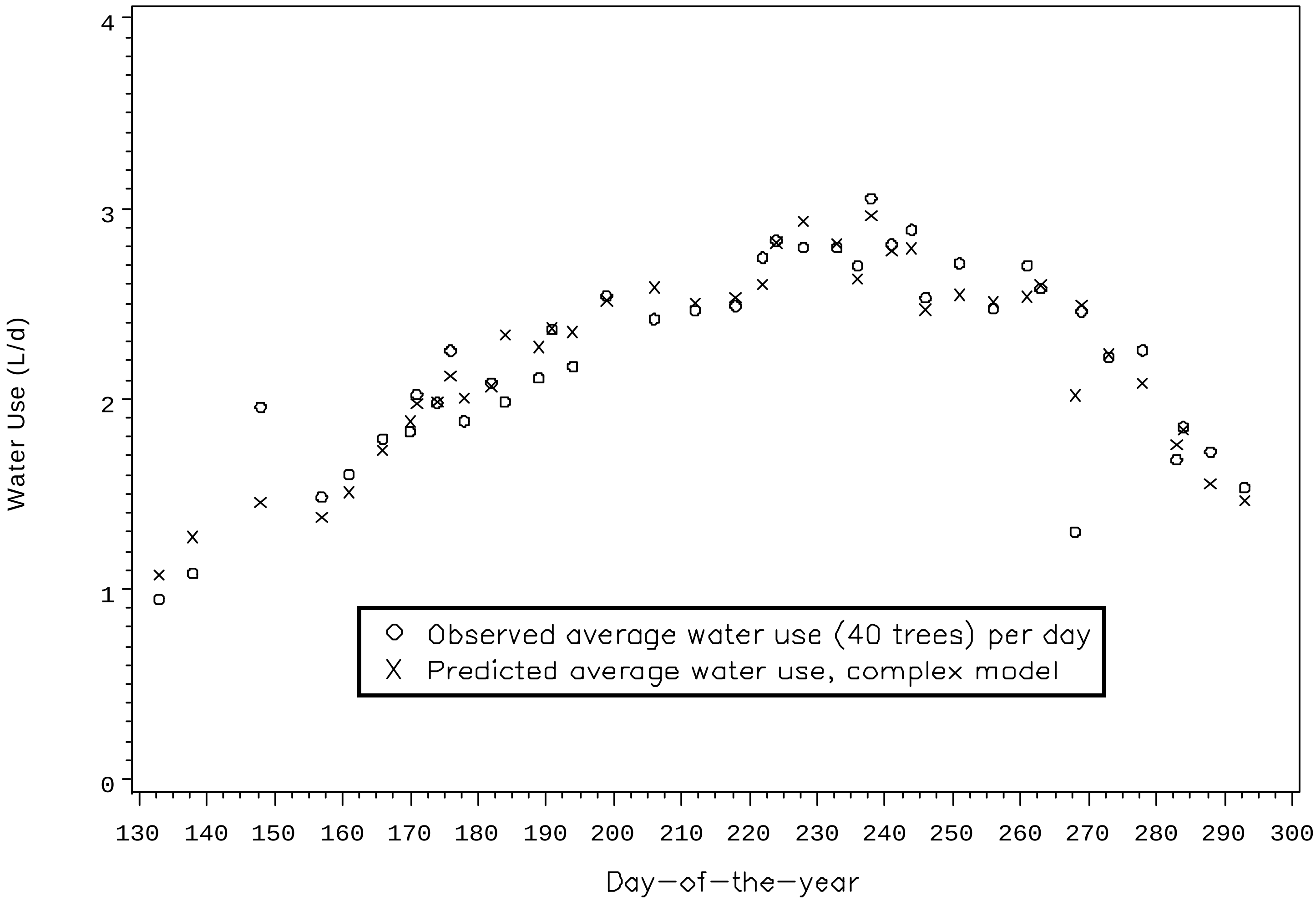

Figure 8. Observed average daily water use (O) and corresponding predictions from the complex model ( ).

SUMMARY

The purpose of this dissertation was to describe water use and growth patterns of red and sugar maples during two production cycles in P+P and through 3 years after transplanting to field soil. To accomplish this water use was studied using gravimetric methodology, thermal balance sap flow gauges, porometer readings, electrical conductivity blocks and environmental models.

The initial study tested the effect of frequent (3 times a day) versus standard (once a day) irrigation on the growth and water use patterns of red and sugar maple during their first and second years in the P+P system. Frequent irrigation resulted in increased trunk diameter growth of both groups of red maple and the older sugar maples, compared to standard irrigation. Height growth data showed that red maples of both irrigation treatments showed less height growth in the second production cycle. Differences in daily sap flow pattern were detected between red and sugar maple, and between red maples irrigated 1X and 3X daily.

The second study followed the establishment of trees from the 3X irrigation treatment in the field. Irrigation frequency requirement was found to decrease as the trees grew, but was also dependent on environmental effects, size at planting, source of water (rainfall versus irrigation) and species. Under differing environmental conditions irrigation frequency requirement ranged from 3 to 15 days for 1-yr red maples in 1999. When first planted, large trees needed irrigation more frequently than smaller trees, although this size-related difference was lost as the trees became established. The 2-yr red maples required more frequent irrigation than the other groups three years after planting, possibly because they were still not fully established. Saturating rainfall

delayed irrigation approximately one day compared to irrigation, possibly because rainfall alters relative humidity for several days. Red maple appears to use water faster than sugar maple and therefore requires more frequent irrigation after transplanting. Size of 2-yr red maple was matched by 1-yr red maples during the first year after transplanting, indicating that there is no benefit to planting 2-yr versus a 1-yr red maple beyond initial impact. Sugar maple maintained significant height and trunk diameter differences between 1-yr and 2-yr trees three years after transplanting.

A major focus of my research was the development of predictive models of water use during P+P production. Although models of water use during container production have been developed by others this study was unique because it addressed larger containers in P+P production. The statistical procedures and form of the final complex model are also novel approaches.

Development of this type of model requires many accurate data points gathered during varying conditions of growth and development. The most efficient way to obtain data of the required precision was to measure gravitational water use. The required data were collected from 2 species, in each of 2 production cycles during 2 growing seasons. Data were collected from days without rain, but the collection provides a reasonably wide range of environmental conditions, including temperature ranging from 3 to 32 ºC and hourly windspeeds reaching 9.29 $m \cdot s^{-1}$ (and 4.424 $m \cdot s^{-1}$ daily average). The wide range of environmental conditions and plant material increased variability in the data and therefore decreased model fit, but it assured better description of water use in a variety of situations.

The simple model provides good estimates of water use with a minimum of input variables, requiring only species, average trunk diameter and average daily temperature. The environmental model uses Penman-van Bavel predicted evapotranspiration and other environmental variables to modify estimates of water use based on tree size, species and production cycle. The complex model presents two alternate models. The first offers a very good model based on species, production cycle, trunk cross-sectional area, air temperature and day-of-the-year, which is quite practical for growers. The second alternative also uses the function of day-of-the-year as a regressor, but it makes slightly better predictions by using functions of four environmental variables. Use of the *mixed* and *nlmixed* procedures of SAS® is encouraged because these procedures can remove variation associated with individual experimental units and can reduce autocorrelation problems so that truly important relationships can be identified. I expect that this form of analysis will become standard for all studies of this nature.

