WATER USE BY EMORY OAK IN SOUTHEASTERN ARIZONA:

ESTIMATION BY SAP-FLOW MEASUREMENTS

by

Shaun Hajo Folkerts

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APPROVAL BY THESIS COMMITTEE

This thesis has been approved on the date shown below:

Dr. Peter F. Ffolliott Professor of Watershed Management	3/25/99 Date
Dr. H. Randal Gimblett Associate Professor of Landscape Resources	March 24, 1999 Date
Dr. Gerald J. Gottfried Research Forester, USDA Forest Service	March 22, 1999 Date

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ABSTRACT

Water use by mature and sprout (coppice) forms of Emory oak (Quercus emoryi) was estimated by the sap-flow method. Five standards and five coppice trees were sampled in an area that had been harvested for fuelwood and five mature trees were sampled in an uncut area. Differences were recognized between coppice and standards in the cut area and between coppice trees and mature trees from the uncut area. Regression equations were derived relating estimated annual water use to tree diameter, height, and crown measurements for both cut- and uncut-area trees. Seasonal water use by each tree form showed relationship to precipitation, but little relationship to temperature and relative humidity. Woodland density and tree size measurements facilitate extrapolation of water use from the 15 sampled trees to a per area basis. Water use was approximately 1900 cubic meters per hectare per year, based upon drc measurements, for the uncut area and 3168 cubic meters for the cut area. Estimated water use on a per unit area was approximately 1.67 times greater for the cut area than the uncut area.

INTRODUCTION

The northern Sonoran desert receives little rainfall and must support both its native flora and fauna and an ever-increasing human population in southeastern Arizona which places greater demands on the land, water, and biotic resources of the area. As a result, it is increasingly important to ensure proper management of Arizona woodlands such that it is managed and developed in an ecologically sustainable manner. Oak woodlands are an important economic and environmental resource, providing wood products, forage, wildlife habitat, watershed protection, and recreation. Conservation and sustainable development of oak woodlands within the framework of integrated resource management require a more complete knowledge of its ecological function.

A major concern is the availability of adequate water supplies for domestic, agricultural, and natural consumption. Knowledge of hydrologic processes is essential to the understanding of soil-vegetation relationships required to manage for sustainability (Baker et al. 1995). Therefore, it is increasingly vital to learn as much as possible about every aspect of the water cycle. Despite the vast extent and environmental importance of the oak woodlands in the southwestern United States and northern Mexico, few complete hydrological studies have been conducted in the area (Sellers and Hill 1974, Lopes and Ffolliott 1992). Studies have been conducted in the oak woodlands of southeastern Arizona regarding individual hydrologic components such as interception, throughfall, infiltration, runoff, erosion, and sedimentation (Baker et al. 1995), yet none to date have focused specifically on evapotranspiration.

Evapotranspiration losses from tree and shrub forms of oak on the woodlands have been perceived as a factor limiting the amount of recoverable water, yet has never been quantified. Water use by oak affects the entire hydrologic cycle and the responses of other ecosystem components such as understory plants, animal populations, downstream riparian ecosystems, and groundwater recharge. This study evaluated the impact of Emory oak (Quercus emoryi), a species representative of the lower elevations of the oak woodlands of southeastern Arizona, on the hydrologic cycle with quantitative estimates of water use by individual trees, stands, and on an area basis. It also examined the response of Emory oak to climatic conditions and management activities. Extrapolation of individual tree data provided an estimate of water use on a larger scale.

An index of water use of tree and shrub forms of the Emory oak can be used to characterize water use by oak-dominated stands of the Southwest. An increased understanding of the ecological, physiological, and hydrological dynamics of oak-dominated ecosystems can be used to determine viable integrated resource management options and evaluate existing activities.

LITERATURE REVIEW

Oak Type

Twelve different oak species have been identified in Arizona (Chojnacky 1988; McPherson 1992). Many of these are found in southeastern Arizona woodlands; the most common are Emory, Arizona white (Quercus arizonica), and Mexican blue oak (Q. oblongifolia). Often, border pinyon (Pinus discolor) and alligator juniper (Juniperus deppeana) are found intermixed. Grasses such as grama (Bouteloua spp.), muhly (Muhlenbergia spp.), three-awns (Aristida spp.), and bluestems (Andropogon spp.), and forbs, such as sages (Artemisia spp.) and deer-vetch (Lotus rigidus), grow beneath the woody overstories (Gottfried 1992, McPherson 1992, Caprio and Zwolinski 1994). Several species of cactus (Opuntia spp.) can be found, including cholla and prickly pear varieties. More than 180 different birds and mammals use the woodlands as habitat.

The oak woodlands are generally characterized by an arid climate. The mean temperature of the woodland is 15.7° C., and 140 to 200 frost-free days can be expected (Sellers and Hill 1974). Precipitation in the Sonoran desert is bi-modal, with short, intensive midwinter rainy periods and mid- to late summer monsoons. Fifty to seventy percent of rainfall occurs in the "growing season" months of July and August (Bahre 1991). Precipitation averages 467 millimeters and ranges between 373 and 600 millimeters per year, increasing with elevation (Lopes and Ffolliott 1992). A 38-year collection of precipitation data by Coronado National Memorial showed the mean yearly precipitation to be just over 500 millimeters. Soil stays moist for a longer duration following winter rains than summer rains due to decreased temperatures and subsequent decreased evapotranspiration. Evaporation rates can be eight-times greater in June than in December (Baker et al. 1995). Groundwater is recharged in the winter and spring months and used in the summer and fall (Quinn 1982). Snow is not a major factor because of its short duration on the ground (or vegetation) surface.

Classification

The oak woodlands of southeastern Arizona have been classified by the Society of American Foresters as the western live oak type (Ffolliott 1980). They are also commonly referred to as the encinal (from the Spanish for "oak") or Madrean evergreen woodland. Ninety-two percent of the oak type is classified by the USDA Forest Service as "high site," that is, land capable of producing wood products on a sustainable basis (Conner et al. 1990).

History

The oak woodlands have been historically affected by natural disturbances such as fire, pests, disease, drought, and climatic fluctuations and adjustments over longer time periods (McPherson 1992). Historic fire occurrence intervals have been estimated at 10 to 20 years. Due to changes in cattle grazing, wood harvesting, fire suppression, and the creation of firebreaks by humans, the historic intensity and lateral spread of fire has been altered, which consequently altered its influence.

Native Americans found an abundance of fuelwood for heating and cooking in the oak woodlands. The arrival of Europeans caused the woodlands to become increasingly utilized for buildings, structures, fenceposts, and fuelwood, and the understory forage for livestock grazing. Cattle, introduced as early as 1540, fluctuated in number from several thousand to more than 200,000 in Cochise, Pima, and Santa Cruz counties by the 1890s (McClaran et al. 1992). Leaves and small stems of oak species can comprise as much as 25 percent of cattle winter diets.

As human populations steadily increased, additional demands were placed upon the oak woodland communities for construction materials, fuelwood, and grazing purposes. With increasing fossil-fuel usage, demands for fuelwood gradually tapered off during the middle 20th century, but reemerged with the fuel crisis of the 1970s. The woodlands continue to be utilized for wood products, forage, wildlife habitat, and recreation and tourism.

Tree Characteristics

The two principle oak species found at lower elevations in the oak woodlands in southeastern Arizona are not true evergreens, but rather are drought-deciduous. One is Emory oak, a variety of red oak, which can be a shrub or a large tree to 15 meters tall and with a diameter of up to one meter (Little 1950). It is identified by its ashy-grey bark and veins on whitish leaf undersides. The other species is Arizona white oak, which can grow to a height of 20 meters and a diameter of one meter.

Emory oak can reach an age of 200 years, and Arizona white oak, 250 years (Sanchini 1981). McPherson (1992) warns about problems in accurately determining age of lower-elevation oaks, due to possible differences in stem and plant ages as a result of repeated sprouting of cut stems. Determining age by dendrochronological methodology is difficult because evergreen oaks do not necessarily produce a new growth ring each year (Swetnam, personal communication). This can result in underestimation of actual age because some growth rings are absent or too small to differentiate.

Stand Characteristics

The oak woodlands are found at the southern end of the Basin/Range province in southeastern Arizona, New Mexico, western Texas, and the Sierra Madre Occidental of Northern Mexico. Open oak woodland occurs at elevations of 1,400 to 1,700 meters.

Pygmy conifer-oak woodlands occur at 1,520 to 2,130 meters, pinyon-oak woodlands and Chiricahua pine-oak woodlands occur at 1,830 to 2,130 meters (Gottfried et al. 1995).

The oak type covers 80,300km^2 in aggregate (Conner et al. 1990). Fifty percent is National Forest land and 40 percent is in private hands in Arizona. Ffolliott and Gottfried (1992) estimated oak woodland volume in southern Arizona from less than 7 to more than 35 cubic meters per hectare. Average basal area is estimated at 3.6 square meters per hectare (Fowler and Ffolliott 1995).

Growth and Mortality

Low precipitation rates and high temperatures contribute to the slow growth and low density of oak stands (Bennett 1995). Annual growth rates are estimated at less than one percent, approximately 0.25 to 0.50 cubic metres per hectare per year (Ffolliott 1992). Natural mortality rates are low due in part to previous thinnings of older individuals (Conner et al. 1990).

Regeneration

Acorns are produced in trees aged 40 (Emory oak) or 60 (Arizona white oak) years to approximately 160 years (Sanchini 1981). McPherson (1992) determined germination and establishment rates are related to litter depth, depth of the acorn beneath the soil surface, and acorn moisture content. Seedlings account for only 19 percent of oak regeneration (Borelli 1990). The low seedling establishment rates are due to herbivory, interference from other plants, and environmental conditions (Weltzin and McPherson 1995). Bahre (1977, cited in Weltzin and McPherson 1995) showed that cattle grazing in particular adversely affected oak seedling establishment in Arizona.

The majority of oak trees come from stump or root (coppice) sprouts (Borelli 1990, Bennett 1995). Coppice was defined as "a forest crop raised from shoots produced from the cut stumps of the previous crop" (Evans 1992). The result of coppicing is relatively small, often multiple-stemmed trees of irregular form (Gottfried et al. 1995), in stands varying from a few scattered individuals to several hundred stems per acre (Ffolliott 1992). Harvesting of oak stands can result in vigorous sprouting and stand enclosure within seven years (Deecken 1988).

Transpiration Process

Water and nutrients are absorbed by plants from the soil through their root systems and into the specialized vascular system tissue known as xylem. Xylem is permeable and allows exchange of nutrients along the flow path as necessary. Cohesion theory states that a plant's respiratory system is driven by vaporization of water at outermost cell wall evaporation sites and the adhesive properties of water to draw additional water through the xylem from the roots to these newly created voids

(Kozlowski and Pallardy 1997). Continuity of the xylem columns is necessary to maintain proper respiratory function (Noggle and Fritz 1976).

Researchers measured sap flow at various depths beneath the bark of selected sessile oak (Quercus petraea) trees in a thirty-two year old stand in northeastern France (unpublished, cited in Breda et al. 1992). It was found that 80 percent of the total sap flow in the xylem occurred in the first eleven millimeters (equivalent to five or six annual rings) of the sapwood.

Water that reaches the leaves is used in the photosynthetic process. Excess water is lost to the atmosphere in the form of water vapor that has been converted from liquid form within the leaf. This is transpired water. It is released through the stomata, small pores of variable aperture, which the plant uses to regulate the transfer of substances between the leaf and atmosphere. According to Campbell (1977), the driving force for vapor loss is the vapor density difference between the substomatal cavities in the leaf and the ambient air. Moisture can be absorbed through the stomatal openings of leaves and sent in a downward direction in extremely dry soils.

Transpiration is a measure of the amount of water a tree withdraws from the soil or groundwater supply. Quantification of transpiration by a tree enables estimates of water withdrawn from the ground and lost to the atmosphere on an individual tree, stand, unit-area, or woodland basis. Transpired water is unavailable for alternative downslope water use, competing vegetation, or recharge of groundwater, a loss of extreme importance in areas of limited water availability.

Estimating Transpiration

Several methods have been developed to estimate transpiration of water by plants. Each of these has merits and limitations. Seven methods were identified and described. This section concludes with descriptions of studies which compared many of these methods to the one used in the study presented herein.

Tent Method

The tent method involves enclosing the study plant in a medium (usually plastic) impermeable to moisture (Brooks et al. 1997). The moisture content of air entering and exiting the "tent" is monitored. Any increase in air moisture exiting the tent is attributed to evapotranspiration from the contained plant-soil-water system. Excluding evaporation of water from the soil by covering it with plastic media results in an estimate of the plant transpiration component of the system. A problem in the use of the method is that it necessarily creates an artificial environment inside the tent. Maintaining adequate airflow can reduce such negative effects by balancing outside temperature and humidity with that inside the tent.

Scholander Pressure Chamber

Estimates of a plant's internal water deficit and water stress can be made through water potential measurements. Water potential is defined as "the amount of work that a unit volume of water is capable of doing in reference to an equal unit of pure, free water at the same location in space" (Brooks et al. 1997). A branch terminus is removed from a plant and sealed, except for the cut end of the stem, in a chamber capable of sustaining high pressures. An inert gas is introduced into the chamber and gradually builds pressure. When xylem sap appears at the end of the stem, it is at equilibrium with the water potential of the cells of the conducting system of the plant. Low water potential indicates a high degree of absorption ability and high water potential indicates the relative ability of the measured part to supply cells of parts of the plant with lower water potential (Noggle and Fritz 1976). Water pressure potential in the leaf is decreased through transpiration (Brooks et al. 1997). Thus transpiration of a leaf can be estimated as a function of water potential measurements and extrapolated to estimate transpiration of the tree as a function of its total leaf area.

Lysimeters

All water inputs and outputs in a controlled system on an individual plant basis are measured by the lysimeter method. Transpiration produces changes in water flow (drainage type of lysimeter) or overall weight (weighing type of lysimeter) of the plant and its container (Brooks et al. 1997). Because all input and output data are known, the changes in water flow or plant and soil weight are a result of the remaining unknown component, which is calculated and attributed to transpiration losses over a given time period. A limitation of the method is that it is best applied to smaller plants. Lysimeters are relatively expensive and difficult to apply to larger plants.

Water Budget Method

Inputs to a system must balance output from the system. Water budget methods estimate transpiration by measuring a system's physical inputs (precipitation) and outputs (runoff, interception, evapotranspiration, etc.) and calculating transpiration as a function of them (Brooks et al. 1997). If all other parameters are known, the calculated difference between inputs and outputs is attributed to transpiration. Evapotranspiration is a combination of the transpiration component of a water budget with the evaporation component (water lost directly to the atmosphere from open water bodies, plant surfaces, or soil).

Brooks et al. (1997) presented a water budget as:

$$ET = P - Q - \Delta S - \Delta l$$

where ET is evapotranspiration in millimeters, P is precipitation over the time period in millimeters, Q is streamflow in millimeters, ΔS is a change in storage of the watershed, and Δl is change in deep seepage.

Federer (1970) identified four parameters that must be measured to estimate evapotranspiration via the water budget method: water input above the surface (usually precipitation), flow in or out on the surface (streamflow), flow in or out below the surface (deep seepage), and change in water content of the soil and vegetation volume and snow cover.

Haworth (1992) studied the influence of the oak type on deposition of precipitation. A reduction in precipitation throughfall of up to 70 percent was measured beneath tree canopies. It was concluded that the oaks' influence on precipitation distribution increased with increasing tree size (larger canopy to intercept precipitation) and decreased with increasing storm size (once maximum interception capacity had been exceeded). Lopes and Ffolliott (1992) identified the dominant factor in determining the amount of runoff as the intensity of the precipitation event. Haworth (1992) also noted that four soil-water relationships were modified by oak trees: the proportion of precipitation reaching the soil, water storage in the soil, water quality, and the amount of water lost through evapotranspiration.

Energy Budget Method

The energy budget method estimates transpiration from a tree as a function of energy losses from evapotranspiration by the tree. The energy budget equation for estimating the energy used in evapotranspiration is:

$$ET = (R - G - H_s) / H_v$$

where ET is evapotranspiration in centimeters per day, R is net radiation in calories per square centimeter per day, G is heat of conduction to the ground in calories per square centimeter per day, H_s is sensible heat in calories per square centimeter per day, and H_v is latent heat of vaporization in calories per cubic centimeter (adapted from Penman et al. 1967, cited in Brooks et al. 1997). Subtraction of losses and known output terms from all inputs enables estimation of evapotranspiration from measurements of the individual components of a system in a manner much like that of the water budget method.

According to a study near Bordeaux, France, on maritime pines (Pinus pinaster), researchers noted that the energy balance approach is effective due to the fact it allows simultaneous measurements of evaporation without transpiration at different levels of a canopy (Diawara et al. 1991).

Potential Evapotranspiration

Potential evapotranspiration is the amount of water that could be evaporated in a unit time from a soil-plant system of completely shaded, uniform short height, green crops without water as a limiting factor (Penman 1948, cited in Brooks et al. 1997). This serves as a basis for an index which can be applied to vegetation under different circumstances. One method of establishing this index is based upon water evaporation from a standardized pan. Pan evaporation has been used to develop evaporation indices from lake bodies and evapotranspiration indices for certain plant species (Brooks et al. 1997).

The effectiveness of estimating transpiration from potential evapotranspiration estimates is dependent upon several factors; identified factors include soil water capacity, soil moisture content, permanent wilting point of the vegetation, and rooting depth of mature vegetation (Brooks et al. 1997). Relationships between such factors and transpiration have been expressed in the form of species-specific equations.

Potential evapotranspiration can also be determined empirically using derived equations. The best known is Penman's equation, based upon a simplified energy budget with the addition of aerodynamic terms (Brooks et al. 1997).

Hamon (1966) estimated potential evapotranspiration using temperature and length of daylight as independent variables. Hamon's studies of the arid American west (no location given), estimated that 90 percent of the 254 to 381 millimeters of annual precipitation was lost to evaporation. Calculated potential evapotranspiration in the Madrean archipelago was 760 to 1020 millimeters per year; while that for actual evapotranspiration was an estimated 250 to 760 millimeters (Baker et al. 1995).