Precise irrigation regimes are important because of increasing conservation and pollution concerns and the increasing cost of acquiring high quality irrigation water. The results of this research and the models developed from it are of immediate use to growers and arborists who are concerned about water use.

APPENDIX A

SAS PROGRAMS AND OUTPUT

List of SAS Code and Translation

Tree Categorical Variables

A = Production cycle 1 (first) or 2 (second)
N = Tree number, used to identify individual experimental units
S = Species 1 (red maple) or 2 (sugar maple)
TreeYear =(Y*1000)+n, identifies a unique tree and year combination
Y = Year 1 (1997) or 2 (1998)

Tree Size and Water Use

BA = $\pi \cdot (CAL/2)^2$, basal area, stem cross-sectional area
CAL = Sem diameter (cm at 16 cm above media)
WU = Water use (L/day)

Environmental Variables

RH = relative humidity (%)
T = Day-of-the-year
TA = air temperature (C)
VPD = vapor pressure deficit
WS = Wind speed (m/s)
ET = Penman-Van Bavel estimate of potential evapotranspiration

Prefixes
D = daytime average
L= log transformation
N = nighttime average

Suffix
XX2 = squared transformation

SAS Programs

Simple Model

```
proc sort data= nlin; by y n; run;
/* simple model */
proc mixed data=nlin;
  class s a y n ;
  model wu = ba*s ta*ba*s/  s outp=predicted;
  repeated / subject=y*n type=sp(exp)(t);
run;
```

Environmental Model

```
proc sort data=nlin; by treeyear; run;
/*the environmental model*/
proc mixed data=nlin;
  class TreeYear S A Y N T;
  model wu = S*A S*A*CAL S*A*ET CAL*ET
      LWS S*A*LRH S*A*DRHXX2
      S*A*NRH S*A*LNTA  S*A*VPD
      /noint s outp=pred2;
  repeated / subject=TreeYear type=sp(exp)(T);
run;
```

Complex Model

```
proc sort data= nlin; by treeyear; run;
/* The complex model -PROC NLMIXED-
Two species and two production cycles with ba et BAET and TA AND RH */
proc nlmixed data=nlin method=FIRO maxiter=300;
   parms         /* species 1, production cycle 1 */
      B11=-1.5 beta12=.265 b13=2.71 b14=.07 b15=.2 b16=.2 b17=.2 b18=.2
                 /* species 2, production cycle 1 */
      B21=-0.5 beta22=.189 b23=2.99 b24=.08 b25=.2 b26=.2 b27=.2 b28=.2
                 /* species 1, production cycle 2 */
      B31=-1.5 beta32=.265 b33=2.71 b34=.07 b35=.2 b36=.2 b37=.2 b38=.2
                 /* species 2, production cycle 2 */
      B41=-0.5 beta42=.189 b43=2.99 b44=.08 b45=.2 b46=.2 b47=.2 b48=.2
      sig2 = 0.18
      s2bran12=0.01 s2bran22=0.01 s2bran32=0.01 s2bran42=0.01;
      B12 = Beta12 + bran12; B22 = Beta22 + bran22;
      B32 = Beta32 + bran32; B42 = Beta42 + bran42;

 if ((s=1) and (a=1)) then
    norandmodel =
B11+Beta12*(SIN(2*(T/365*2*3.14159+B13))+5*COS(T/365*2*3.14159+B13))
        +b14*bA+b15*ET+b16*bAET+b17*TA+B18*RH;

 if ((s=2) and (a=1)) then
    norandmodel =
B21+Beta22*(SIN(2*(T/365*2*3.14159+B23))+5*COS(T/365*2*3.14159+B23))
        +b24*bA+b25*ET+b26*bAET+b27*TA+B28*RH;

 if ((s=1) and (a=2)) then
    norandmodel =
B31+Beta32*(SIN(2*(T/365*2*3.14159+B33))+5*COS(T/365*2*3.14159+B33))
        +b34*bA+b35*ET+b36*bAET+b37*TA+B38*RH;

 if ((s=2) and (a=2)) then
    norandmodel =
B41+Beta42*(SIN(2*(T/365*2*3.14159+B43))+5*COS(T/365*2*3.14159+B43))
        +b44*bA+b45*ET+b46*bAET+b47*TA+B48*RH;

mod1=B11+B12*(SIN(2*(T/365*2*3.14159+B13))+5*COS(T/365*2*3.14159+B13))
     +b14*bA+b15*ET+b16*bAET+b17*TA+B18*RH;
mod2=B21+B22*(SIN(2*(T/365*2*3.14159+B23))+5*COS(T/365*2*3.14159+B23))
     +b24*bA+b25*ET+b26*bAET+b27*TA+B28*RH;
mod3=B31+B32*(SIN(2*(T/365*2*3.14159+B33))+5*COS(T/365*2*3.14159+B33))
     +b34*bA+b35*ET+b36*bAET+b37*TA+B38*RH;
mod4=B41+B42*(SIN(2*(T/365*2*3.14159+B43))+5*COS(T/365*2*3.14159+B43))
     +b44*bA+b45*ET+b46*bAET+b47*TA+B48*RH;

  model wu ~ Normal(mod1*((s=1)and(a=1)) + mod2*((s=2)and(a=1)) +
                    mod3*((s=1)and(a=2)) + mod4*((s=2)and(a=2)),sig2);

  random bran12 bran22 bran32 bran42 ~ Normal([0,0,0,0],
                [s2bran12,0,s2bran22,0,0,s2bran32,0,0,0,s2bran42])
                subject=TreeYear;

  predict norandmodel out=NLMixedPredictions; run;
```

Program to Construct Graph of Means and Predicted Means (Complex Model)

```
/* program to construct graph of means and predicted means */
proc sort data=nlin; by t; run;
proc means data=nlin noprint;
   var wu;
   by t;
   output out=overall1 mean=avewu; run;
proc means data=nlin noprint;
   var t;
   by t;
   output out=overall2 mean=avet; run;
proc sort data=nlmixedpredictions; by t; run;
proc means data=nlmixedpredictions noprint;
   var pred;
   by t; output out=overall3 mean =avepred; run;
proc means data=nlin noprint;
   var ba;
   by t;
   output out=overall4 mean=aveba; run;
proc means data=nlin noprint;
   var t;
   by t;
   output out=overall5 mean=avet; run;

data overall;
   merge overall1 overall2 overall3 overall4 overall5; run;

   symbol1 color=black, value=X,  HEIGHT=.75, interpol=NONE, l=1;
   symbol2 color=black, value=CIRCLE, HEIGHT=.75, interpol=NONE, l=1;
proc gplot data= overall;
   plot avepred*avet/overlay vaxis = 0 to 4;
   plot2  avewu*avet/vaxis = 0 to 4; run;
```

Simple Model Terms with Sine-Cosine Tansformation

```
proc sort data= nlin; by treeyear; run;
/*-PROC NLMIXED- Two species and two production cycles with BA TA*BA*/
proc nlmixed data=nlin method=FIRO maxiter=300;
   parms    /* species 1, production cycle 1 */
      B11=-1.5 beta12=.265 b13=2.71 b14=.07 b15=.2
            /* species 2, production cycle 1 */
      B21=-0.5 beta22=.189 b23=2.99 b24=.08 b25=.2
            /* species 1, production cycle 2 */
      B31=-1.5 beta32=.265 b33=2.71 b34=.07 b35=.
            /* species 2, production cycle 2 */
      B41=-0.5 beta42=.189 b43=2.99 b44=.08 b45=.2
      sig2 = 0.18
      s2bran12=0.01
      s2bran22=0.01
      s2bran32=0.01
      s2bran42=0.01;
      B12 = Beta12 + bran12;
      B22 = Beta22 + bran22;
      B32 = Beta32 + bran32;
      B42 = Beta42 + bran42;

 if ((s=1) and (a=1)) then
    norandmodel = B11+Beta12*(SIN(2*(T/365*2*3.14159+B13))
            +5*COS(T/365*2*3.14159+B13))+b14*bA+b15*BA*TA;
 if ((s=2) and (a=1)) then
    norandmodel = B21+Beta22*(SIN(2*(T/365*2*3.14159+B23))
            +5*COS(T/365*2*3.14159+B23))+b24*bA+b25*BA*TA;
 if ((s=1) and (a=2)) then
    norandmodel = B31+Beta32*(SIN(2*(T/365*2*3.14159+B33))
            +5*COS(T/365*2*3.14159+B33))+b34*bA+b35*BA*TA;
 if ((s=2) and (a=2)) then
    norandmodel = B41+Beta42*(SIN(2*(T/365*2*3.14159+B43))
            +5*COS(T/365*2*3.14159+B43))+b44*bA+b45*BA*TA;

mod1=B11+B12*(SIN(2*(T/365*2*3.14159+B13))+5*COS(T/365*2*3.14159+B13))
     +b14*bA+b15*BA*TA;

mod2=B21+B22*(SIN(2*(T/365*2*3.14159+B23))+5*COS(T/365*2*3.14159+B23))
     +b24*bA+b25*BA*TA;

mod3=B31+B32*(SIN(2*(T/365*2*3.14159+B33))+5*COS(T/365*2*3.14159+B33))
     +b34*bA+b35*BA*TA;

mod4=B41+B42*(SIN(2*(T/365*2*3.14159+B43))+5*COS(T/365*2*3.14159+B43))
     +b44*bA+b45*BA*TA;

  model wu ~ Normal(mod1*((s=1)and(a=1)) + mod2*((s=2)and(a=1)) +
                    mod3*((s=1)and(a=2)) + mod4*((s=2)and(a=2)),sig2);

  random bran12 bran22 bran32 bran42 ~ Normal([0,0,0,0],
                [s2bran12,0,s2bran22,0,0,s2bran32,0,0,0,s2bran42])
                subject=TreeYear;

  predict norandmodel out=NLMixedPredictions2; run;
```

Program Output

Output from the Simple Model

The Mixed Procedure

Model Information

Data Set	WORK.WITMER
Dependent Variable	wu
Covariance Structure	Spatial Exponential
Subject Effect	Y*N
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Between-Within

Class Level Information

Class	Levels	Values
S	2	1 2
A	2	1 2
Y	2	1 2
N	60	1 2 3 4 5 6 7 8 17 18 19 20 21 22 23 24 33 34 35 36 37 38 39 40 49 50 51 52 53 54 55 56 65 66 67 68 69 70 71 72 86 88 141 163 164 166 168 169 170 173 174 175 176 177 178 179 180 181 182 187

Dimensions

Covariance Parameters	2
Columns in X	6
Columns in Z	0
Subjects	80
Max Obs Per Subject	26
Observations Used	1631
Observations Not Used	49
Total Observations	1680

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	3056.05412091	
1	2	2855.39308916	224.37683289
2	3	2303.41590236	0.04525593
3	2	2200.30819126	0.02444807
4	2	2197.27551036	0.00832629
5	1	2193.59696439	0.00037148
6	1	2193.44477990	0.00000101
7	1	2193.44437944	0.00000000

Convergence criteria met.

Covariance Parameter Estimates

Cov Parm	Subject	Estimate
SP(EXP)	Y*N	14.1514
Residual		0.3681

Fit Statistics

-2 Res Log Likelihood	2193.4
AIC (smaller is better)	2197.4
AICC (smaller is better)	2197.5
BIC (smaller is better)	2202.2

Null Model Likelihood Ratio Test

DF	Chi-Square	Pr > ChiSq
1	862.61	<.0001

Solution for Fixed Effects

Standard

Effect	S	Estimate	Error	DF	t Value	Pr > |t|
ta*ba*S	1	0.008322	0.000583	1547	14.28	<.0001
ta*ba*S	2	0.01211	0.000781	1547	15.50	<.0001
ba*S	1	0.07671	0.01492	1547	5.14	<.0001
ba*S	2	-0.02324	0.01985	1547	-1.17	0.2418
S	1	0.8628	0.08143	78	10.60	<.0001
S	2	0.7019	0.07835	78	8.96	<.0001

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
ta*ba*S	2	1547	221.97	<.0001
ba*S	2	1547	13.91	<.0001
S	2	78	96.27	<.0001

Output from the Environmental Model

The Mixed Procedure

Model Information

Data Set	WORK.NLIN
Dependent Variable	wu
Covariance Structure	Spatial Exponential
Subject Effect	TreeYear
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Between-Within

Class Level Information

Class	Levels	Values
TreeYear	80	1001 1002 1003 1004 1005 1006 1007 1008 1017 1018 1019 1020 1021 1022 1023 1024 1033 1034 1035 1036 1037 1038 1039 1040 1049 1050 1051 1052 1053 1054 1055 1056 1065 1066 1067 1068 1069 1070 1071 1072 2001 2003 2007 2008 2017 2018 2021 2022 2033 2034 2036 2037 2051 2054 2055 2056 2065 2068 2069 2070 2086 2088 2141 2163 2164 2166 2168 2169 2170 2173 2174 2175 2176 2177 2178 2179 2180 2181 2182 2187
S	2	1 2
A	2	1 2
Y	2	1 2
N	60	1 2 3 4 5 6 7 8 17 18 19 20 21 22 23 24 33 34 35 36 37 38 39 40 49 50 51 52 53 54 55 56 65 66 67 68 69 70 71 72 86 88 141 163 164 166 168 169 170 173 174 175 176 177 178 179 180 181 182 187
T	41	133 138 148 157 161 166 170 171 174 176 178 182 184 189 191 194 199 206 212 218 222 224 228 233 236 238 241 244 246 251 256 261 263 268 269 273 278 283 284 288 293

Dimensions

Covariance Parameters	2
Columns in X	34
Columns in Z	0
Subjects	80
Max Obs Per Subject	26
Observations Used	1631
Observations Not Used	49
Total Observations	1680

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	2668.69656376	
1	2	2485.66302270	53.88864978
2	2	1911.38649072	0.00806251
3	2	1822.34374129	0.09046646
4	4	1804.73827785	0.00192720
5	1	1803.81924630	0.00007466
6	1	1803.77609062	0.00000009
7	1	1803.77604238	0.00000000

Convergence criteria met.