Sap-flow Measurements

The sap-flow (or sap-flux) method is based on measuring the internal flow of water, in the form of sap, as it ascends vertically through the xylem tissue of a plant. Water is drawn from the soil into the plant through the root system, flows through conducting tissues of the stem and branches, and is released through physiological processes at the leaves. The time needed for a tracer applied to the sap of a tree to pass a given vertical distance (usually on the main stem) between sensor probes which are situated in the xylem stream is measured. The time measurement allows calculation of water flow through the plant once the two-dimensional cross-sectional area of conducting tissue is determined (Swanson 1962).

The method assumes that all water taken up by the plant will pass the measured point, water "use" by the plant takes place entirely above the measuring point, and there is perfect uniformity of efficiency in the conducting tissue. The method also assumes that no water storage takes place above the point being measured and that the measured xylem is an indicator of sap movement (Swanson 1972). A more detailed discussion of the development of the sap-flow method, and comparison studies between the sap-flow method and estimates of transpiration by other methodologies is presented in the following paragraphs because the sap-flow measurements were the basis of estimating water use in this study.

Development of the Sap-flow Method. Irish botanist Henry Dixon studied the movement of sap as a function of the transpiration process for decades (Dixon 1924, Swanson 1994). The idea of applying heat as a tracer to determine sap-flow rates was attributed to a German scientist named Huber, who conducted research on the topic in the early 1930s (Swanson and Whitfield 1981). Huber and Austrian researcher Wilhelm Schmidt improved upon the idea throughout the following decades.

Marshall (1958) derived formulae for the determination of transpiration rates based upon different time, temperature, and probe spacing configurations. Marshall pioneered the use of probes implanted in plants, as earlier efforts relied on a heater attached to the plant's surface. The formulae also accounted for properties of the wood (Swanson 1994). Swanson (1962) outlined the construction and use of sap-flow instrumentation and the necessary calculations required to estimate sap-flow rates for measurements obtained by a sap-flow meter. Additions and changes to the instruments and formulae have been implemented over the years including the introduction of the heat-balance method in the late 1960s (Swanson 1994). This method better accounted for external influences (such as solar radiation) as well as radial heat loss within the plant.

Swanson and Whitfield (1981) detailed the problems with the sap-flow method: e.g. sensor spacing, analysis method, and the possible underestimation of actual flow rates due to interruptions in the flow pathway due to probe size and thermal differences between the probe and the wood. These researchers implanted the thermistor probes. resulting in healing processes and resin production around the wound. The resin isolated the sensors from the flow pathway. and led the researchers to conclude "when measurements were within a few days of probe installation, good results were obtained ... this means that ... measurements should be carried out with freshly installed probes" (Swanson and Whitfield 1981). In the study reported upon herein, all probes were inserted moments before measurement of sap flow.

Cohen et al. (1985) reported disturbance of the sap-flow pathway by thermistor insertion resulted in an underestimation of water flow rate by about 45 percent in a study on Douglas-fir (Pseudotsuga menziesii) in a laboratory setting; Douglas-fir has a spiral sap-flow pattern. Reduction in the size of the diameter of the probes was shown to lessen the degree of underestimation.

Precise placement of the thermistors and heating element within the xylem flow is vital to accurate estimates of water use. Miller et al. (1980) experimented with the placement of thermistors at differing depths in black oak (Quercus velutina), and determined that the best thermistor placement was at the cambium-xylem interface. It was also demonstrated that simultaneous measurement of thermistors placed on varied aspects of the tree had only minor velocity increases on the side of the tree with the most crown exposed to sunlight. Complete crown exposure in smaller trees resulted in an even distribution of sap velocities around the stem.

Comparative Studies. Researchers have conducted studies to determine the validity and accuracy of the sap-flow method in comparison to the other methods of estimating transpiration. These comparison studies established a reference, based upon alternative methods, for the expected accuracy of sap-flow measurements in subsequent research.

A study of black oak (Quercus velutina) in the northeastern United States showed that heat pulse velocity measurements consistently overestimated actual sap flow by 35 percent to 40 percent compared to the Scholander pressure chamber method (Miller et al. 1980). The overestimation was attributed to the distribution of flow velocity within the xylem vessels. Peak flow velocity occurred at the depth to which the probes were implanted in the center of the xylem, a problem which did not affect estimates attained with the pressure chamber technique. Error for a stand was estimated at 15 percent in calculations of transpiration from sap-flow rates due to the assumption that the tree boles were perfectly round.

Swanson (1972) attained a 0.98 correlation coefficient between heat pulse velocities and daily total transpiration based upon an experiment involving a potted Aleppo pine (Pinus halipensis) in Arizona. The lysimeter was enclosed in plastic, so all weight losses during the measurement period were attributed to transpiration. Swanson found a poor relationship between heat pulse velocity and transpiration based upon the lysimeter method when the Aleppo pine were subjected to high stress levels. A study performed on citrus trees (Citrus sinensis) in a laboratory in Israel found estimates of water use to be 45 percent greater by weighing lysimeter than estimates made by the sap-flow method (Cohen et al. 1981). A mean correction factor of 0.553 (coefficient of variation was 2.4%) was established to relate sap-flow measurements to transpiration estimates obtained by lysimeter. Overall accuracy of sap-flow determination on Citrus sinensis was approximately five percent. Swanson and Whitfield (1981) found agreement within five percent between corrected measurements taken by heat pulse velocity method and by lysimeter on Aleppo pine (Pinus halipensis).

Researchers found what seems to indicate agreement between the sap-flow method and energy balance calculations in a study on maritime pine (Pinus pinaster) near Bordeaux, France (Diawara et al. 1991). Zhang et al. (1997) conducted a comparison study based upon a stand of poplar trees (Populus trichocarpa) in southern Great Britain. Agreement (r-squared = 0.886) was noted between sap-flow measurements and estimated transpiration rates by energy balance method using the Penman-Monteith equation. The study showed the sap-flow method, combined with other empirical methods, to be a useful research tool.

In a study on grapefruit trees (Citrus paradisi) in Israel, Cohen (1991) found sap flow to be a useful method of water use estimation based upon comparative measurements of potential evapotranspiration. The agreement (r-squared = 0.962) between the water use estimations obtained by the two methods was not affected by climatic variation, but it was adversely affected by low amounts of soil water available for uptake. It was also mentioned that it might be possible to extrapolate water use by the orchard by taking into account the large variability in estimated water use between trees. The effects of severe drought were measured on stands of sessile oak (Quercus petraea) in northeastern France using the sap-flow and potential evapotranspiration methods (Breda et al. 1992). There was general agreement between the two methods over the three-year course of the experiment; a higher Penman potential evapotranspiration rate was attributed to soil evaporation, which was not accounted for in the sap-flow method. The study also found uniform canopy transpiration of dominant and codominant trees on a sapwood-area basis with both methods.

Most of the comparison studies show a strong correlation between the sap-flow and other methods of estimating transpiration. Sap flow rates were shown to overestimate transpiration based upon comparison with the Scholander pressure chamber method in the study by Miller et al. (1980) and to underestimate transpiration rates by about the same percentage (35-45%) when compared to rates obtained by weighing lysimeter in the Cohen et al. (1981) study. All comparison studies agree that the sap-flow method is a useful method of estimating sap-flow when recommended modifications and improvements are incorporated.

Summary

The literature review introduced the oak woodlands of southeastern Arizona as an important resource in terms of its role in the ecosystem and for its many uses by man. A specific species common to these woodlands, the Emory oak, was introduced and described. The transpiration process was described and its role in the hydrologic cycle examined. The sap-flow method was selected from the several available methods of estimating transpiration due to its relative ease of use, low cost, and ability to estimate transpiration accurately, as evidenced by several studies of comparison with other methods.

DESCRIPTION OF STUDY

Objectives

The literature review has provided the background for the problem which this study addresses: to estimate water use by the Emory oak of southeastern Arizona by measuring sap-flow. This primary goal of the study can be further defined by subdividing it into more specific objectives.

The objectives of this study were to:

1. Obtain estimates of water use (transpiration) of Emory oak from sap-flow measurements,
2. Relate estimates of water use to individual tree characteristics and meteorological factors,
3. Estimate water use of Emory oak on an area basis, and
4. Quantify transpiration for oak woodlands in the context of a water budget.

Study Area

The study area was located in the Coronado National Forest of southeastern Arizona, approximately 25 kilometers south of Sierra Vista and 150 kilometers south-southeast of Tucson (Figure 1). The area lies on a south-facing slope of the Huachuca

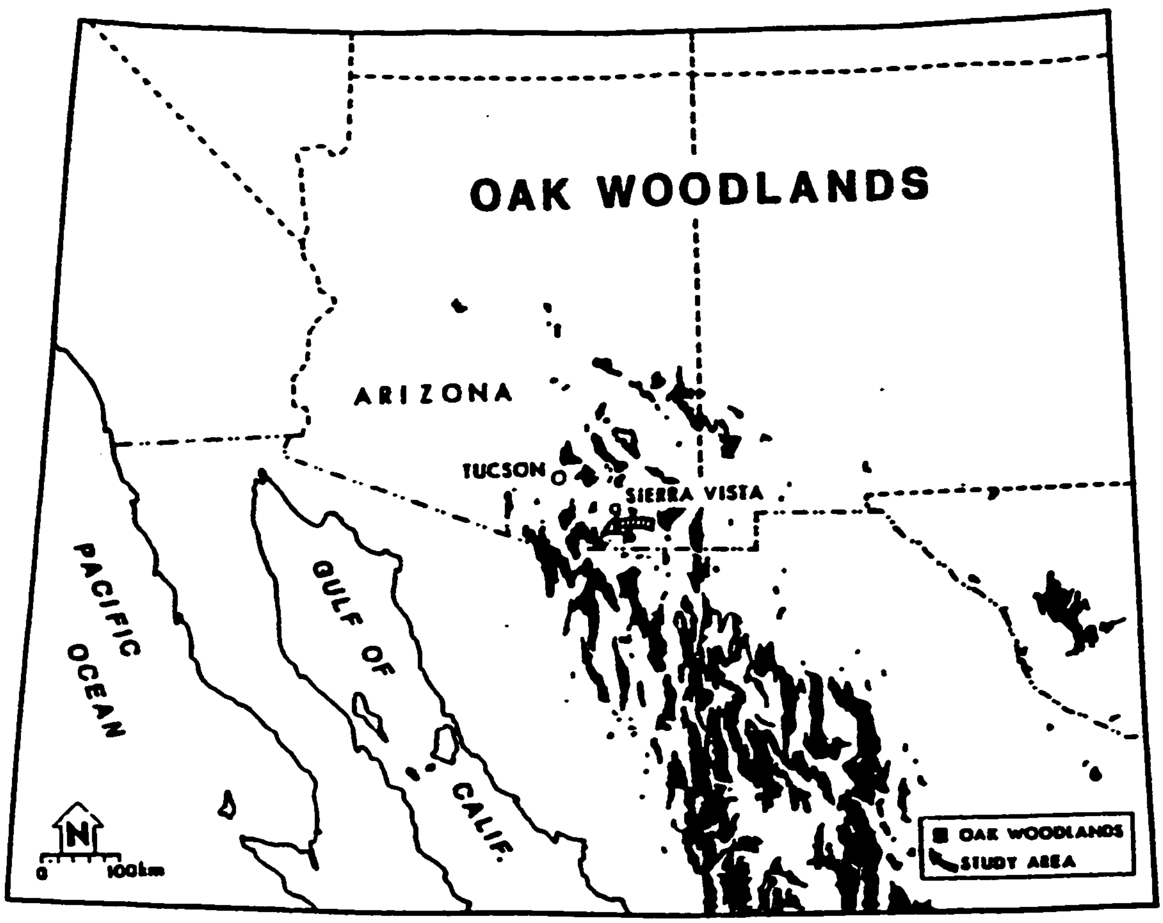

Figure 1. Study area.

Mountains in the San Rafael Valley. Coronado National Memorial is located approximately six kilometers to the east, and the Huachuca Mountains are found to the north and west. The international border between the United States and Mexico is situated a few kilometers south of the area. The elevation of the study site is 1,750 meters. It has a slope of five percent or less and has a predominantly southern aspect.

The Casto-Martinez-Canelo type is the dominant soil of the area. The soils are classified as Udic and Aquic Haplustalfs and Udic Paleustalfs and are deep, moderately fine to very finely textured, gravelly, and have moderate rates of infiltraton (Hendricks 1985). The soils were formed from parent materials consisting of mixed sedimentary and igneous rock. The soils have slow or very slow permeability, a clayey texture, and a high degree of rock fragmentation. The mean soil temperature is estimated to be between 12 and 15°C.

Soil texture on the study area was 72 percent to 80 percent sand, 16 percent to 20 percent silt, and four percent to eight percent clay. Based upon these percentages, the site has a soil texture class of loamy sand to sandy loam. Areas beneath and between the trees have a litter layer of leaves, twigs, and grasses, with frequent occurrences of bare soil where there is less protection from the effects of water, wind, and grazing.

Methods

Two sampling sites were selected at the study site. One sampling site was last harvested of Emory oak trees in 1890; the timber was used in mining structures in nearby Tombstone (Bennett, personal communication, 1998). This site was the "uncut area" in the study, and was comprised primarily of mature Emory oak trees with a few root suckers and stump sprouts. Permit-based selection-cut fuelwood harvesting took place on the other sampling site, referred to as the "cut area" in the study, for several months beginning in November 1980. It was comprised of mature Emory oak (standards) and numerous coppice sprouts, those trees regenerated from vegetative sprouting of dormant buds following a thinning practice. The age of the oldest coppice on this site was 16 years. Both sampling sites are shown in Figure 2.

The uncut area represented a typical stand of Emory oak that had not been subjected to recent fuelwood cutting. The cut area represented an area that had been altered by removal of trees for fuelwood. This particular coppice treatment removed some mature trees and left other trees standing (the standards) to foster the growth of coppice sprouts by providing them protection from strong winds and intense sunlight. This silvicultural treatment is commonly practiced in the oak woodlands of southeastern Arizona. Estimating water use on both the uncut and cut areas enable comparisons of water use from areas that had not had fuelwood removed with an area that had. Knowing the difference in water use between the two areas can enable managers to make more

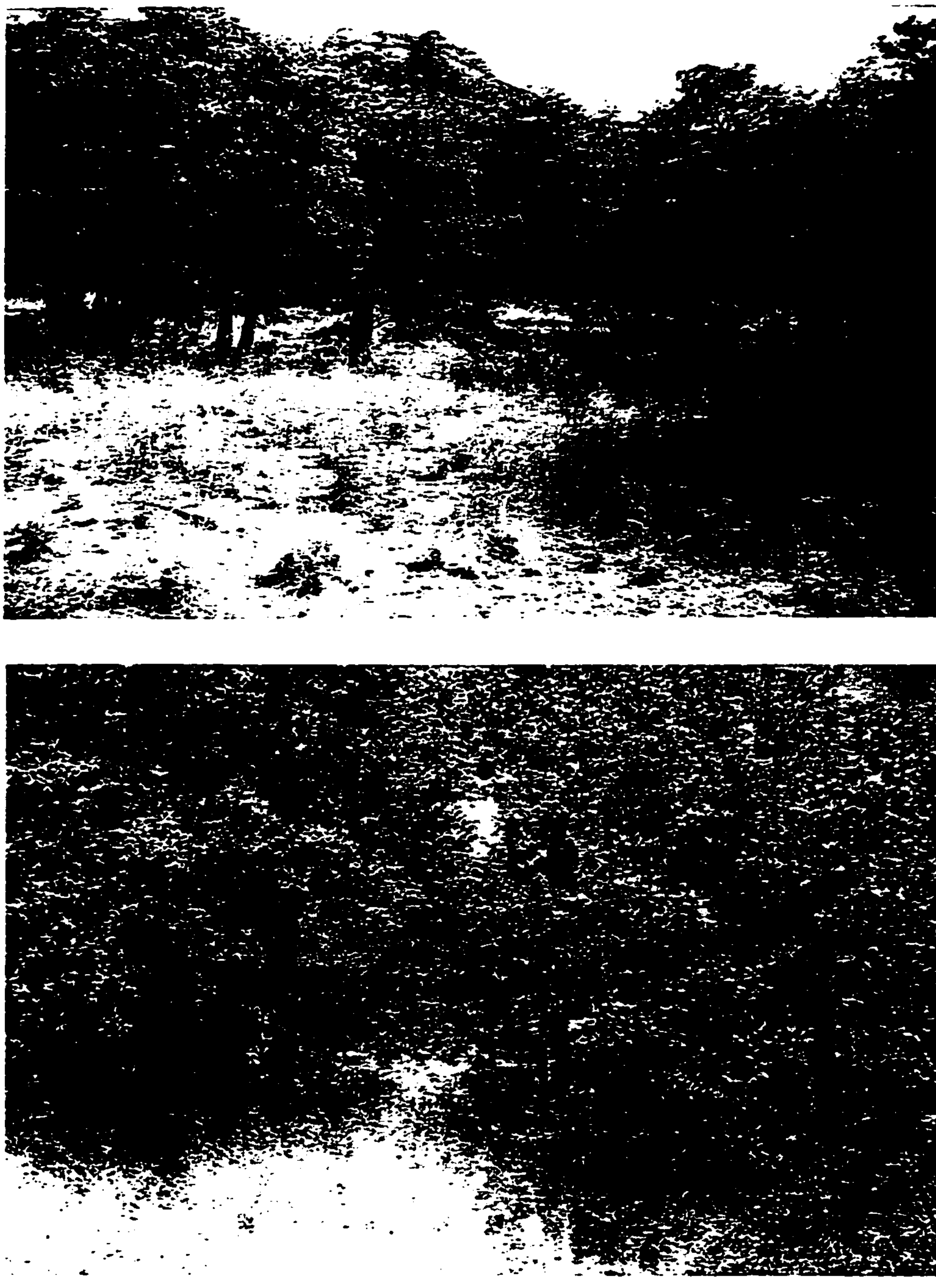

Figure 2. Uncut area (top) and cut area (bottom) showing size and density of trees.

informed decisions regarding the application and extent of future treatments.