Covariance Parameter Estimates

Cov Parm	Subject	Estimate
SP(EXP)	TreeYear	17.5642
Residual		0.3248

Fit Statistics

-2 Res Log Likelihood	1803.8
AIC (smaller is better)	1807.8
AICC (smaller is better)	1807.8
BIC (smaller is better)	1812.5

Null Model Likelihood Ratio Test

DF	Chi-Square	Pr > ChiSq
1	864.92	<.0001

Solution for Fixed Effects

Effect	S	A	Estimate	Standard Error	DF	t Value	Pr > |t|
S*A	1	1	3.8584	1.5474	76	2.49	0.0148
S*A	1	2	9.1298	1.1178	76	8.17	<.0001
S*A	2	1	1.5396	1.4203	76	1.08	0.2818
S*A	2	2	0.1758	1.0689	76	0.16	0.8698
CAL*S*A	1	1	-0.1810	0.1164	1521	-1.55	0.1202
CAL*S*A	1	2	1.0396	0.1590	1521	6.54	<.0001
CAL*S*A	2	1	-0.3755	0.1735	1521	-2.16	0.0306
CAL*S*A	2	2	0.2267	0.1399	1521	1.62	0.1053
et*S*A	1	1	-0.3251	0.03952	1521	-8.23	<.0001
et*S*A	1	2	-0.5085	0.06291	1521	-8.08	<.0001
et*S*A	2	1	-0.2429	0.03885	1521	-6.25	<.0001
et*S*A	2	2	-0.3426	0.05549	1521	-6.18	<.0001
CAL*et			0.1502	0.01639	1521	9.16	<.0001
lws			-0.1398	0.01848	1521	-7.57	<.0001
lrh*S*A	1	1	3.0801	1.4568	1521	2.11	0.0347
lrh*S*A	1	2	10.1582	1.1353	1521	8.95	<.0001
lrh*S*A	2	1	0.7338	1.3050	1521	0.56	0.5740
lrh*S*A	2	2	1.0827	1.0963	1521	0.99	0.3235
drhxx2*S*A	1	1	-2.3665	0.6928	1521	-3.42	0.0007
drhxx2*S*A	1	2	-7.4069	0.5165	1521	-14.34	<.0001
drhxx2*S*A	2	1	-0.07978	0.6088	1521	-0.13	0.8958
drhxx2*S*A	2	2	-1.1940	0.4970	1521	-2.40	0.0164
nrh*S*A	1	1	-1.8723	0.8761	1521	-2.14	0.0327
nrh*S*A	1	2	-8.0279	0.6644	1521	-12.08	<.0001
nrh*S*A	2	1	-0.2928	0.7758	1521	-0.38	0.7059
nrh*S*A	2	2	-1.4106	0.6194	1521	-2.28	0.0229
lnta*S*A	1	1	0.7624	0.1242	1521	6.14	<.0001
lnta*S*A	1	2	1.6284	0.1249	1521	13.04	<.0001
lnta*S*A	2	1	0.1799	0.1241	1521	1.45	0.1475
lnta*S*A	2	2	1.1808	0.1239	1521	9.53	<.0001
vpd*S*A	1	1	0.008852	0.02905	1521	0.30	0.7606
vpd*S*A	1	2	-0.1637	0.02892	1521	-5.66	<.0001
vpd*S*A	2	1	0.05835	0.02878	1521	2.03	0.0428
vpd*S*A	2	2	-0.03119	0.02883	1521	-1.08	0.2794

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
S*A	4	76	19.30	<.0001
CAL*S*A	4	1521	16.55	<.0001
et*S*A	4	1521	20.50	<.0001
CAL*et	1	1521	83.92	<.0001
lws	1	1521	57.25	<.0001
lrh*S*A	4	1521	21.51	<.0001
drhxx2*S*A	4	1521	55.64	<.0001
nrh*S*A	4	1521	38.97	<.0001
lnta*S*A	4	1521	75.19	<.0001
vpd*S*A	4	1521	9.33	<.0001

Output from the Complex model

The NLMIXED Procedure

Specifications

Data Set	WORK.WITMER
Dependent Variable	wu
Distribution for Dependent Variable	Normal
Random Effects	bran12 bran22 bran32 bran42
Distribution for Random Effects	Normal
Subject Variable	treeyear
Optimization Technique	Dual Quasi-Newton
Integration Method	First Order

Dimensions

Observations Used	1631
Observations Not Used	49
Total Observations	1680
Subjects	80
Max Obs Per Subject	26
Parameters	33

Parameters

B11	beta12	b13	b14	b15	b16
-1.5	0.265	2.71	0.07	0.2	0.2

b17	B21	beta22	b23	b24	b25
0.2	-0.5	0.189	2.99	0.08	0.2

b26	b27	B31	beta32	b33	b34
0.2	0.2	-1.5	0.265	2.71	0.07

b35	b36	b37	B41	beta42	b43
0.2	0.2	0.2	-0.5	0.189	2.99

b44	b45	b46	b47	sig2	s2bran12
0.08	0.2	0.2	0.2	0.18	0.01

s2bran22	s2bran32	s2bran42	NegLogLike
0.01	0.01	0.01	72081.7461

Iteration History

Iter	Calls	NegLogLike	Diff	MaxGrad	Slope
1	80	26410.541	45671.21	100626.3	-2.01E10
2	114	6423.9467	19986.59	29853.51	-288773
3	148	2289.21993	4134.727	9468.263	-11133.6
4	182	1844.98754	444.2324	1091.736	-992.091
5	250	1799.29479	45.69275	1170.644	-38.332
6	284	1727.68613	71.60867	1641.062	-32.831