A representative group of 15 trees was chosen for bi-weekly sampling, consisting of five mature trees from the uncut area, five standards from the cut area, and five coppice trees from the cut area. Fifteen trees was the largest sample size that could be sampled in one day. The five trees from the uncut area were of a size similar to the five standards of the cut area. Each tree was sampled approximately every two weeks in a random manner regarding time of day and aspect of the sampling point on the tree.

Field Procedures

The sap-flow method is one of the few methods applicable to field measurement of trees and shrubs. This method was chosen for this study because it is non-destructive, inexpensive, and allowed measurement of multiple trees on a single sampling date

The sap-flow method involves the precise measurement of the time needed for the ascent of a column of sap containing a tracer to flow completely past a certain point in the tree. The tracer used in this study was heat, applied to the sap-flow pathway by a miniature heating element at the end of a stainless-steel hypodermic needle approximately 10 centimeters in length. Two thermistors, also built into the ends of hypodermic needles, were placed into the sap-flow pathway at precisely measured distances above and below the probe containing the heating element.

An aluminum drill jig was constructed and attached to the tree with a racheting nylon strap. The jig enabled accurate placement and support of the three miniature probes. A small drill bit was used with the jig to remove outer woody material (bark) and the tips of the probes were inserted into the sap-flow stream of the xylem just below the bark layer. The probes were connected to an aluminum instrument switchbox, which housed gauges, switches, a circuitboard, and two batteries, via heavy-gauge insulated wiring of approximately one meter, with RCA-type plugs at the probe end and a spade terminal block at the switchbox end. The switchbox gauges were balanced so that there was no resistance between the thermistors in the xylem column prior to measurement.

A brief pulse of heat to the sap from the heating element probe disrupted the thermistors' state of balance, which was monitored by a gauge on the main instrument box. A stopwatch was used to determine the time required for the disruption in resistance balance to dissipate due to the vertical ascent of the heated sap past the thermistors. The elapsed time was noted in minutes and seconds in a field log. Using formulae derived by Swanson (1962), the elapsed times were converted to estimates of water use by the tree on each of the sampling dates. The equipment used in this study was designed and constructed based upon Swanson's (1962) specifications and is shown in Figure 3. Appendix A presents the detailed procedures and methodologies employed in the use of the sap-flow meter.

Diameter at the root collar (drc), diameter at breast height (dbh), total tree height, crown length (from the top of the tree to the bottom of the crown), and crown diameter (two perpendicular measurements of the extent of the crown in a horizontal plane) were

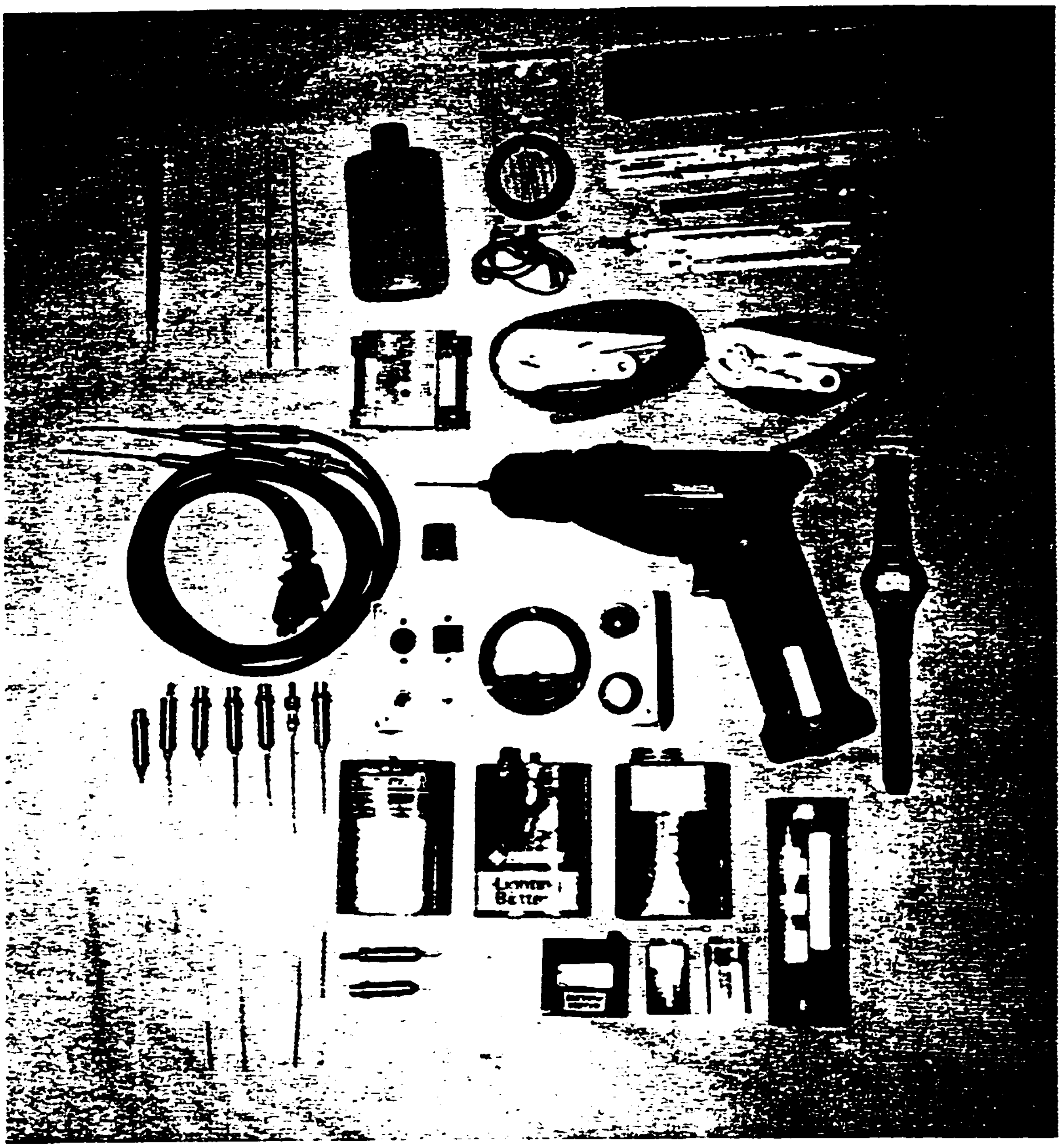

Figure 3. Sap-flow and meteorological measurement epuipment.

measured for each sample tree. Bark depths were measured with a bark-depth gauge and sapwood and heartwood depths were measured with a non-destructive coring tool. The last two measurements were used (in conjunction with the diameter measurements) to calculate the cross-sectional area of the sapwood. Knowledge of sapwood was necessary in the calculations of water use estimates.

Precipitation measurements were collected daily at Coronado National Memorial, located approximately 8 kilometers to the east. These data were assumed to be representative of the sampling area. Temperature and relative humidity were recorded on the study area at the start, midpoint, and conclusion of each sampling day. Temperature data were collected by reading a basic analog thermometer. A two-bulb sling psychrometer and relational slide rule were used to obtain relative humidity measurements.

An objective of the study was to estimate water use by Emory oak on an area basis. This estimate required knowledge of the stand characteristics on an area basis. Measurements of tree frequencies were taken on three 1/50 hectare plots at the study area. Sample trees were contained in these plots. One plot was located in the uncut area, while the other plots were located in the cut area. Drc and dbh of trees within the plots were measured.

Analytical Procedures

Each of the data points was converted from a field-measured elapsed time to sap velocity in centimeters per hour. The elapsed times were first converted from a minute:second format into total number of seconds and finally to sap-flow in centimeters per hour (Swanson, 1962).

The area of the sapwood was computed from the measurements of bark and sapwood depths and thicknesses. Flow was computed based on the formula Q=AV, where Q is sap-flow in cubic centimeters per unit time, A is area of the sap-wood in square centimeters, and V is velocity of sap-flow as measured by the sap-flow meter in centimeters per unit time. This expression of flow, which for purposes of this study is the estimated transpiration rate of a tree at the time of measurement, was converted to liters of water use per day.

Transpiration rates were then calculated for each of the trees on the sampling dates. The results from each of the five trees of each tree-form (mature trees on the uncut area, standards on the cut area, and coppice on the cut area) were averaged to estimate water use by each tree-form on each sampling date. Comparison of estimates among the different tree-forms was analyzed by t-test to determine if there were significant differences in estimated water use among of the three tree-forms.

Estimates of the quantity of water used by each of the sample trees on an annual basis were made. One year of daily water use (transpiration) was summed for each tree to give total water use in liters per year.

Individual tree characteristics were related to estimated annual water use on scatter plot diagrams. A regression analysis enables statements about the degree of relationship between factors and was performed between estimated total water use for all trees and drc, dbh, total tree height, crown volume, crown length, and average crown diameter. Best-fit equations, r-squared values (the proportion of total variability that is explained by the regression equation), and standard errors of estimate ($S_{x.y}$) were calculated for estimated water use as a function of individual tree characteristics using the least-squares method.

Crown volume is considered to be an index of the transpirational area (leaf surface) of the tree. Crown volume was calculated from the formula $V=(\pi d^2 h)/12$ where V is crown volume of the sampled trees in cubic meters, d is the crown diameter (square root of the product of two perpendicular crown diameter measurements) in meters, and h is the height (length) of the crown in meters (Philip 1994). Crown diameter and crown length serve as "proxy variables" for crown volume. Measurement of one of these variables can be used to estimate water use by crown volume based upon its regression equation if the relationship between the proxy variable and crown volume is known.

The effects of precipitation, temperature, and relative humidity on water use were evaluated through qualitative interpretations. Water use as a function of precipitation was described based upon visual inspection of a graph and was not explained statistically. There was not an adequate analysis of water use as a function of either temperature or relative humidity from the measurements taken on each of the sampling dates.

The regression equation based upon water use by drc was solved for the drc of each tree located within each of the three 1/50-hectare plots. The result was estimated annual water use in liters per year per tree. Individual tree estimates were summed to estimate annual water use per plot. The results for the two plots of the cut area were combined, as they occurred in close proximity in the cut area. These estimates were extrapolated to an area basis as estimates of annual water use per hectare for the uncut and cut areas. Water use by standards on the cut area and water use by coppice sprouts on the cut area were calculated and compared to estimated annual water use by the mature trees on the uncut area. A conversion was performed to estimate the total annual water use in millimeters on a unit depth basis for each tree-form and area type (uncut or cut).

RESULTS AND DISCUSSION

Water Use by Individual Trees

The measured elapsed times ranged from approximately one to eight minutes. Converting the elapsed times to estimated water use resulted in a range of rates from six liters per day to 51 liters per day for the mature trees on the uncut area and standards on the cut area. The range of water use estimates in liters per day for the coppice sprouts on the cut area was two to nine. Figures 4, 5, and 6 show the average estimated water use and standard deviations of Emory oak trees on a daily basis. Figure 4 shows that of mature trees on the uncut area; Figure 5, standards on the cut area; and Figure 6 represents the average estimated daily water use of the coppice on the cut area. Appendix B consists of summary tables of daily water use measurements of individual trees.

Comparisons were made to ascertain whether differences occurred among the tree forms. A comparison was made between the mature trees on the uncut area and the standards on the cut area. There were no differences in daily water use between the mature trees on the uncut area and the standards on the cut area on 31 (83.8 percent) of the sampling dates due to random distribution of error. Possible explanations for the differences which occurred on the other six sampling dates include differences in the time of day each tree form was sampled or changes in meteorological factors (cloud cover, radiation intensity, wind speed, temperature, relative humidity, etc.) from the time the

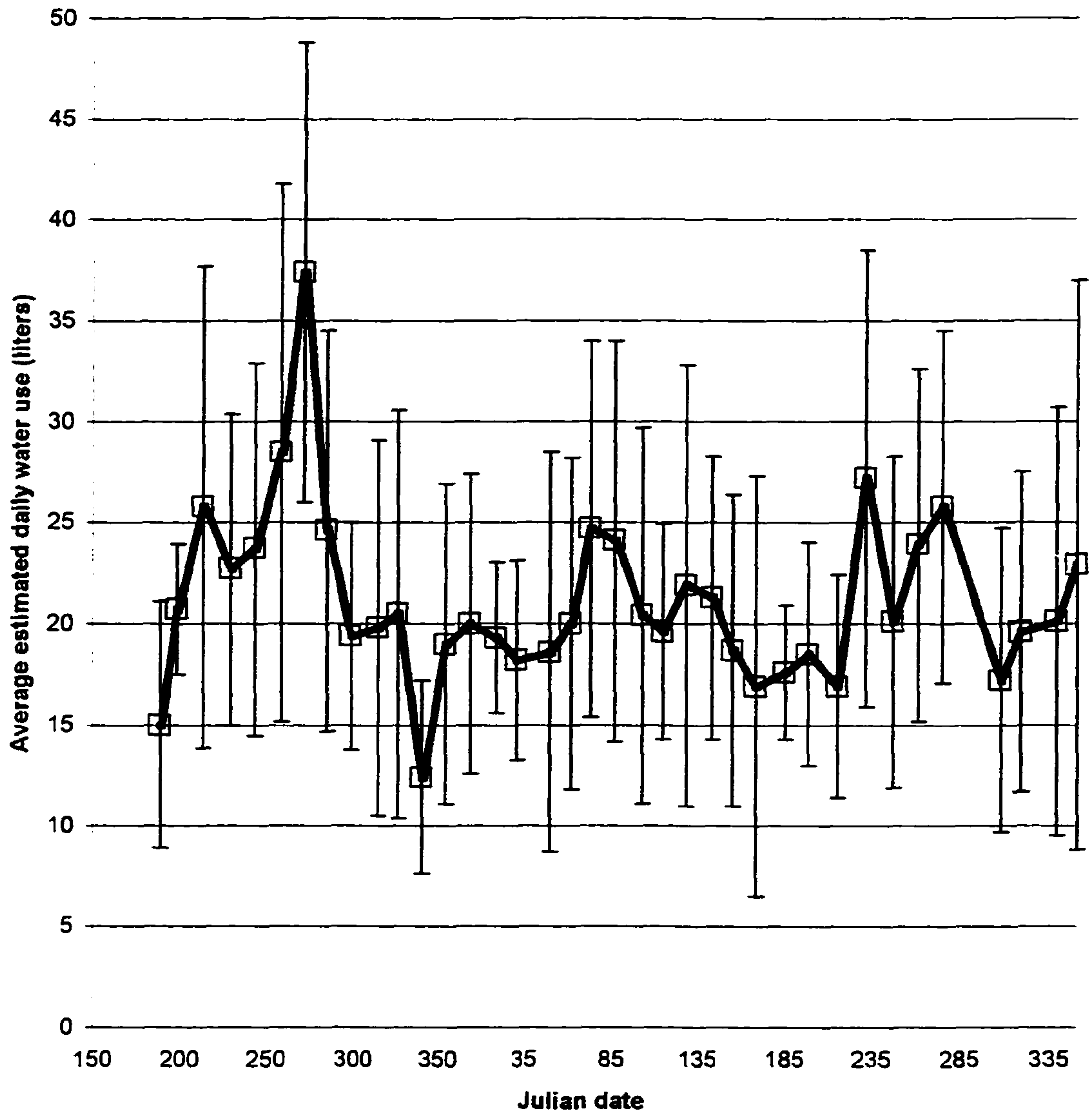

Figure 4. Estimated daily water use of mature trees on the uncut area.

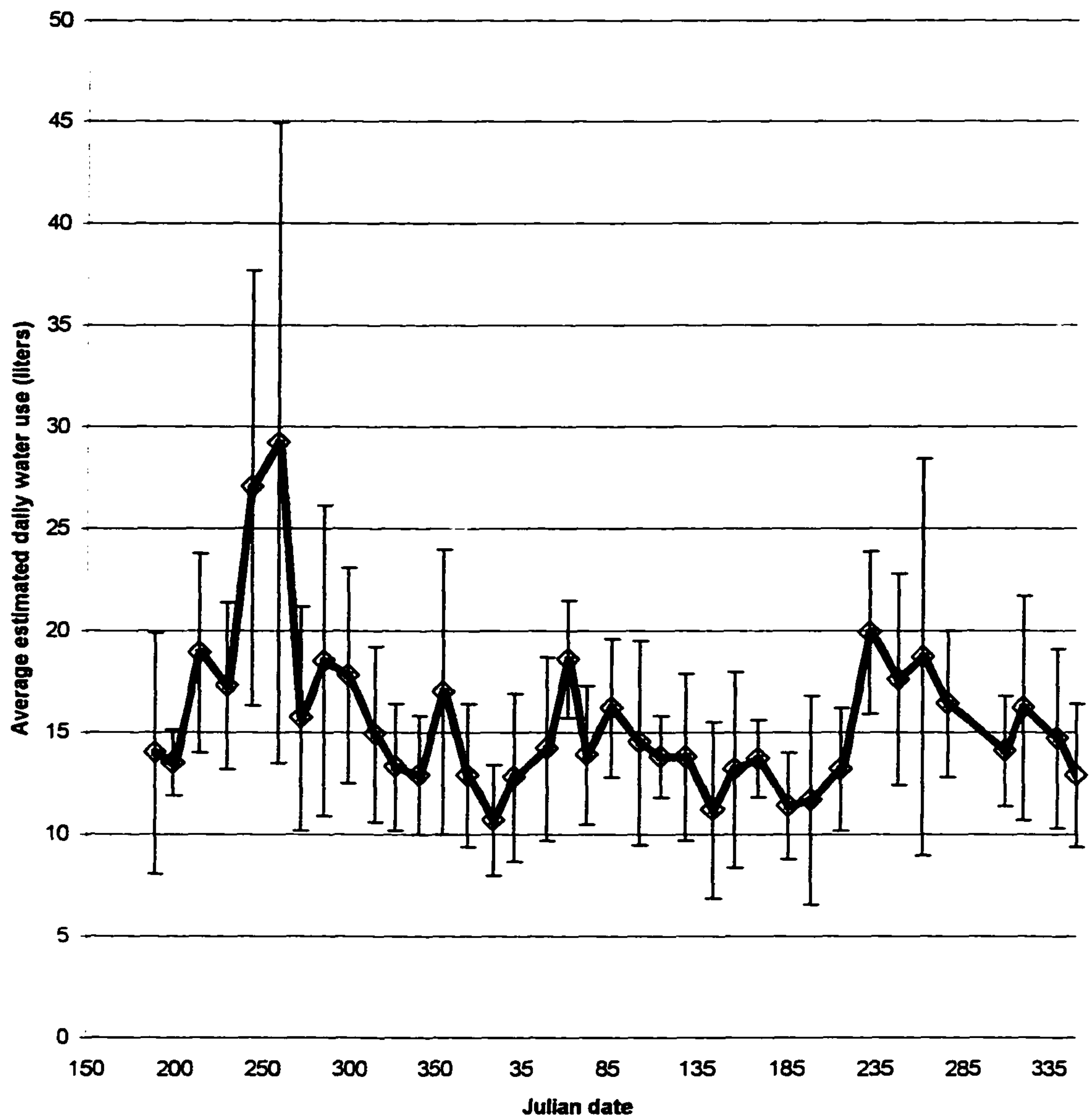

Figure 5. Estimated daily water use of standards on the cut area.