7	318	1645.9921	81.69403	3043.569	-63.7529
8	352	1589.22166	56.77044	2692.454	-84.4229
9	386	1564.71375	24.50791	3588.377	-58.8918
10	420	1524.77706	39.93669	991.8178	-70.2533
11	454	1466.02613	58.75093	2435.394	-39.2777
12	558	1462.08714	3.938988	3692.265	-65.3421
13	626	1399.39453	62.69261	5535.472	-140.794
14	661	1384.98327	14.41126	1787.236	-161.798
15	729	1326.65751	58.32576	1153.719	-49.2315
16	763	1220.39088	106.2666	1671.518	-63.1726
17	832	1129.8839	90.50699	2046.045	-251.997
18	867	1079.18301	50.70089	1850.18	-225.053
19	902	1060.56548	18.61753	1312.271	-82.4476
20	936	1052.468	8.097479	1692.973	-37.1672
21	1004	1037.38236	15.08565	714.7224	-22.0182
22	1039	1030.64312	6.739232	434.1508	-13.753
23	1074	1027.92665	2.716475	458.9332	-6.56864
24	1109	1026.00792	1.918732	985.1628	-3.65669
25	1143	1023.68653	2.321386	575.3161	-2.14034
26	1211	1018.6306	5.055932	973.5312	-5.54511
27	1314	1014.76989	3.860707	1015.222	-11.8664
28	1348	1010.83131	3.938586	1031.191	-22.3165
29	1417	1009.95751	0.873796	1023.983	-2.58104
30	1451	1008.73111	1.226397	973.9133	-9.71175
31	1485	1007.01778	1.713334	638.0253	-3.09539
32	1520	1005.74463	1.273153	330.7033	-3.22513
33	1554	1004.36117	1.383455	2077.206	-1.59502
34	1588	1002.15514	2.206029	557.5285	-2.43516
35	1656	996.978022	5.17712	1662.074	-7.34168
36	1690	994.410658	2.567364	846.7268	-6.20557
37	1725	992.802617	1.608041	444.7746	-2.20102
38	1759	991.241746	1.560871	780.1814	-0.65863
39	1793	990.172112	1.069634	393.2443	-1.96547
40	1827	988.902612	1.2695	388.7666	-0.9847
41	1861	987.131942	1.77067	317.1987	-0.81424
42	1895	984.645183	2.486758	775.6951	-1.69629
43	1929	980.857165	3.788019	938.8849	-2.57657
44	1963	976.868423	3.988742	407.117	-4.10318
45	1998	974.547988	2.320435	306.597	-2.52012
46	2032	972.030426	2.517562	1715.271	-1.61255
47	2135	966.030081	6.000345	957.1972	-6.88073
48	2239	964.475532	1.554549	822.9087	-14.1807
49	2273	961.77126	2.704272	439.1775	-17.5039
50	2308	960.310347	1.460914	254.4422	-3.25089
51	2343	959.933882	0.376465	192.3047	-0.4961
52	2411	959.198675	0.735207	1230.65	-0.39624
53	2445	958.316472	0.882203	600.7524	-1.53578
54	2479	957.217114	1.099358	339.1774	-1.8068
55	2514	956.610667	0.606447	100.1269	-0.79528
56	2549	956.217853	0.392814	327.4253	-0.21132
57	2583	955.5852	0.632653	262.4103	-0.47792
58	2617	954.837958	0.747242	456.2378	-0.60511
59	2685	952.61568	2.222278	416.1984	-0.87761
60	2719	949.642584	2.973097	265.613	-1.94684
61	2754	948.907782	0.734801	360.2229	-1.21355
62	2788	948.192845	0.714937	543.9486	-0.62748
63	2822	946.932555	1.26029	185.1181	-1.03446

64	2856	946.244408	0.688147	993.2571	-1.60951
65	2890	945.198767	1.045641	432.4417	-2.46949
66	2924	943.385623	1.813143	406.8038	-1.19599
67	2958	940.967508	2.418115	1064.955	-2.50855
68	2992	939.594615	1.372893	765.071	-1.71504
69	3026	938.29008	1.304535	317.9436	-2.11983
70	3061	937.777526	0.512554	237.0004	-0.70343
71	3095	937.06755	0.709976	249.1926	-0.47439
72	3163	932.698859	4.368691	385.6458	-1.30504
73	3197	928.353328	4.345531	579.7374	-4.25489
74	3266	927.246635	1.106693	725.8776	-1.27697
75	3300	926.592845	0.65379	256.7001	-1.05792
76	3334	925.712067	0.880779	180.1873	-1.05835
77	3368	924.20086	1.511207	1247.421	-0.62181
78	3436	920.041312	4.159548	247.221	-3.46419
79	3470	913.763017	6.278295	791.7089	-3.74965
80	3504	907.916247	5.84677	823.1301	-8.81898
81	3539	906.32976	1.586487	312.3904	-14.8262
82	3573	904.507346	1.822414	247.4407	-4.92901
83	3608	903.857111	0.650235	74.07209	-0.69645
84	3643	903.462023	0.395088	387.4486	-0.48637
85	3711	900.637745	2.824278	1013.472	-0.52834
86	3745	897.645326	2.992419	375.5751	-3.27911
87	3780	896.408793	1.236533	219.2803	-1.09465
88	3814	895.339392	1.069401	1064.056	-0.92704
89	3848	893.784644	1.554748	188.6798	-1.36734
90	3917	893.209652	0.574992	309.9331	-1.64417
91	3952	892.964146	0.245507	268.4891	-0.49435
92	3986	892.853006	0.111139	133.1929	-0.20706
93	4054	892.525044	0.327962	117.4424	-0.46248
94	4088	891.994903	0.530141	205.6087	-0.25066
95	4122	891.764515	0.230388	139.7256	-0.48392
96	4156	891.36813	0.396385	125.4171	-0.60665
97	4190	891.224045	0.144085	222.8037	-0.3921
98	4224	890.986785	0.237261	147.921	-0.65188
99	4259	890.886465	0.10032	32.46821	-0.16188
100	4294	890.86307	0.023395	65.04036	-0.0142
101	4362	890.787412	0.075658	134.4718	-0.02882
102	4430	890.202234	0.585178	100.4573	-0.14744
103	4465	890.116073	0.086162	35.90435	-0.14388
104	4500	890.092986	0.023086	88.41018	-0.01723
105	4568	889.877013	0.215973	397.3611	-0.02472
106	4636	889.240181	0.636831	350.3201	-0.33893
107	4671	889.128529	0.111652	185.352	-0.1979
108	4706	889.092294	0.036236	36.29398	-0.06805
109	4740	889.050612	0.041682	362.961	-0.0185
110	4808	888.668374	0.382238	301.5486	-0.07489
111	4842	888.171751	0.496623	217.1774	-0.38261
112	4877	888.07893	0.092821	64.28446	-0.15462
113	4912	888.0576	0.021329	38.70795	-0.02701
114	4980	887.947795	0.109805	87.58402	-0.01789
115	5048	886.981809	0.965986	252.9064	-0.20715
116	5083	886.536445	0.445364	128.7924	-0.54979
117	5118	886.502427	0.034018	41.20511	-0.05042
118	5153	886.48403	0.018398	72.07283	-0.01965
119	5221	886.256092	0.227937	111.5981	-0.0206
120	5289	885.280967	0.975125	280.2882	-0.41439