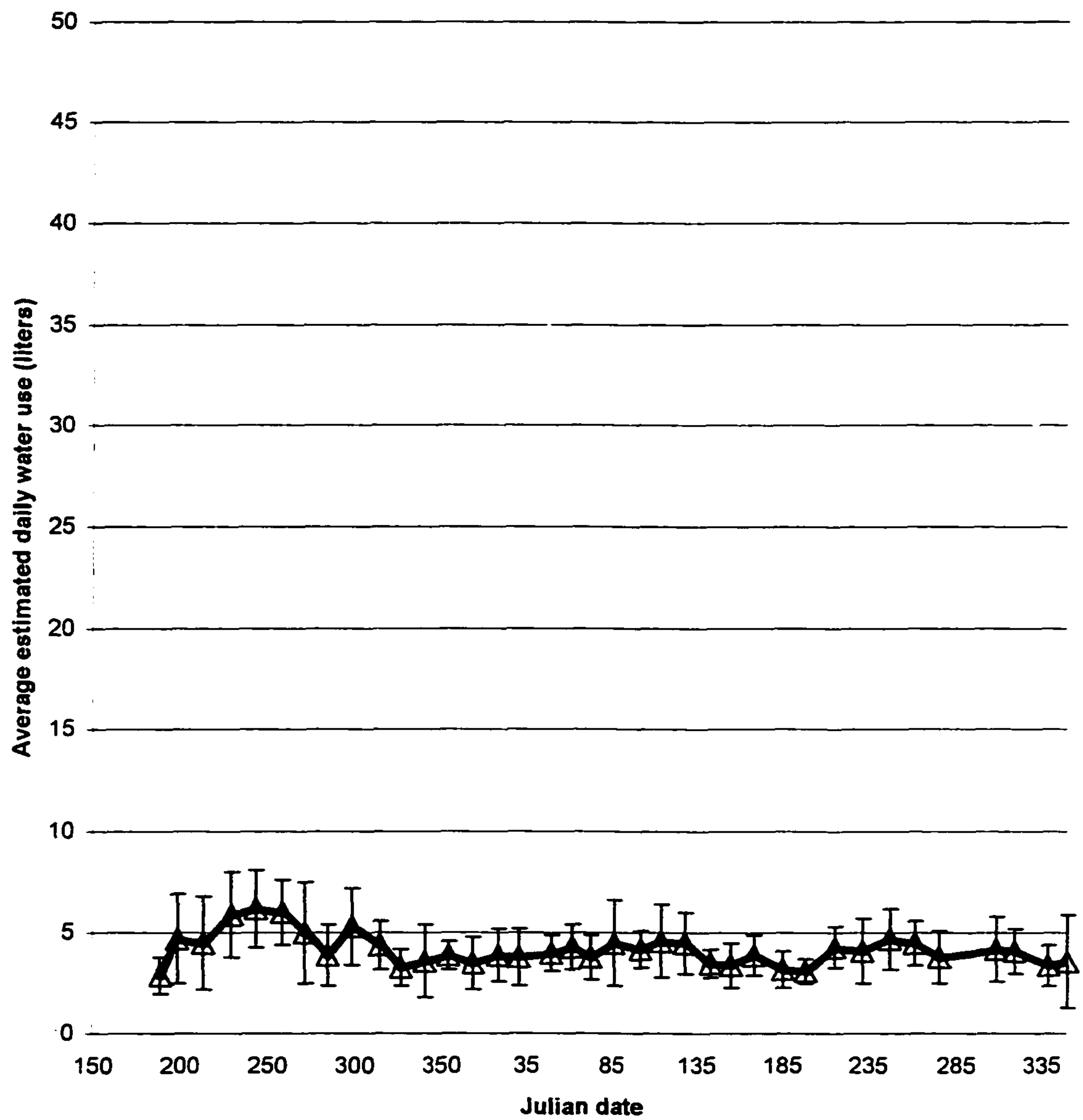

Figure 6. Estimated daily water use of coppice on the cut area.

five trees of one tree form was sampled to the time the next tree form was sampled.

A comparison was also made between the standards and coppice on the cut area. Differences existed between the standards and coppice on the cut area on 100 percent of the 37 sampling dates. A comparison made between mature trees on the uncut area and coppice on the cut area indicated that there was a difference on 100 percent of the 37 sampling dates.

These results indicated similar water use between the mature trees on the uncut area and the standards on the cut area. This was likely the result of the two tree-forms having similarly-sized crown and xylem volumes, and well-developed root systems. Each of these tree-forms was different from coppice sprouts in terms of water use due to differences in these characteristics.

The average daily water use for a mature tree on the uncut area was 20.5 liters, that for one of the standards on the cut area was 14.6 liters, and that for a coppice sprout on the cut area was 4.0 liters. Average daily water use in liters was summed for a one-year period to estimate annual water use for the 15 sample trees. For a mature tree on the uncut area, and a standard and a coppice sprout on the cut area, estimated annual water use was 7500 liters, 5340 liters, and 1450 liters, respectively.

Relationships of Water Use to Individual Tree Characteristics

The individual tree characteristics of the sample trees are summarized in Table 1. A non-linear regression analysis between annual water use and the drc of the sample trees is shown in Figure 7. There were two data points on Figure 7 which seem to fall outside the range of the others. One outlier was tree number 3, on the uncut area. It had an estimate of annual water use which was much greater in proportion to its drc (which was similar to the other trees in its tree-form) than all of the other trees. The other outlier was tree 15, a standard on the cut area which showed water use at about the same rate as the other mature trees and standards, but proportionally had a larger drc than the rest of the sample trees. The fact that these two trees yielded results which seemed to fall outside the range of the other trees was attributed to natural variability among individual trees.

Regression analyses were also performed to relate annual water use to the other individual tree characteristics. A high r-squared value for estimated annual water use as a function of dbh (Figure 8) was likely attributable to greater uniformity among dbh measurements of the trees; there were no obvious outlying points. Figure 9 shows the regression of estimated annual water use and total tree height. The relationship between estimated annual water use and crown volume is shown in Figure 10. Figures 11 and 12 represent the relationship of estimated annual water use to crown length and crown diameter, respectively.

In all of the regression figures (7-12), it was possible to identify the coppice trees

Table 1. Individual tree characteristics of 15 sampled trees.

Tree Form	Tree Number	Diameter Root Collar	Diameter Breast Height	Total Tree Height	Crown Height	Average Crown Diameter	Crown Volume
		cm.	cm.	m.	m.	m.	cu. m.
Mature	1	23.1	17.8	7.6	6.1	3.7	22.3
	2	23.4	18.3	6.6	5.2	4.6	28.4
	3	24.6	22.6	5.5	3.2	3.8	12.2
	4	22.9	19.1	6.6	5.0	3.1	12.2
	5	19.1	13.0	5.2	3.8	2.9	8.4
	Mean	22.6	18.2	6.3	4.7	3.6	16.7
	Std. Dev.	2.1	3.4	1.0	1.2	0.7	8.3
Standards	6	22.4	15.5	5.9	4.1	3.4	12.1
	9	24.1	15.5	6.6	4.3	3.6	14.3
	12	20.8	14.7	4.9	3.7	2.9	8.0
	14	21.6	16.5	6.1	4.6	3.3	12.9
	15	33.0	18.5	5.9	4.3	3.7	15.6
	Mean	24.4	16.1	5.9	4.2	3.4	12.6
	Std. Dev.	5.0	1.5	0.6	0.3	0.3	2.9
Coppice	7	9.1	6.4	4.6	3.4	2.1	3.7
	8	10.4	6.9	4.6	2.1	1.5	1.3
	10	8.9	6.1	4.1	2.6	2.3	3.5
	11	7.6	5.1	3.8	2.6	2.1	2.9
	13	10.4	7.1	4.1	2.9	1.5	1.6
	Mean	9.3	6.3	4.2	2.7	1.9	2.6
	Std. Dev.	1.2	0.8	0.4	0.5	0.4	1.1

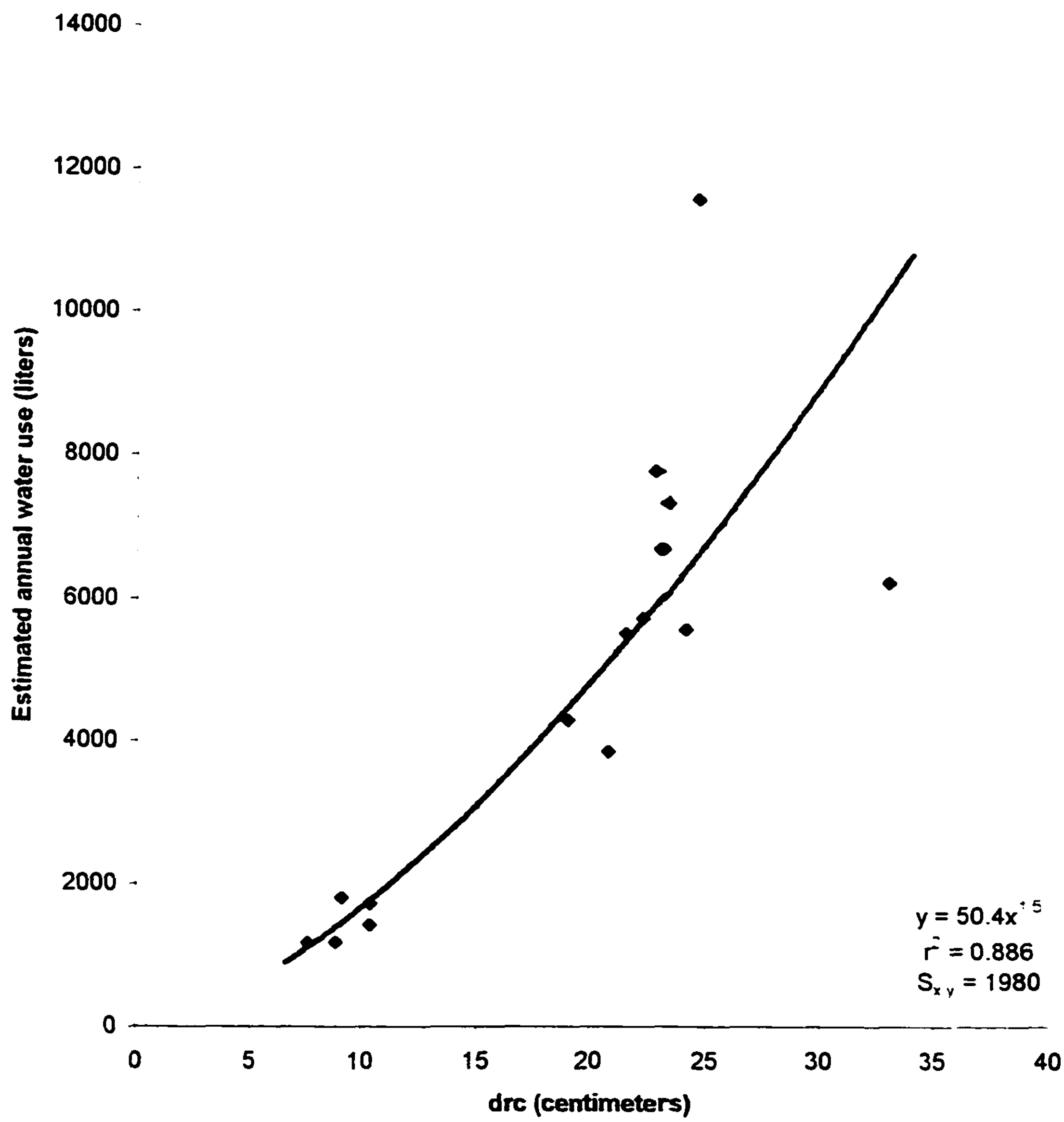

Figure 7. Estimated annual water use as a function of drc.

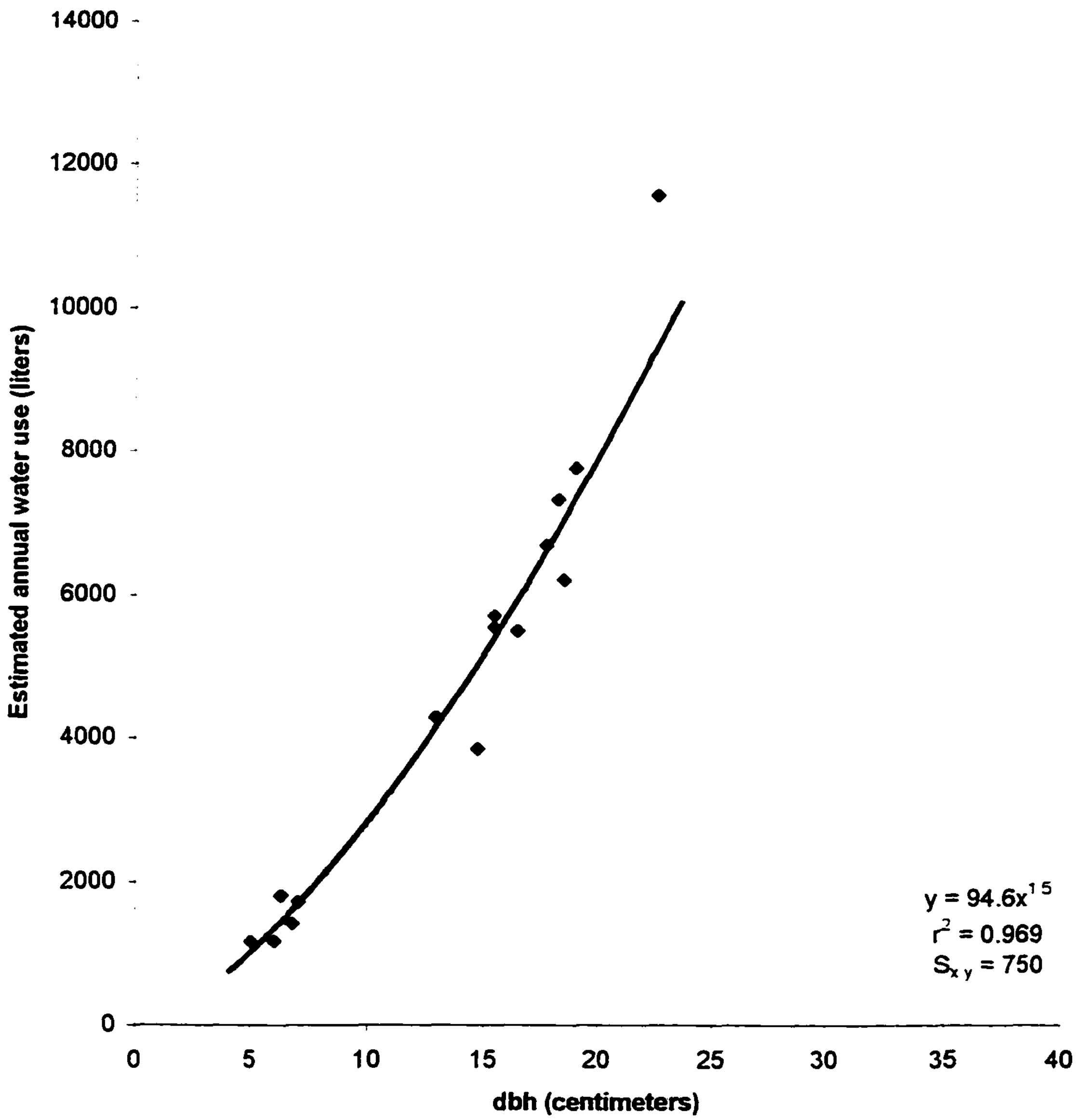

Figure 8. Estimated annual water use as a function of dbh.