121	5324	884.791411	0.489557	172.5077	-0.55977
122	5359	884.753677	0.037734	42.32081	-0.06259
123	5394	884.740493	0.013184	59.35486	-0.01461
124	5462	884.586479	0.154014	64.62627	-0.01706
125	5564	880.94167	3.64481	700.718	-0.33214
126	5769	875.481847	5.459823	820.9072	-8.15846
127	5838	873.8644	1.617447	834.9796	-19.945
128	5872	871.612861	2.251539	766.1514	-58.4598
129	5906	869.431739	2.181122	269.9241	-5.4025
130	5975	868.157671	1.274068	869.997	-1.65172
131	6010	867.839028	0.318644	91.75763	-0.91022
132	6045	867.778196	0.060831	29.83307	-0.12146
133	6080	867.751569	0.026627	37.85582	-0.03279
134	6114	867.740246	0.011322	149.9131	-0.02837
135	6182	867.679786	0.060461	115.6344	-0.05388
136	6250	867.112052	0.567734	283.746	-0.06366
137	6285	866.771221	0.340831	85.7548	-0.42539
138	6320	866.725742	0.045479	28.26493	-0.08328
139	6355	866.719772	0.00597	29.96779	-0.00585
140	6423	866.6486	0.071172	119.5123	-0.00723
141	6491	866.088743	0.559856	211.8722	-0.13051
142	6526	865.912942	0.175801	105.5162	-0.25564
143	6561	865.901853	0.011089	38.3978	-0.02089
144	6596	865.9001	0.001754	16.5154	-0.002
145	6630	865.897695	0.002404	15.33015	-0.00084
146	6698	865.879285	0.01841	93.83733	-0.00355
147	6800	865.491467	0.387818	154.0115	-0.02837
148	6868	863.735763	1.755703	148.9307	-0.62915
149	6903	863.355716	0.380047	18.59405	-0.61807
150	6938	863.349563	0.006154	13.89604	-0.01393
151	6973	863.349087	0.000476	14.23871	-0.00063
152	7041	863.342919	0.006168	46.79325	-0.00036
153	7143	863.10498	0.237938	138.3067	-0.01353
154	7177	862.702185	0.402795	108.6833	-0.35197
155	7212	862.605181	0.097004	19.85652	-0.1882
156	7247	862.603747	0.001434	3.665415	-0.00289
157	7282	862.603692	0.000056	0.393839	-0.0001
158	7317	862.603689	2.256E-6	0.143142	-2.36E-6

NOTE: GCONV convergence criterion satisfied.

Fit Statistics

-2 Log Likelihood	1725.2
AIC (smaller is better)	1791.2
AICC (smaller is better)	1792.6
BIC (smaller is better)	1869.8

Parameter Estimates

Parameter	Estimate	Standard Error	DF	t Value	Pr > |t|	Alpha
B11	0.8430	0.2049	76	4.11	<.0001	0.05
beta12	0.2863	0.03795	76	7.54	<.0001	0.05
b13	2.1932	0.05117	76	42.86	<.0001	0.05
b14	-0.1674	0.05602	76	-2.99	0.0038	0.05
b15	-0.09515	0.03464	76	-2.75	0.0075	0.05
b16	0.03523	0.007288	76	4.83	<.0001	0.05
b17	0.02643	0.008246	76	3.21	0.0020	0.05
B21	0.7426	0.2217	76	3.35	0.0013	0.05
beta22	0.09634	0.02333	76	4.13	<.0001	0.05
b23	2.7979	0.08484	76	32.98	<.0001	0.05
b24	-0.1699	0.06561	76	-2.59	0.0115	0.05
b25	-0.08301	0.04027	76	-2.06	0.0427	0.05
b26	0.05573	0.01324	76	4.21	<.0001	0.05
b27	0.01441	0.008134	76	1.77	0.0806	0.05
B31	1.9110	0.6311	76	3.03	0.0034	0.05
beta32	0.4558	0.04428	76	10.29	<.0001	0.05
b33	2.4522	0.02678	76	91.58	<.0001	0.05
b34	-0.08766	0.06745	76	-1.30	0.1977	0.05
b35	-0.1936	0.08330	76	-2.32	0.0228	0.05
b36	0.02487	0.009159	76	2.72	0.0082	0.05
b37	0.01848	0.008031	76	2.30	0.0242	0.05
B41	-0.3728	0.2906	76	-1.28	0.2034	0.05
beta42	0.1949	0.03368	76	5.79	<.0001	0.05
b43	2.8196	0.04520	76	62.38	<.0001	0.05
b44	0.06098	0.03983	76	1.53	0.1299	0.05
b45	-0.01646	0.05437	76	-0.30	0.7629	0.05
b46	0.01298	0.008285	76	1.57	0.1214	0.05
b47	0.05945	0.008120	76	7.32	<.0001	0.05
sig2	0.1458	0.005268	76	27.68	<.0001	0.05
s2bran12	0.01267	0.005024	76	2.52	0.0137	0.05
s2bran22	0.001985	0.000843	76	2.35	0.0211	0.05
s2bran32	0.02756	0.009279	76	2.97	0.0040	0.05
s2bran42	0.009539	0.003553	76	2.68	0.0089	0.05

Parameter Estimates Continued

Parameter	Lower	Upper	Gradient
B11	0.4348	1.2511	-0.00159
beta12	0.2107	0.3619	-0.0004
b13	2.0913	2.2951	0.001365
b14	-0.2790	-0.05580	-0.00029
b15	-0.1642	-0.02615	0.001039
b16	0.02072	0.04975	0.006215
b17	0.01001	0.04285	0.006477
B21	0.3010	1.1843	-0.00367
beta22	0.04986	0.1428	0.003281
b23	2.6290	2.9669	-0.00122
b24	-0.3005	-0.03920	0.002508
b25	-0.1632	-0.00281	-0.00067
b26	0.02936	0.08209	0.005252
b27	-0.00179	0.03061	0.000703
B31	0.6540	3.1681	0.000118
beta32	0.3676	0.5440	0.000903
b33	2.3989	2.5055	-0.00248
b34	-0.2220	0.04668	-0.0091
b35	-0.3596	-0.02773	-0.00851
b36	0.006626	0.04311	-0.07794
b37	0.002481	0.03447	-0.03219
B41	-0.9516	0.2060	0.102479
beta42	0.1278	0.2619	-0.00172
b43	2.7296	2.9096	-0.00166
b44	-0.01834	0.1403	-0.0188
b45	-0.1248	0.09183	-0.01938
b46	-0.00352	0.02948	-0.02706
b47	0.04327	0.07562	-0.01365
sig2	0.1353	0.1563	-0.00246
s2bran12	0.002667	0.02268	0.012611
s2bran22	0.000306	0.003664	-0.14314
s2bran32	0.009075	0.04604	0.045993
s2bran42	0.002463	0.01661	0.028623

Output from the Simple Components in the Sine-Cosine Model

The NLMIXED Procedure

Specifications

Data Set	WORK.NLIN
Dependent Variable	wu
Distribution for Dependent Variable	Normal
Random Effects	bran12 bran22 bran32 bran42
Distribution for Random Effects	Normal
Subject Variable	TreeYear
Optimization Technique	Dual Quasi-Newton
Integration Method	First Order