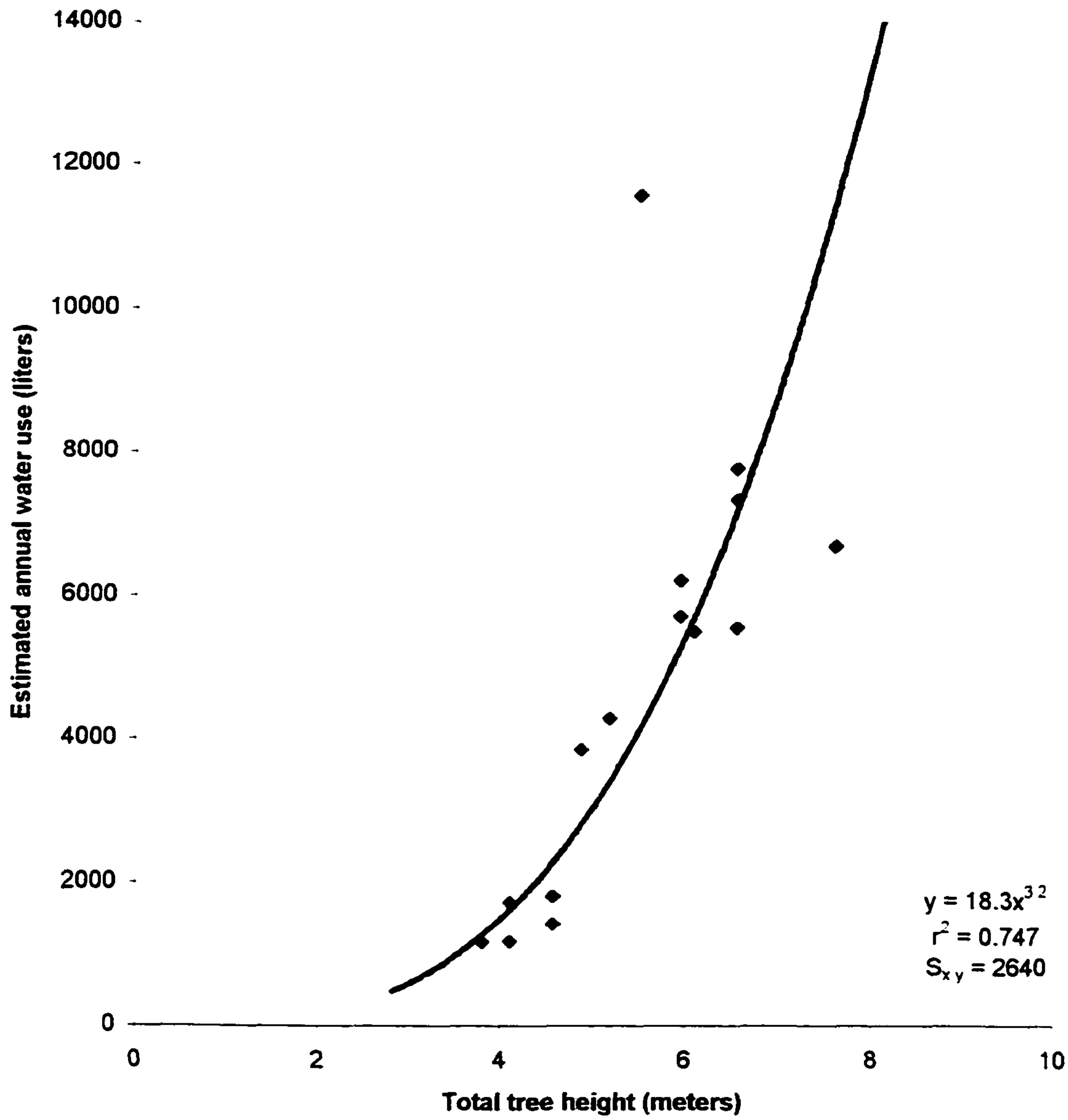

Figure 9. Estimated annual water use as a function of total tree height.

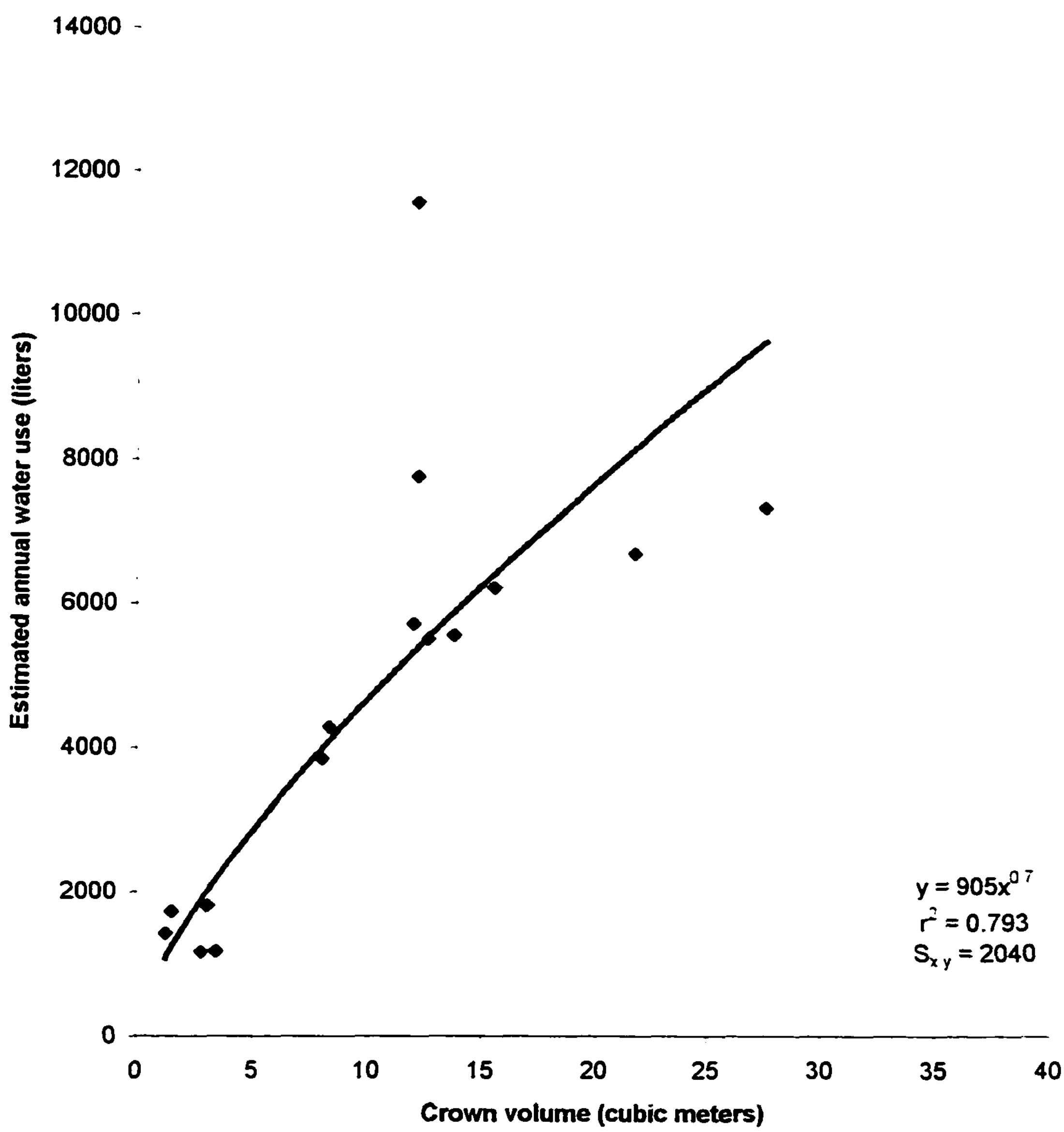

Figure 10. Estimated annual water use as a function of crown volume

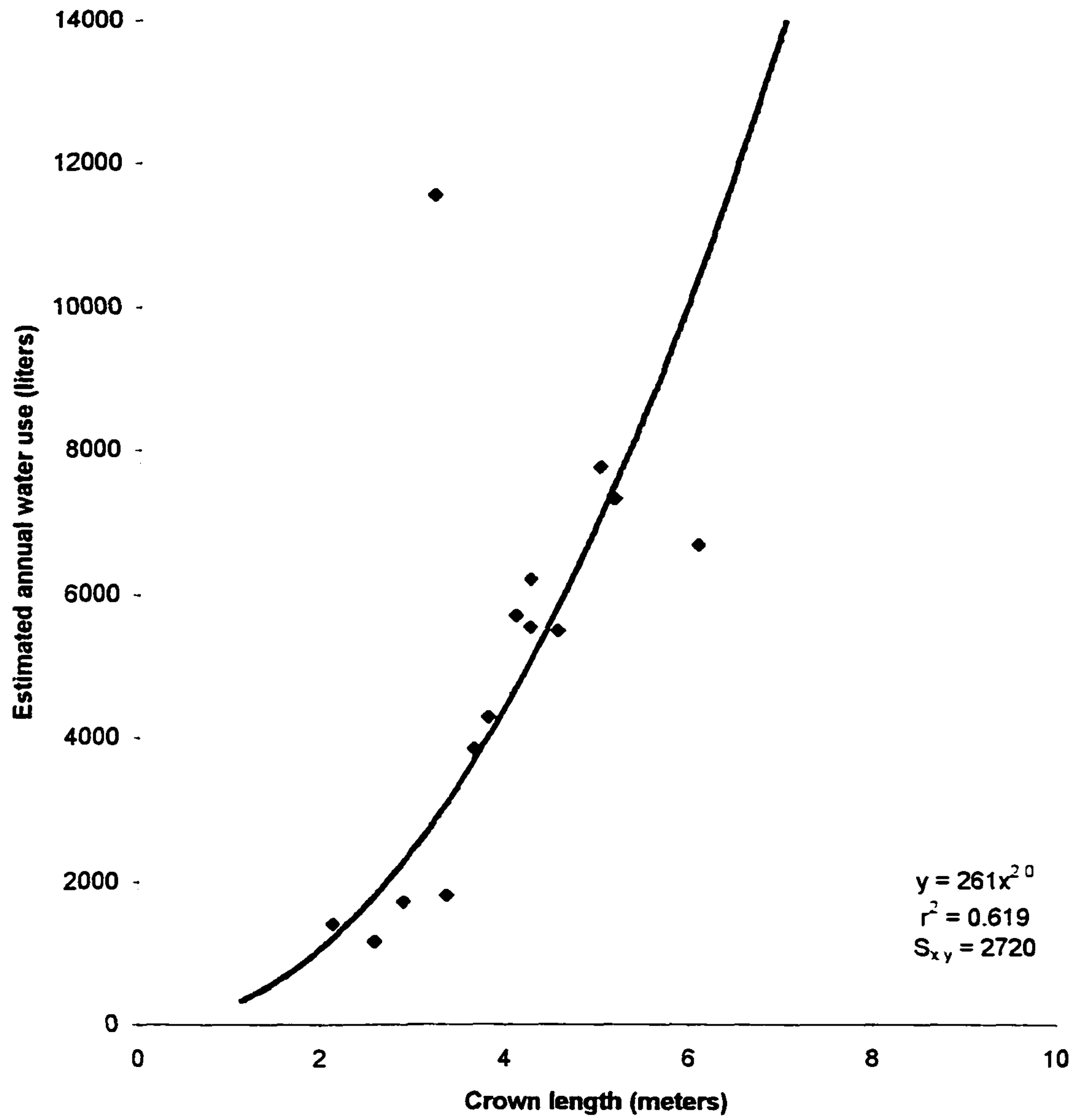

Figure 11. Estimated annual water use as a function of crown length.

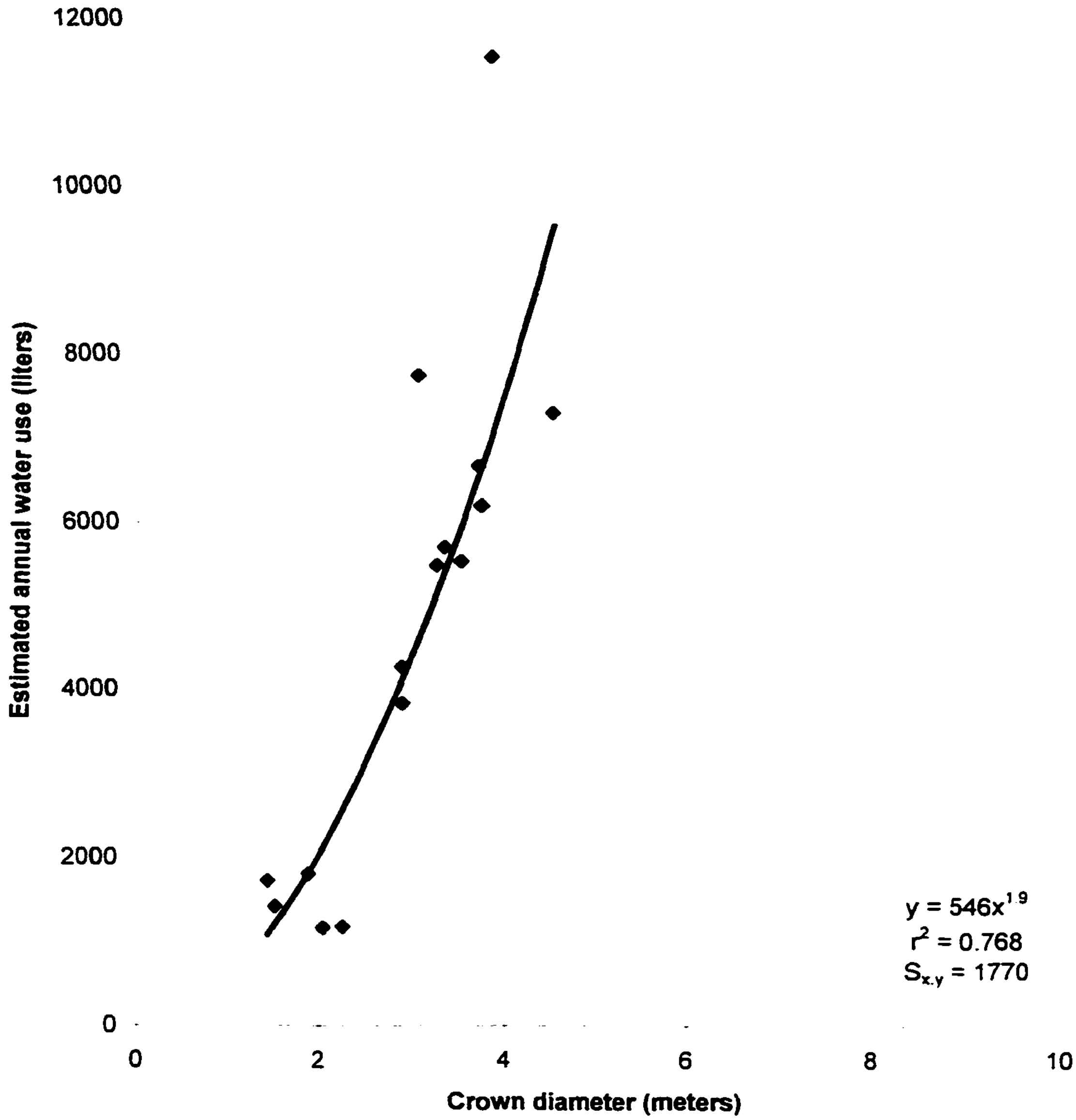

Figure 12. Estimated annual water use as a function of crown diameter.

on the cut area as a function of their water use, which was much less than the estimated annual water use of mature trees on the uncut area or standards on the cut area. In each graph, the lower five data points, corresponding to estimated annual water use in the range of 1150 to 1850 liters, represent the coppice trees. Differentiation of mature trees on the uncut area from standards on the cut area was not visibly apparent in the graphs due to their similar characteristics and annual water use estimates. This determination can be made by referring to Table 1.

All of the figures showed an increase in estimated annual water use with an increase in units of the measured tree characteristic. This was attributed to the larger transpirational area associated with larger trees. Transpirational area is roughly equivalent to the leaf area of the tree. Smaller diameters at root collar or breast height correspond to a smaller leaf area of smaller trees; those trees with larger drcs and dbhs were shown to generally transpire more. The same held true for total tree height and the measurements of the crown. Trees with a greater transpirational area are taller and have crowns with larger lengths, diameters, and volumes than those of smaller trees, and subsequently, used more water.

Relationships of Water Use to Meteorological Factors

Transpiration is a major output of water from a system, and the rate at which transpiration occurs is dependent upon meteorological factors. This section considers possible relationships between estimated water use by each of the tree forms as a function of precipitation, temperature, and relative humidity.

Figure 13 shows daily average estimated water use in liters for mature trees on the uncut area on the same graph as daily precipitation. Figure 14 shows daily average estimated water use for the standards on the cut area in relation to precipitation, and Figure 15 demonstrates the same for coppice.

The results of this research suggest that after a major precipitation event, there appears to be an increase in water use by each of the tree forms following a brief lag time. This lag was likely attributable to the time for the precipitation to infiltrate into the soil, and permeate to a depth where it can be accessed by the trees' root systems. The sampled trees transpired throughout the year. Although drought-deciduous, none of these trees lapsed into complete dormancy relative to water intake as a result of cessation of rainfall. This could be attributed to storage of water in the tree, water storage in the soil, reduced competition for available water from the dieback of understory plants, or a combination of these factors.

Average estimated daily water use for each tree form and average daily temperatures are represented in figures 16, 17, and 18. As daily temperatures decreased with changing seasons, it appears that average estimated daily water use by the trees also decreased. However, there was not a corresponding increase in water usage when temperatures began to climb. Temperature appears to have more immediate and shorter-lasting effects on transpiration than precipitation.