Dimensions

Observations Used	1631
Observations Not Used	49
Total Observations	1680
Subjects	80
Max Obs Per Subject	26
Parameters	25

Parameters

B11	beta12	b13	b14	b15	B21	beta22	b23
-1.5	0.265	2.71	0.07	0.2	-0.5	0.189	2.99

b24	b25	B31	beta32	b33	b34	b35	B41
0.08	0.2	-1.5	0.265	2.71	0.07	0.2	-0.5

beta42	b43	b44	b45	sig2	s2bran12	s2bran22	s2bran32
0.189	2.99	0.08	0.2	0.18	0.01	0.01	0.01

s2bran42	NegLogLike
0.01	468748.122

Iteration History

Iter	Calls	NegLogLike	Diff	MaxGrad	Slope
1	66	158252.238	310495.9	934995.2	-1.07E12
2	93	44547.1605	113705.1	276220.9	-1.882E7
3	120	24987.7692	19559.39	353338.1	-871856
4	173	4337.59471	20650.17	103588.2	-691170
5	201	3166.64522	1170.949	53147.2	-69245.8
6	227	1937.29954	1229.346	33485.46	-11892.4
7	255	1854.43258	82.86696	18994.65	-955.683
8	281	1772.17869	82.25388	18209.02	-1928.04
9	307	1665.34089	106.8378	8628.531	-265.508
10	333	1570.50398	94.8369	15804.6	-155.765
11	359	1420.25419	150.2498	2894.169	-211.889
12	386	1338.3088	81.94538	9373.097	-84.1955
13	413	1328.46943	9.839378	3094.845	-13.5051
14	439	1313.06177	15.40765	4987.517	-3.45236
15	491	1263.18673	49.87504	9955.505	-22.4072
16	518	1241.73479	21.45194	2159.91	-27.3505
17	571	1239.30311	2.431681	4390.565	-4.64547
18	623	1227.81705	11.48606	2810.257	-8.13336
19	702	1214.56643	13.25062	3519.71	-19.8719
20	755	1208.13927	6.427159	4312.093	-21.2562
21	782	1201.61946	6.519812	1488.788	-342.43
22	809	1200.69791	0.921552	1148.097	-11.6763
23	888	1197.81687	2.881043	687.8965	-2.76929
24	941	1195.66918	2.147687	1768.344	-2.19069
25	993	1187.92866	7.740516	5738.027	-16.3547
26	1019	1180.44454	7.484125	4767.993	-8.10794
27	1046	1176.19827	4.246264	515.0661	-5.25798
28	1072	1173.14272	3.055552	2513.581	-2.11331
29	1124	1164.79565	8.347072	1857.232	-6.87134
30	1176	1139.22596	25.56969	20883.94	-10.3541
31	1202	1124.07544	15.15052	2307.684	-79.415

32	1255	1118.68569	5.389749	2197.205	-11.6045
33	1281	1117.12596	1.559727	2895.681	-12.8243
34	1333	1112.67199	4.453974	2040.581	-5.16944
35	1386	1109.30763	3.364364	1358.256	-4.56383
36	1438	1099.60984	9.697789	4187.851	-8.60742
37	1464	1091.93846	7.671381	6951.602	-23.5756
38	1490	1080.30498	11.63347	1625.988	-19.8398
39	1517	1074.11391	6.191067	3223.064	-5.34414
40	1543	1068.29531	5.818606	1847.133	-5.53686
41	1569	1060.35988	7.935425	1598.87	-5.98778
42	1621	1025.82742	34.53246	4021.761	-9.03236
43	1648	1014.47205	11.35537	1583.751	-20.043
44	1675	1007.91888	6.55317	2662.817	-6.02235
45	1701	998.623723	9.29516	2491.749	-7.58201
46	1727	990.905913	7.71781	1738.192	-11.2545
47	1754	987.069544	3.836369	1170.507	-6.26137
48	1780	983.989464	3.08008	3816.488	-2.29591
49	1806	982.613672	1.375791	674.6659	-8.03351
50	1832	980.172585	2.441088	589.0572	-2.40396
51	1886	979.666568	0.506017	656.5886	-2.6739
52	1912	978.928243	0.738325	695.6502	-0.82841
53	1964	976.518129	2.410114	2000.004	-0.82764
54	1990	974.241598	2.276531	4283.667	-2.97976
55	2016	973.536967	0.704632	724.0346	-5.43733
56	2068	971.988503	1.548463	376.4774	-2.69487
57	2094	970.894547	1.093957	3335.797	-1.44398
58	2146	968.366578	2.527969	686.4004	-3.13564
59	2198	961.331887	7.034691	1291.202	-2.49622
60	2251	958.669994	2.661893	681.7601	-8.71492
61	2278	957.249681	1.420313	961.1546	-3.80703
62	2304	955.859048	1.390633	900.5166	-2.97674
63	2330	954.285589	1.573459	997.7101	-5.07341
64	2356	952.762614	1.522975	1015.106	-1.41935
65	2382	951.893322	0.869292	2096.771	-1.29556
66	2408	950.644673	1.248649	607.4057	-1.6914
67	2461	950.045186	0.599486	369.8235	-0.76058
68	2488	949.821918	0.223268	731.341	-0.35855
69	2540	949.014436	0.807483	1614.806	-0.32818
70	2592	945.132394	3.882042	2359.715	-1.38347
71	2619	943.651514	1.48088	180.9142	-2.4873
72	2646	943.473665	0.177849	231.8118	-0.28792
73	2672	943.209924	0.263741	213.7705	-0.16905
74	2699	943.063439	0.146485	209.2808	-0.17491
75	2725	942.823966	0.239473	310.4383	-0.16688
76	2777	941.96921	0.854756	1038.183	-0.49704
77	2804	941.477116	0.492095	205.4454	-0.52655
78	2831	941.235369	0.241747	321.8978	-0.1198
79	2883	940.370858	0.864511	762.7556	-0.35061
80	2935	936.828283	3.542575	1442.958	-1.34604
81	2962	934.665064	2.163219	555.1059	-2.39615
82	2989	933.833875	0.83119	638.1779	-0.8876
83	3016	933.445946	0.387929	286.3915	-0.50274
84	3042	932.912957	0.532989	680.9535	-0.33198
85	3094	930.968668	1.944288	979.4762	-0.75996
86	3120	928.639364	2.329305	618.3956	-2.26858
87	3147	928.011092	0.628272	493.9798	-0.93444
88	3200	927.797049	0.214043	344.3828	-0.43155
89	3227	927.741058	0.055991	56.79311	-0.09284
90	3254	927.711257	0.029801	145.6004	-0.02045
91	3306	927.497852	0.213405	310.4031	-0.03854
92	3358	926.869997	0.627855	1160.142	-0.31476
93	3410	924.07895	2.791047	980.1104	-0.81827
94	3436	921.1242	2.95475	986.9178	-2.7082
95	3463	920.171682	0.952518	451.043	-1.38696
96	3516	919.608239	0.563443	451.134	-0.98375
97	3543	919.206645	0.401595	442.493	-0.41837
98	3570	919.107825	0.09882	262.8366	-0.22956
99	3597	919.047831	0.059994	166.0867	-0.07501
100	3649	918.762835	0.284996	443.2088	-0.10835
101	3701	917.541366	1.221468	1072.925	-0.46375
102	3728	916.758679	0.782687	279.1279	-1.14248
103	3755	916.571611	0.187068	315.7488	-0.16852