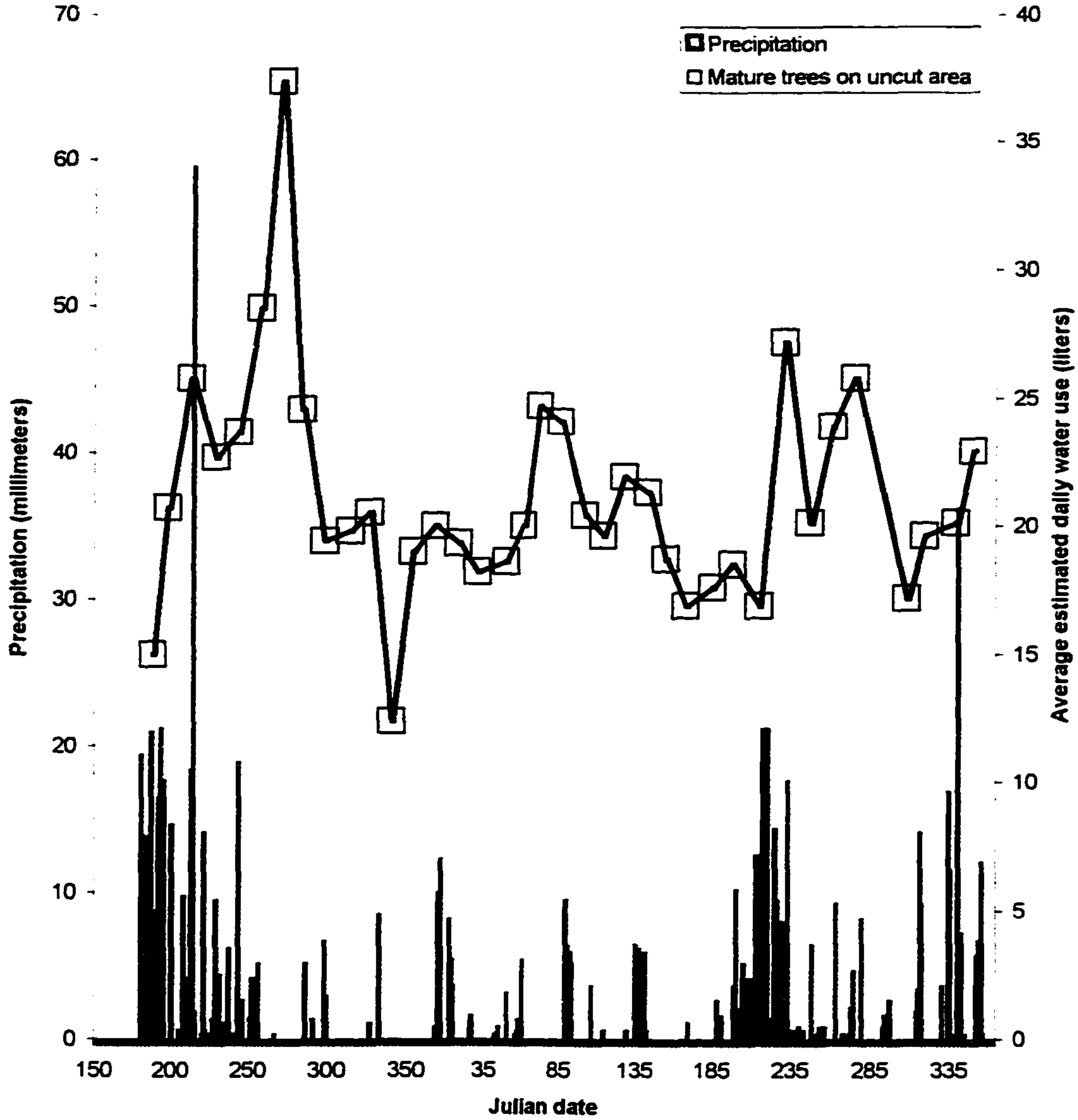

Figure 13. Estimated daily water use of mature trees on uncut area and daily precipitation.

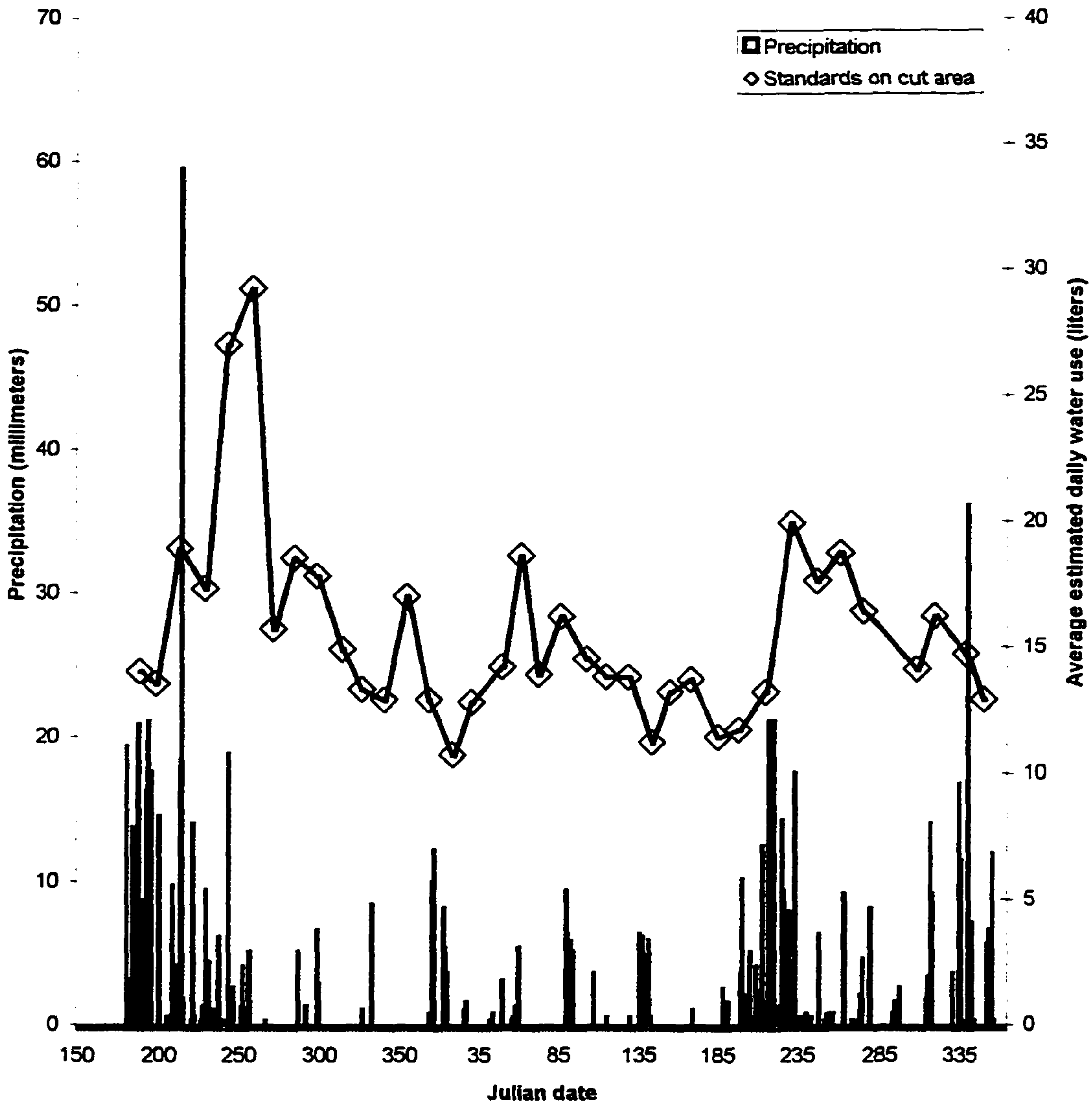

Figure 14. Estimated daily water use of standards on cut area and daily precipitation.

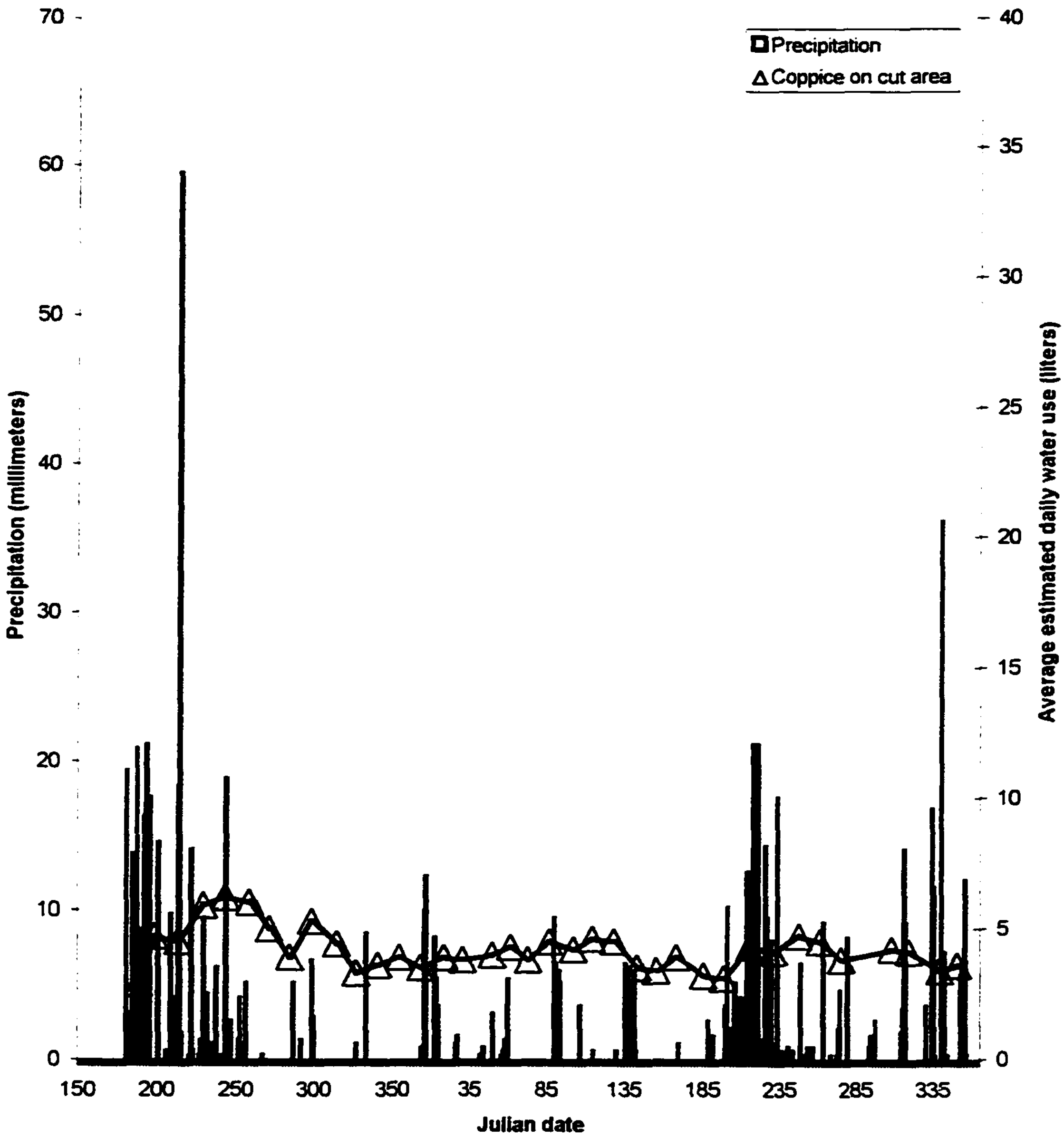

Figure 15. Estimated daily water use of coppice on cut area and daily precipitation.

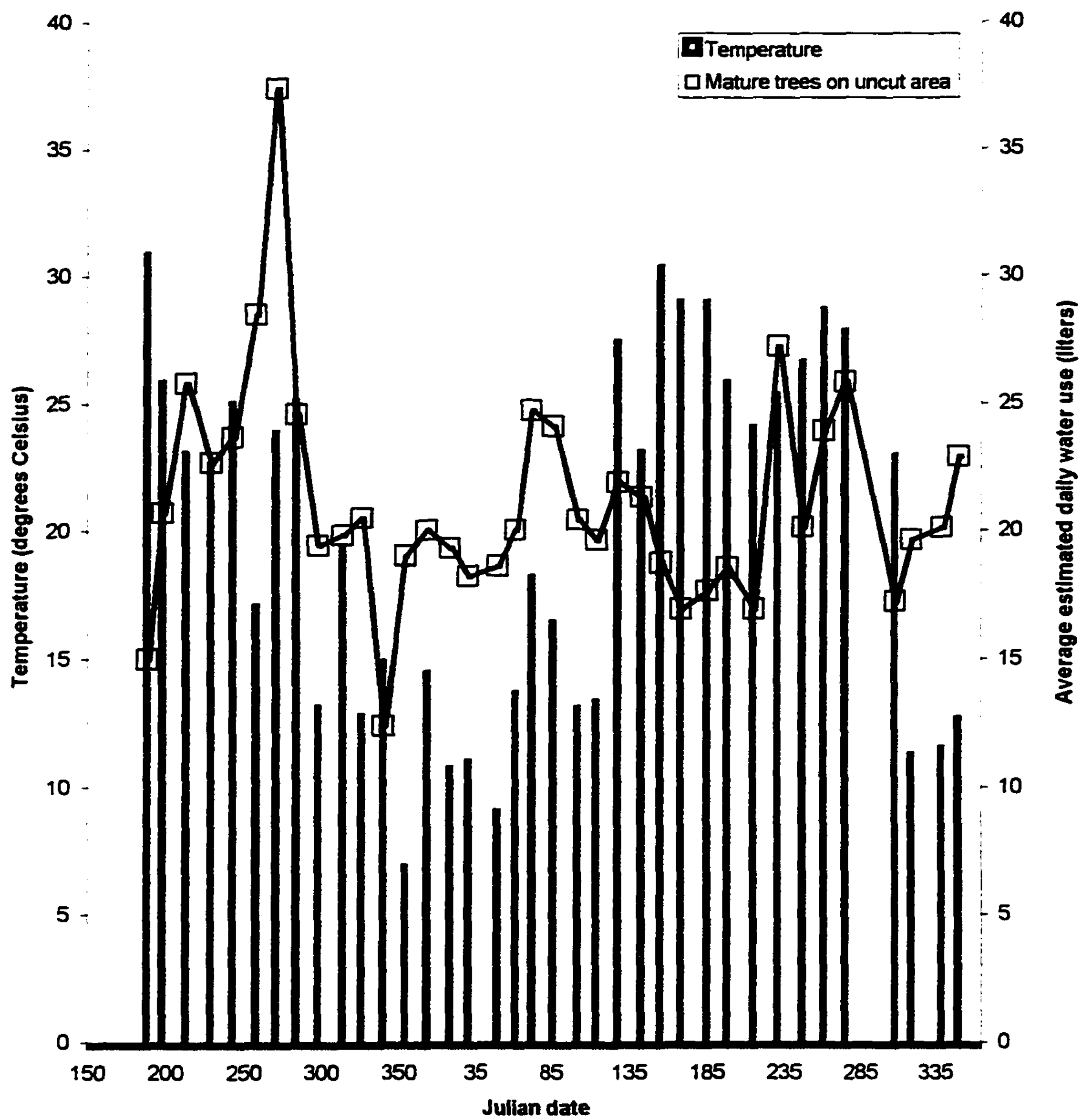

Figure 16. Estimated daily water use of mature trees from uncut area and average daily temperature.

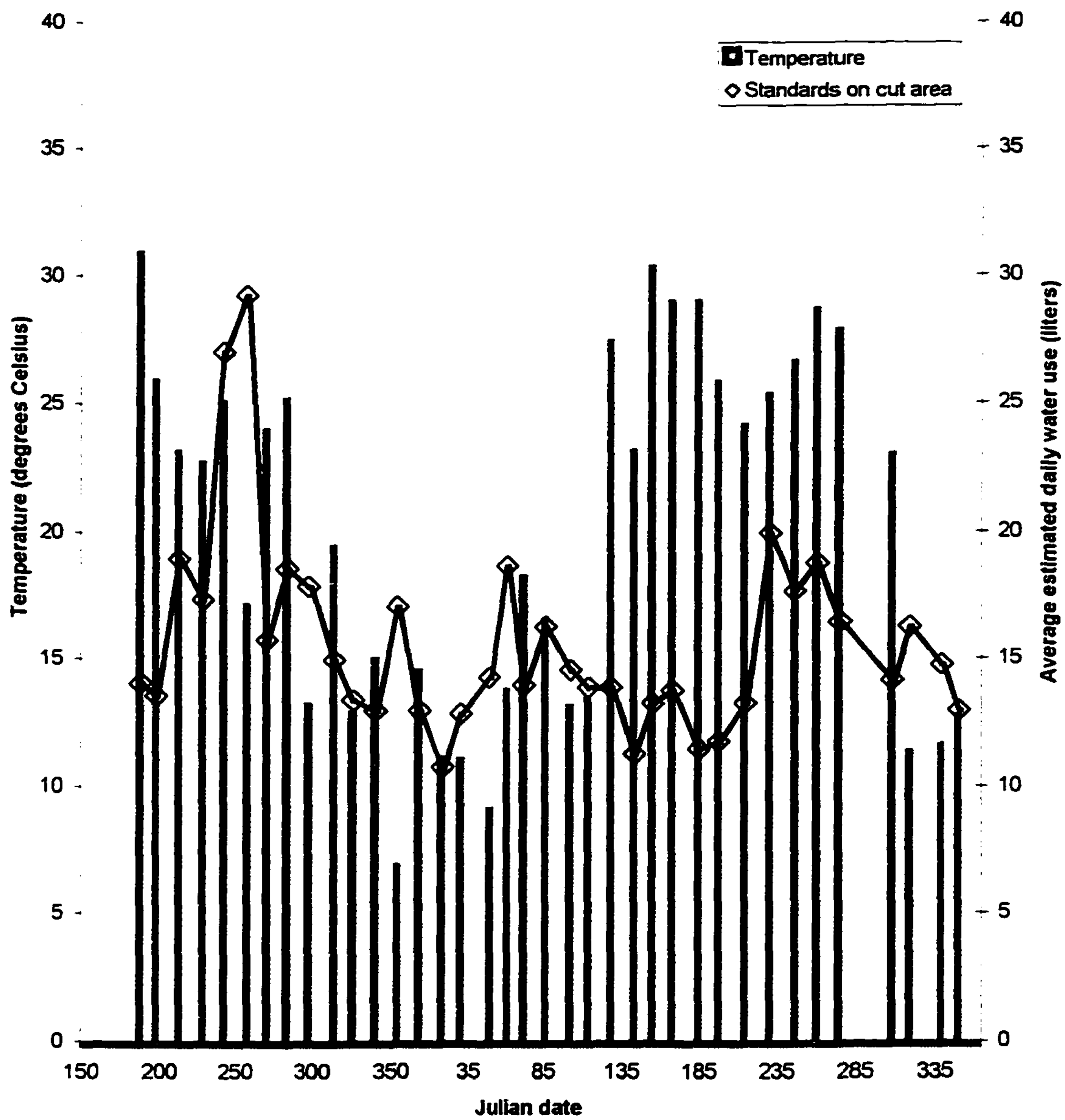

Figure 17. Estimated daily water use of standards on cut area and average daily temperature.

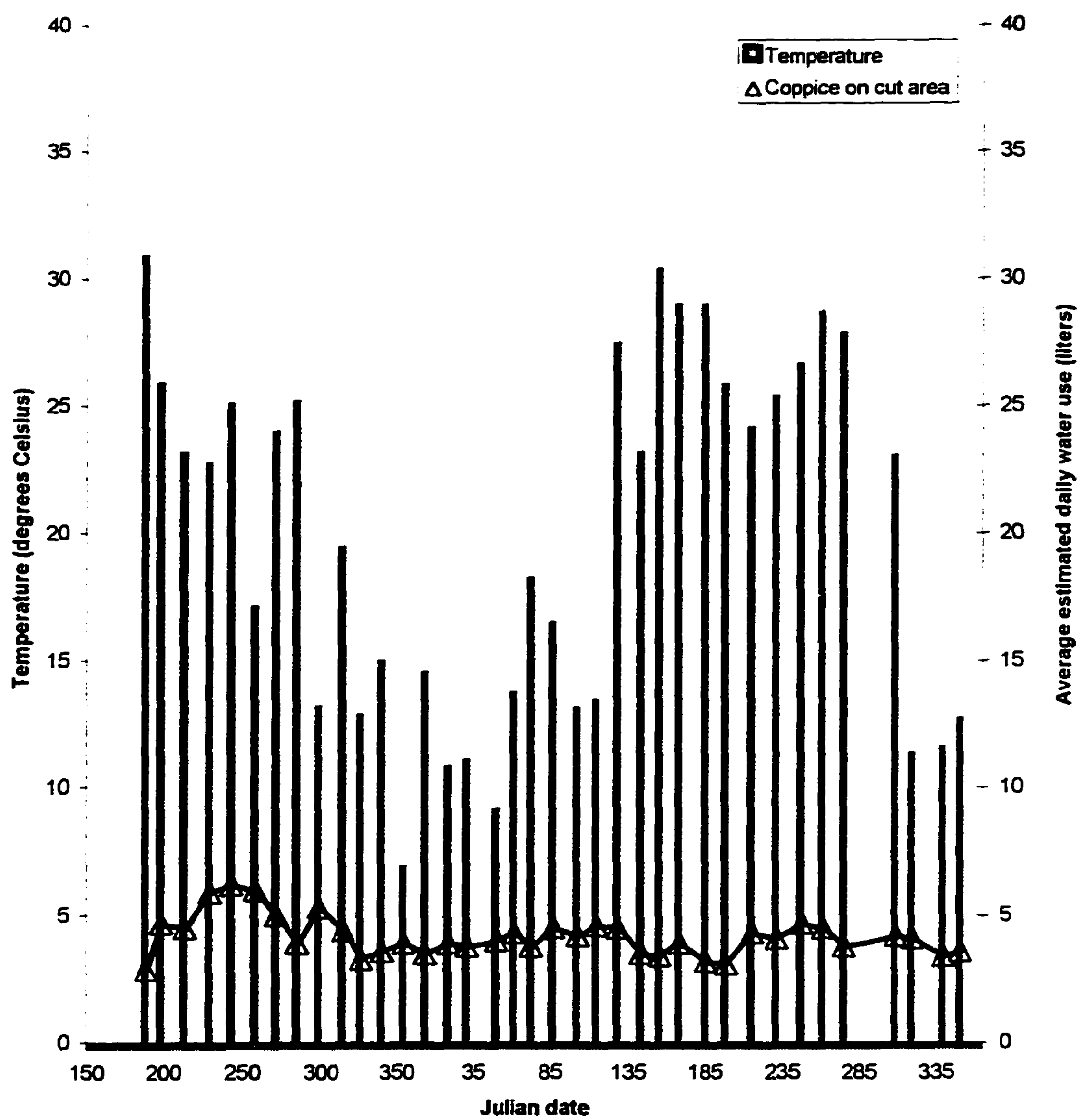

Figure 18. Estimated daily water use of coppice on cut area and average daily temperature.

There also appears to be little relationship between average estimated daily water use by the sample trees and relative humidity (Figures 19, 20, and 21). Relative humidity also appears to have more immediate and shorter-lasting effects on transpiration than precipitation.

Water Use on an Area Basis

The regression equation calculated for estimated annual water use as a function of drc (Figure 7) was applied to the drc measurements of each tree tallied within each of the three 1/50 hectare plots to estimate annual water use on an area basis. One plot was located in the uncut area of the study, while the other two plots were established in the cut area. The results of the two plots on the cut area were combined, resulting in a plot area of 1/25 hectare. On this plot of the cut area, for purposes of distinguishing a standard from a coppice sprout, trees with a drc of 14 centimeters or less were considered a coppice sprout, while trees with larger drcs were standards. Table 2 presents a summary of the plot measurements.

The uncut area was estimated to use 1900 cubic meters of water per hectare annually, while the estimate for the cut area was 3168 cubic meters per hectare annually. Therefore, the cut area is estimated to use 1.67 times more water annually than an equivalent area of the uncut type; this was attributed to the occurrence of a large number of vigorous coppice sprouts on the cut area. Although estimations of water use by

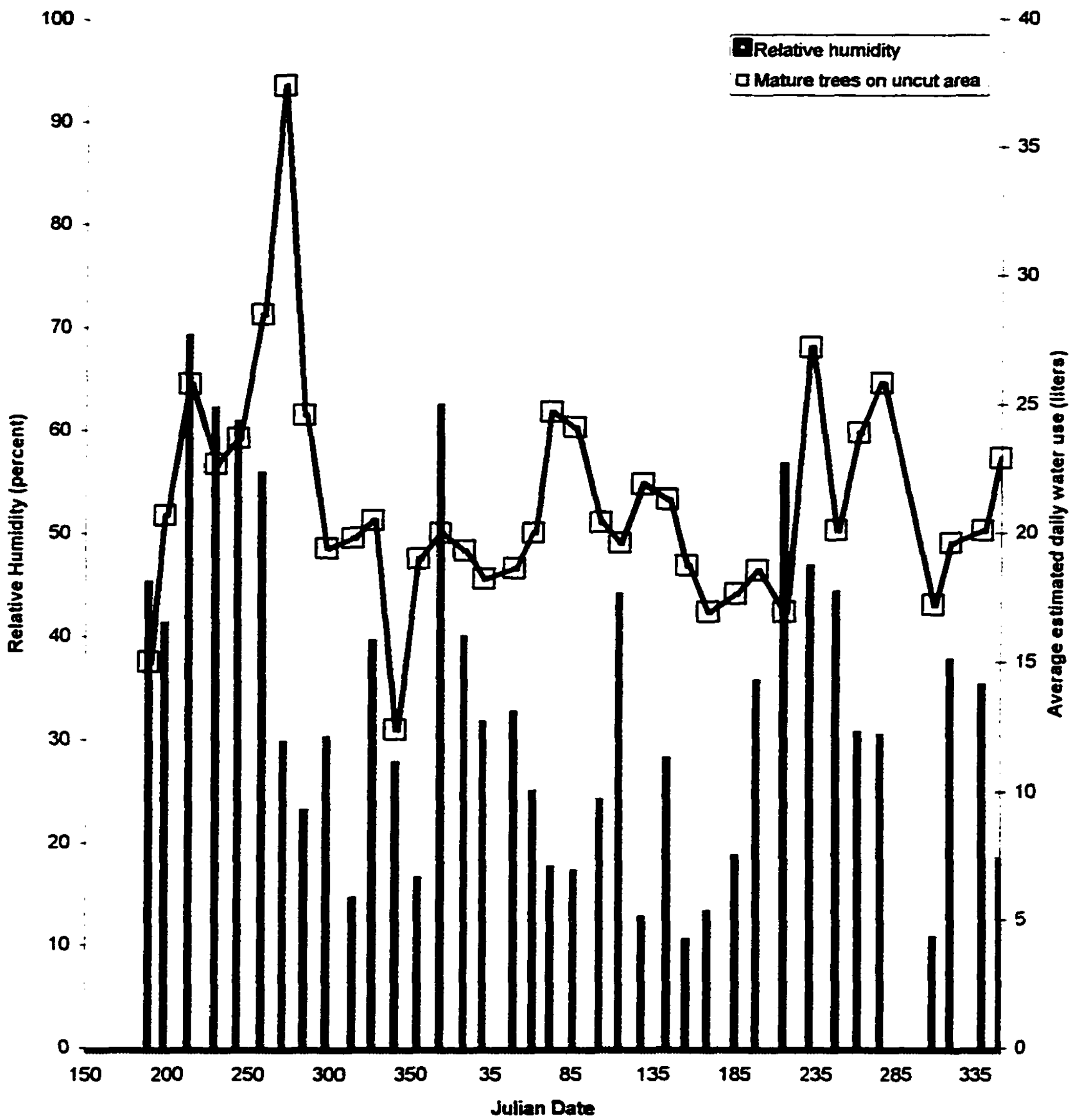

Figure 19. Estimated daily water use of mature trees on uncut area and average daily relative humidity..

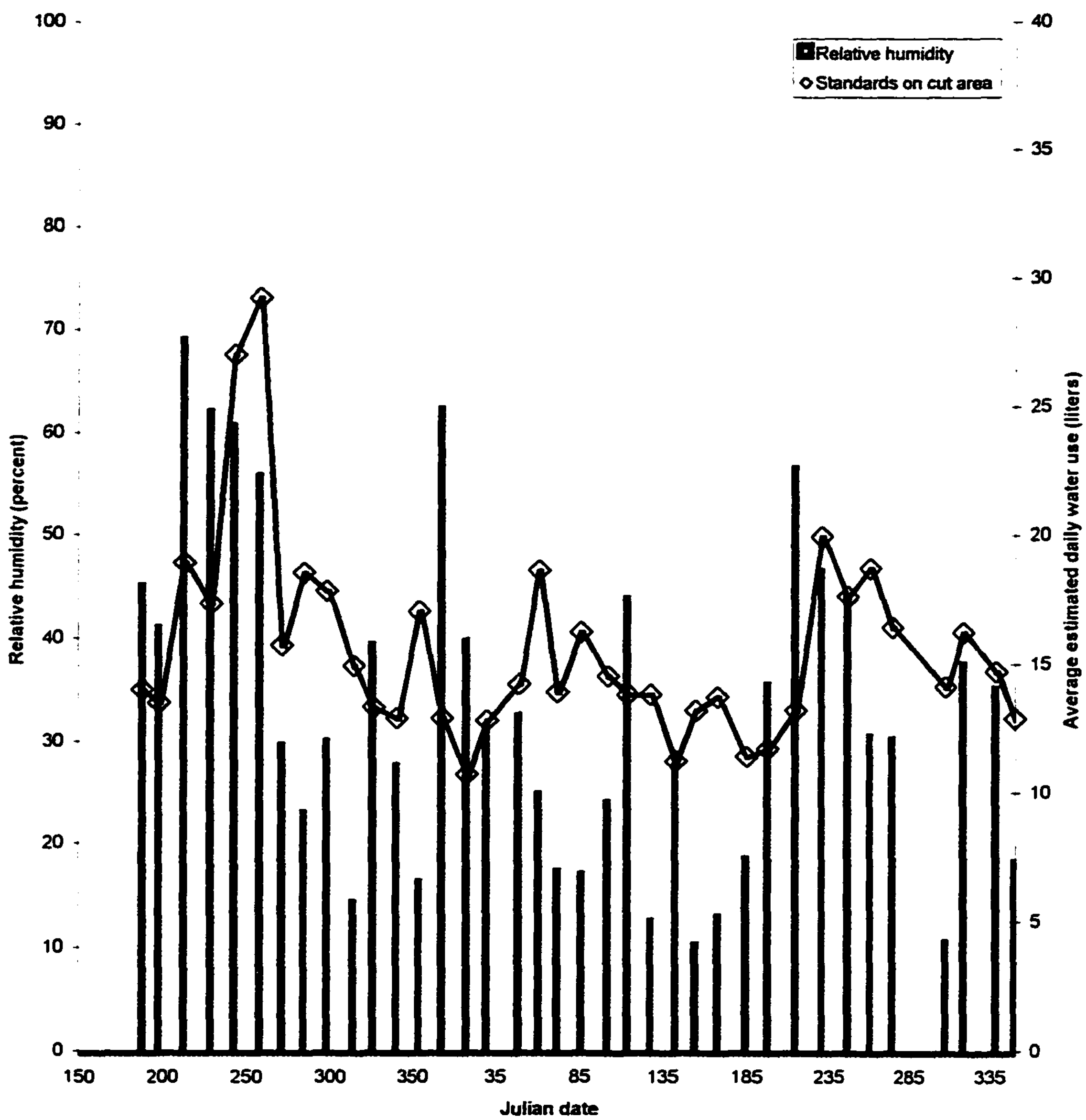

Figure 20. Estimated daily water use of standards on cut area and average daily relative humidity.

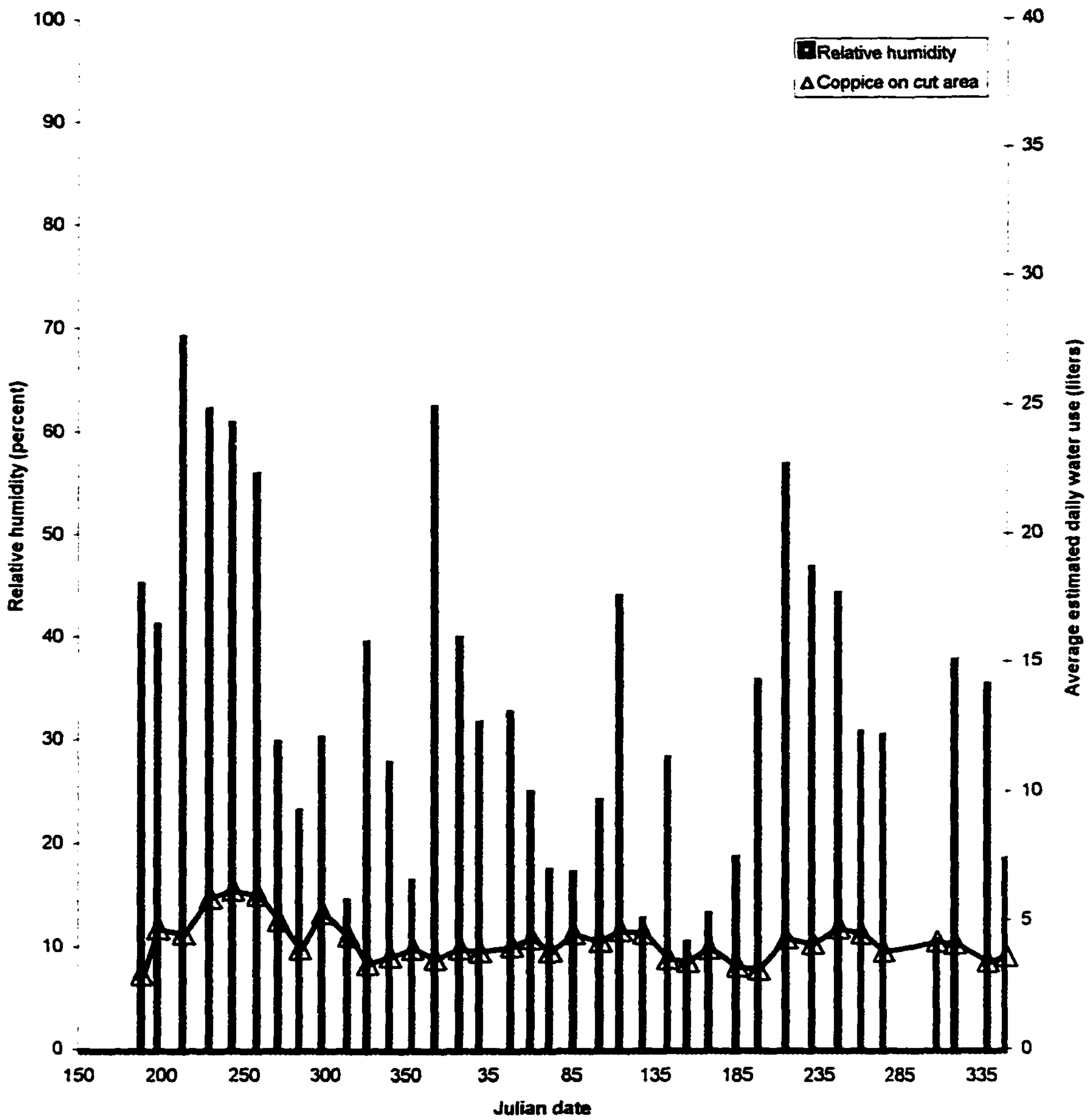

Figure 21. Estimated daily water use of coppice on cut area and average daily relative humidity.

Table 2. Densities and summary of drc measurements on sample plots.

	Density		DRC	
	Number per hectare	Basal area per hectare	Average	Range
		sq. m.	cm.	cm.
Mature trees on uncut area	442.7	12.1	18.4	14.0 - 24.1
Standards on cut area	444.8	15.9	20.8	15.2 - 33.0
Coppice on cut area	914.3	1.6	6.6	3.3 - 14.0
Standards plus coppice	1359.1	17.5	11.2	3.3 - 33.0

individual mature or standard trees were higher than those for individual coppice sprouts. water use estimates by area were higher for the cut area than the uncut due to differences between the areas. Equal size areas of uncut and cut areas contain similar numbers of mature trees and standards, but the uncut area also supports coppice sprouts. Estimates of water use for each tree form were based upon sap-flow measurements of five trees of each form. Water use by an individual coppice sprout was considerably less than that of a non-sprout. However, Table 2 shows that there are more than twice as many sprout trees than standards per unit of cut area. Therefore, frequency and density of trees per unit area are both higher in the cut area and result in higher estimates of water use when compared to the uncut area.

Water use on an area basis by standards versus coppice sprouts was also examined, using the same drc-based regression equation. Of the 3168 cubic meters of water used annually per hectare of cut area, 2310 cubic meters were used by the standards, while the coppice sprouts transpired only 858 cubic meters.