104	3782	916.471706	0.099905	376.5783	-0.14817
105	3809	916.408984	0.062722	251.3384	-0.06147
106	3861	916.236767	0.172218	425.0814	-0.07635
107	3913	914.500137	1.736629	1364.294	-0.28993
108	3939	911.703771	2.796367	793.0767	-1.92974
109	3966	910.110026	1.593745	956.0729	-1.94127
110	3992	908.667494	1.442532	1535.063	-0.90424
111	4018	908.051238	0.616255	558.6234	-4.65134
112	4044	907.653738	0.3975	434.0339	-0.74594
113	4070	907.375195	0.278544	107.296	-1.29358
114	4124	907.316114	0.05908	85.10174	-0.08693
115	4151	907.309062	0.007052	52.29257	-0.01355
116	4178	907.305087	0.003975	65.05862	-0.00222
117	4230	907.243671	0.061415	118.6252	-0.00697
118	4282	906.959992	0.283679	397.1184	-0.12137
119	4334	906.235736	0.724256	127.6014	-0.39655
120	4361	906.039517	0.196219	51.874	-0.37915
121	4388	906.029843	0.009674	40.124	-0.01969
122	4415	906.029473	0.00037	40.12186	-0.00049
123	4467	906.023062	0.006411	40.14269	-0.00031
124	4519	905.982361	0.040701	96.52903	-0.01571
125	4571	905.795564	0.186797	40.57244	-0.05545
126	4598	905.791735	0.003829	40.58506	-0.00646
127	4625	905.791495	0.00024	40.58439	-0.00034
128	4677	905.789954	0.001541	40.58498	-0.00012
129	4755	905.732302	0.057652	162.7898	-0.00324
130	4939	897.018321	8.713981	776.3695	-0.11859
131	4993	896.860453	0.157868	1088.874	-5.35658
132	5019	895.14897	1.711483	343.3888	-29.5354
133	5046	894.595915	0.553055	210.9006	-1.26521
134	5073	894.561622	0.034293	152.8535	-0.04447
135	5099	894.519965	0.041657	325.669	-0.01568
136	5151	894.015697	0.504268	574.1864	-0.06193
137	5177	893.852901	0.162796	1461.03	-0.45203
138	5203	893.606065	0.246836	445.8912	-0.58983
139	5230	893.578337	0.027727	37.12936	-0.05516
140	5257	893.577731	0.000607	6.211585	-0.00111
141	5284	893.577703	0.000028	0.851406	-0.00004
142	5311	893.577702	2.584E-7	0.081148	-1.89E-6

NOTE: GCONV convergence criterion satisfied.

Fit Statistics

-2 Log Likelihood	1787.2
AIC (smaller is better)	1837.2
AICC (smaller is better)	1838.0
BIC (smaller is better)	1896.7

Parameter Estimates

Parameter	Estimate	Standard Error	DF	t Value	Pr > |t|	Alpha	Lower	Upper	Gradient
B11	0.6618	0.08195	76	8.08	<.0001	0.05	0.4986	0.8250	0.000014
beta12	0.2658	0.03234	76	8.22	<.0001	0.05	0.2014	0.3302	-0.00007
b13	2.3403	0.04098	76	57.10	<.0001	0.05	2.2587	2.4219	0.000227
b14	-0.04726	0.03607	76	-1.31	0.1941	0.05	-0.1191	0.02459	-0.00112
b15	0.006021	0.001376	76	4.38	<.0001	0.05	0.003281	0.008761	-0.0296
B21	0.5761	0.09717	76	5.93	<.0001	0.05	0.3826	0.7697	0.000258
beta22	0.1286	0.02162	76	5.95	<.0001	0.05	0.08552	0.1716	0.000574
b23	2.8985	0.06220	76	46.60	<.0001	0.05	2.7747	3.0224	-0.0001
b24	-0.05782	0.04590	76	-1.26	0.2117	0.05	-0.1492	0.03360	0.001108
b25	0.007507	0.002162	76	3.47	0.0009	0.05	0.003200	0.01181	0.019293
B31	0.9472	0.2509	76	3.78	0.0003	0.05	0.4475	1.4468	0.000454
beta32	0.4399	0.04380	76	10.04	<.0001	0.05	0.3527	0.5271	0.001833
b33	2.4891	0.02283	76	109.05	<.0001	0.05	2.4437	2.5346	0.006515
b34	0.01878	0.03082	76	0.61	0.5442	0.05	-0.04261	0.08016	0.000074
b35	0.002992	0.000705	76	4.24	<.0001	0.05	0.001587	0.004397	0.076875
B41	0.5022	0.1256	76	4.00	0.0001	0.05	0.2520	0.7523	0.000303
beta42	0.2019	0.02883	76	7.00	<.0001	0.05	0.1445	0.2593	0.000855
b43	2.9171	0.04215	76	69.21	<.0001	0.05	2.8332	3.0011	-0.0002
b44	-0.01487	0.02501	76	-0.59	0.5538	0.05	-0.06468	0.03494	0.001462
b45	0.008738	0.000948	76	9.21	<.0001	0.05	0.006849	0.01063	0.042088
sig2	0.1527	0.005512	76	27.70	<.0001	0.05	0.1417	0.1637	-0.01068
s2bran12	0.008166	0.003177	76	2.57	0.0121	0.05	0.001839	0.01449	-0.01778

s2bran22	0.002503	0.001068	76	2.34	0.0217	0.05	0.000376	0.004629	-0.0217
s2bran32	0.02499	0.008339	76	3.00	0.0037	0.05	0.008380	0.04160	-0.01234
s2bran42	0.007697	0.002763	76	2.79	0.0067	0.05	0.002195	0.01320	-0.08115

VITAE

Robert Kirk Witmer was born on 27 September 1971, in Chambersburg, Pennsylvania. He is the son of Donald and Deborah Witmer of Greencastle, Pennsylvania. He received his primary education at Greencastle-Antrim Elementary School, and graduated from Greencastle-Antrim High in 1989.

He enrolled in the Forest Technology program at the Pennsylvania State University's Mont Alto campus in 1989, completing an Associate in Science degree in 1991. Continuing his education, he earned a Bachelor of Science in Forest Science in 1993 studying at Penn State's Mont Alto and University Park Campuses. In January 1994 he enrolled in Penn State's Master of Science program in Forest Resources and completed that degree in August 1996. He enrolled in the doctoral program in Horticulture at Virginia Polytechnic Institute and State University in the fall of 1996, and was granted a Doctor of Philosophy degree in December 2000.