One hectare of standards on the cut area used approximately 10 percent more water than a hectare of the uncut area. Table 1 showed that the mean drc of mature trees of the uncut area was less than that for the standards of the cut area. The 10 percent increase was attributed in part to this difference in mean drc between the two tree forms. Because all area basis extrapolations were based upon the drc measurements of the sample trees, there was a corresponding increase in estimated water use by the standards of the cut area compared to mature trees of the uncut area. This greater water use by the standards of the cut area was also attributed to a greater number of standards on the cut area per hectare compared to mature trees on the uncut area.

These results can be incorporated into a water budget to estimate transpirational losses, one of the larger outputs from the system, as a function of precipitation. Annual precipitation in the last year of the study (1997) was 399.8 millimeters. Since the water input to the system is known, it was possible to estimate the percentage of water loss to transpiration. To do this, water use estimations (transpiration) were converted from volume of water on an area basis to a one-dimensional measurement of depth. Emory oak on the uncut area was estimated to use 190.0 millimeters of water per year, which was equivalent to 47.5 percent of the annual precipitation. Standards and coppice on the cut area were estimated to use 316.8 millimeters of water per year, equivalent to 79.2 percent of the annual rainfall. Therefore, the cut area was estimated to use approximately 32 percent more precipitation than the uncut area. Standards transpired 231.0 millimeters (57.8 percent of precipitation), while the estimate for transpiration by coppice sprouts was 85.8 millimeters (21.5 percent of precipitation).

CONCLUSIONS

Conclusions of this study are:

1. The sap-flow method is a simple method of estimating water use by Emory oak. These estimates of water use can be used for estimation of the transpiration component of the water budget or for comparative analysis of fuelwood harvesting treatments used in oak woodlands.

2. There were no statistical differences in estimated water use between mature Emory oak on the uncut area and standards on the cut area on 84 percent of sampling dates. However, there were differences in estimated water use between mature trees on the uncut area and coppice on the cut area, and between standards and coppice on the cut area on 100 percent of sampling dates.

3. Regression equations were relating estimated water use and measurements of tree characteristics can be a method of calculating water use for other individuals or groups of individuals of the type based upon measurement of a characteristic.

4. Precipitation appears to influence water use by Emory oak after a short lag time following cessation of the precipitation event. Little relationship was apparent between water use and temperature, or between water use and relative humidity.

5. Estimates of water use by individual Emory oak trees extrapolated to estimate water use on an area basis show that water use estimation for the uncut area was

approximately 1900 cubic meters per hectare annually, while that of the cut area was estimated at 3168 cubic meters per hectare annually, greater by a factor of approximately 1.7 times.

6. Emory oak on the uncut area used approximately 48 percent of precipitation, while oak on the cut area used 79 percent. On the cut area, standards used 58 percent of precipitation and coppice sprouts used 22 percent of precipitation.

APPENDIX A:

SAP-FLOW MEASUREMENT PROCEDURE

Each tree was sampled in a random manner in relation to aspect, time of day, and time of season sampled. Aspect was divided into four categories: 'north', 'south', 'east', and 'west.' Time of day was divided into three periods: 'morning' was considered any sample conducted between 07:00 and 10:59, 'afternoon' between 11:00 and 14:59, and 'evening' between 15:00 P.M. and 19:00. Each tree had each aspect sampled at each time of the day in every season, according to a tally chart kept in the field log by the author.

Determination of which of the three sets of trees was sampled first was on a rotational basis. One of the five trees was selected from the set of five, either randomly or on a rotational basis. The aspect on the tree to be sampled was then determined. A simple field method used was the toss of a pen, spun horizontally end over end, into the air. The aspect closest to the direction to which the pen pointed when it landed was the aspect sampled.

A location on the tree to be sampled was the next determination to be made. The point must have been free of any past drill hole marks, must have approximately faced the previously determined direction, and must have been found at approximately 1.5 meters from the ground. The point was also below any major branching and not located on, or immediately above, a scar. The drill jig was attached to the tree on this point and securely fastened using a ratcheting strap. The jig was tightened just enough to hold it firmly to the tree so as to not allow any lateral movement, but not so tight as to harm the tree itself, such as crushing or breaking the bark or otherwise leaving a scar.

The next step required the greatest precision. The author had acquired a skill for finding the correct depth below the bark to be drilled. This skill was acquired partly through measurement and partly through repetitive trial-and-error. A bark coring tool was taken to the field before any actual measurements began and again upon completion of the study. This tool was used on trees similar to the 15 sample trees to gain insight as to the depth below the bark to which the probes must be inserted. Another method used by the author was to repeatedly practice using the instrument on similar trees to become comfortable with its usage before taking measurements for the study. It was learned that the instrument has very narrow tolerances pertaining to the layers of the tree that it can measure. A combination depth measurement and repeated practice enabled the author to place the probes at the proper depth for sap-flow measurement. The instrument was unable to give an accurate measurement unless the proper depth was attained. Proper probe placement was further verified with a confirmation method used when actually drilling a tree for measurement.

The top hole of the jig was always drilled first. This prevents the possible obstruction of an open hole with wood particles that may have fallen from a hole being drilled above. The outer bark was generally thick but soft. and of a dark grey or blackish color. The drill was inserted a few millimeters, then removed to prevent the accumulation of wood particles in the drill bit. This process was repeated until the depth of the outer bark was completely penetrated. The layer immediately beneath the outer bark was thin, hard, and generally dark brown in color. This layer was drilled through more carefully, with the drill inserted less forcefully and more frequently to remove minute amounts of material each time. Eventually this layer was penetrated to expose a soft granular layer. This layer was the layer in which the thermistors and the heating element must lie in a vertical plane. A small amount of the layer was removed by the drill bit for two reasons. First, it enabled a visual inspection and confirmation of the xylem ring. The material from this layer on the end of the drill bit was grainy, moist, and from yellowish- to reddish-brown in color. The second reason for removing a few grains of the layer was that it ensured the probes were inserted well into the layer to avoid the possible influence of other woody material.

The process described above was then repeated for the second and third holes of the drill jig. Each hole was drilled without a depth reference from the previous hole. When the three holes had been drilled, the drill bit was reinserted into the first hole. A mark was placed on the bit where it met a defining edge of the drill jig. The bit was then inserted into the second hole, and a depth comparison was made. The bit was then inserted into the third hole and another depth comparison made. The mark was then cleared, and the bit inserted back into the second hole. A new mark was made from the same reference point on the drill jig. The bit was then inserted into the first and third holes in turn, with corresponding depth comparisons. The process was repeated again for the third hole, its depth compared to the depth of each of the first and second holes. Since the depth to which each hole was drilled was independent of the others, if all three holes were drilled to the same depth, there was almost no chance that the probe tips were not aligned at the same, proper depth. Thus error was reduced with this triple-blind depth drilling method. If any of the above depth comparisons between holes did not match exactly, the jig was removed from the tree and the drilling process was started again once the jig was reattached over a new point close to the old one.

If the depth comparisons matched exactly, the probes were inserted into the holes. The probes had also been aligned to a reference point on the shaft to further safeguard against placement error. The top and bottom probes house the tiny thermistors at their tips and the middle probe contains a small heating element. The thermistor probes are essentially identical, but to avoid error from switching the probes should they be found to be even the slightest bit different, one probe was always inserted into the top hole, and the other always inserted into the bottom hole. The possible falling debris problem mentioned was prevented by always inserting the bottom probe first, followed by the heating element in the middle hole, and lastly, the upper probe in the uppermost hole. The wires were connected to the probes and then plugged into the instrument box, which was subsequently switched on. The unused end of the ratcheting nylon strap was used to separate the thicker barrel portions of the probes, which were in very close proximity to each other outside the drill jig. Any contact between the barrels would close the resistance circuit and register an unbalanced state on the instrument.

Once the probes were in place, separated from each other, and plugged in to the instrument, there was a long waiting period to allow the probes to reach a balanced state of equilibrium. The initial unbalanced state was a result of residual heat from the operator's fingertips, severe wind, contact between the probe barrels, a discontinuity in the probe or one of its leads, or a dead battery in the instrument. From experience, the author found that 22 to 28 minutes was required under normal conditions to reach a state of perfect balance to allow accurate sampling. During the waiting period, the field journal was updated for the specific tree being measured, weather conditions may have been noted, or field observations may have been recorded.

The instrument registered a state of non-balance on a gauge in units of microamperes of direct current voltage between the thermistors. Essentially, the instrument was unitless, having measured only disruption from a perfect state of balance between the probes. Touching the two thermistors together would result in a zero reading on the gauge. The thermistors measured the heat differential between them, which is zero when in direct contact with each other. This was also why a long time was required to reach a balance once they were placed within the tree - to achieve the required perfect balance, sufficient time was allowed for the dissipation of any thermal differences between the thermistors *inside* the tree.

Once sufficient time had elapsed to ensure a state of perfect balance between the thermistors, the gauge on the instrument was zeroed to ensure precisely the same starting and ending point for the experiment. The instrument gauge was adjusted by means of two dials: one to adjust sensitivity and the other to set the thermistors in a state of balance at the exact zero point on the gauge. Sensitivity was related to battery and field condition. For instance, the sensitivity was increased to compensate for a weak battery, and decreased to overcome the disturbance of strong winds. The sensitivity was kept as high as sampling conditions allowed. As a general practice, on a still day and with fresh batteries, the author turned the sensitivity to its maximum and then back two complete revolutions of the dial, but such adjustment was tree-specific and depended on changing sampling and instrument battery conditions.

The second dial was adjusted until the needle on the gauge read absolute zero once sufficient balance time had elapsed. Absolute zero was checked by turning the gauge off and then on again. The off position shows the zero point as it should be when the gauge is on and balanced. The balance knob was adjusted each time the instrument was turned on and off until toggling the on-off switch had no effect on needle position. A stopwatch was then started. If, after two minutes, the needle had moved even the slightest bit from the absolute zero position, the thermistors had not had sufficient time to balance, and additional time was given until the needle stayed constant at zero for two full minutes.

Once this zero position had been attained, sampling was ready to begin. An entry was made in the field log for tree number and aspect. The stopwatch was then reset to zero. *Simultaneously* the stopwatch was started and the heater button on the instrument was depressed. Once the stopwatch had reached one second, the heater button was released. A brief delay was the result of the time required for the heat pulse introduced in the xylem to reach the first thermistor. The needle of the instrument gauge rose slowly and steadily. The time of day, to the nearest minute, was noted at the time the heater button was pressed.

An adequate zero state had not been achieved if the needle retreated slowly backward toward the zero position and then began to rise, and the procedure was repeated once a true balance was reached. If the needle rose consistently and steadily, the sampling procedure continued. The maximum number reached by the needle was recorded in the field log. This maximum refers to the level of sensitivity achieved for the sample attempt. Readings of over 100 (a unitless number) were best, but throughout the course of this study, maxima of 30 or better were deemed an acceptable and usable result. It was more difficult to achieve high numbers on the coppice form of oak tree due to the effects of wind on the relatively shallowly-placed probes. Older, thicker-barked trees produced maxima of 220 or greater.

Once the maximum was reached, the needle progressed toward the zero position. The success of the reading depended upon the operator's ability to stop the watch *exactly* as the needle hit absolute zero. The author used a stopwatch with a lap timer to get a reading each time absolute zero was assumed. For example, if the lap timer was depressed at exactly the zero point, the reading on the watch was the time recorded. If, however, the needle continued to descend slightly toward zero, the lap timer was reset as necessary without affecting the actual running time of the experiment. Once the needle had stopped moving and was settled, the minimum reading was noted. In some cases it stopped at 10 or 20, and the time on the watch represented an unusable result. In this case, the watch was stopped at any time after the needle had stopped moving, and the time was recorded in the field log as a terminated experiment. If the needle did reach absolute zero, the time at which it did so was recorded.

If the needle 'bounced' while on its way to zero, that is, some resistance was met that caused the needle to rise or fall quickly at one point and more slowly at another, the experiment was considered unsuccessful. The needle had to reach a maximum point and return to absolute zero at a consistent rate. Varying needle speed indicated some type of interference. A needle that momentarily backed up in either direction indicated a state of unbalance. For example, the needle must have read "50...40...30...etc.," not "50.40.......30..20...etc.," or "60...50...40...50...40...30...etc."

Another problem which negated successful experiments was that absolute zero must have been reached. The test for this was the comparison between the final resting place of the needle and the zero attained by switching off the instrument. If absolute zero had not been reached, another run was attempted until true zero was reached meeting all of the criteria described above. The needle had to remain at true zero for one full minute. This was done to ensure that the probes were not underbalanced - that their true balance was on the other side of zero. Using the lap timer described earlier, adding 1:00 to the recorded time ensured that the needle stayed at absolute zero long enough to produce a viable reading.

Once an acceptable reading had been attained, it was necessary to duplicate the run to avoid any unforseen sources of error. The above procedure was repeated exactly, except that the sensitivity and balance knobs were *not* adjusted, in order to produce a second successful run to verify the first under *exactly* the same conditions. It was important that the time on the stopwatch was not seen during the subsequent runs until absolute zero was once again reached and held. This avoided any bias error and resulted in true blind verification of the elapsed time of the first run. It was the author's convention that the elapsed time of a successful verification run was within thirty seconds of the elapsed time from the previous successful run.

Once a second successful run was recorded for a tree, the instrument was switched off, the probes and drill jig were removed, and the field log was prepared for the next tree. Subsequent tree number and its aspect were determined as mentioned earlier, and the process was repeated until all fifteen trees had two successful sampling runs. On average, a tree took between 30 and 75 minutes to complete. Some had taken somewhat less time, while others took longer than two hours.

APPENDIX B:

TABLES OF DAILY WATER USE BY INDIVIDUAL TREES

Water use by mature trees on uncut area in liters per day.

Week Number	Tree 1	Tree 2	Tree 3	Tree 4	Tree 5	Total	Average	Standard Deviation
1	12.9	23.5	17.5	14.3	7.0	75.2	15.0	6.1
2	23.8	23.5	20.3	19.7	16.1	103.4	20.7	3.2
3	18.4	34.0	37.1	31.0	8.6	129.1	25.8	11.9
4	14.6	32.2	28.7	21.7	16.1	113.3	22.7	7.7
5	18.4	25.3	38.5	21.7	14.6	118.4	23.7	9.2
6	30.5	14.8	49.7	27.1	20.6	142.7	28.5	13.3
7	32.6	38.7	44.1	50.7	20.9	187.0	37.4	11.4
8	22.5	28.3	39.9	16.7	15.6	123.1	24.6	9.9
9	20.9	18.3	24.5	23.1	10.3	97.1	19.4	5.6
10	31.7	26.6	17.5	15.3	8.2	99.2	19.8	9.3
11	19.6	13.9	35.7	24.1	9.4	102.7	20.5	10.1
12	12.9	10.4	15.4	13.3	10.1	62.2	12.4	2.2
13	15.0	17.4	30.8	22.2	9.8	95.2	19.0	7.9
14	15.9	27.0	28.7	16.7	11.8	100.0	20.0	7.4
15	17.1	20.5	25.2	16.7	16.8	96.3	19.3	3.7
16	17.5	15.2	22.4	23.6	12.0	90.8	18.2	4.9
17	15.0	14.4	34.3	21.2	8.2	93.0	18.6	9.9
18	13.4	19.6	28.0	28.6	10.6	100.1	20.0	8.2
19	16.7	22.6	35.7	33.0	15.4	123.4	24.7	9.3
20	25.0	26.1	39.2	15.3	14.9	120.5	24.1	9.9
21	20.9	20.9	34.3	17.7	8.4	102.2	20.4	9.3
22	19.6	18.7	27.3	19.7	12.5	97.8	19.6	5.3
23	22.5	17.0	37.8	24.1	7.9	109.3	21.9	10.9
24	23.0	31.3	21.7	18.2	12.2	106.5	21.3	7.0
25	16.3	20.9	28.7	20.2	7.4	93.5	18.7	7.7
26	12.5	15.2	34.3	15.8	6.5	84.3	16.9	10.4
27	15.0	15.7	22.4	19.7	15.1	87.9	17.6	3.3
28	19.6	20.0	25.2	17.7	10.1	92.6	18.5	5.5
29	17.5	13.5	24.5	18.7	10.1	84.3	16.9	5.5
30	29.6	19.6	44.1	28.1	14.6	136.0	27.2	11.3
31	20.9	23.9	31.5	12.8	11.5	100.6	20.1	8.2
32	18.8	22.2	36.4	28.1	13.9	119.4	23.9	8.7
33	25.9	27.0	37.8	25.1	13.2	129.0	25.8	8.7
34	11.7	15.2	30.1	17.2	12.0	86.2	17.2	7.5
35	11.7	20.9	26.6	27.6	11.0	97.8	19.6	7.9
36	12.9	15.2	37.8	22.2	12.2	100.4	20.1	10.6
37	17.5	18.3	47.6	18.7	12.2	114.3	22.9	14.1

Water use by standard trees on cut area in liters per day.

Week Number	Tree 6	Tree 9	Tree 12	Tree 14	Tree 15	Total	Average	Standard Deviation
1	10.2	19.7	7.4	12.1	20.6	70.1	14.0	5.9
2	16.1	12.5	11.9	14.0	13.2	67.6	13.5	1.6
3	21.3	24.3	12.1	15.5	21.0	94.3	18.9	4.9
4	11.5	15.8	17.1	22.0	20.2	86.6	17.3	4.1
5	23.3	28.3	21.7	17.1	44.8	135.2	27.0	10.7
6	27.6	19.4	9.6	41.6	47.9	146.1	29.2	15.7
7	19.0	17.8	5.9	18.3	17.5	78.6	15.7	5.5
8	13.5	28.9	10.4	16.1	23.8	92.7	18.5	7.6
9	15.8	20.7	11.4	15.8	25.3	89.0	17.8	5.3
10	16.1	19.7	7.9	15.8	14.8	74.3	14.9	4.3
11	17.1	13.8	8.4	13.7	13.6	66.6	13.3	3.1
12	11.8	9.2	13.3	13.0	17.1	64.5	12.9	2.9
13	14.8	27.3	15.3	19.2	8.2	84.8	17.0	7.0
14	9.9	17.4	9.6	11.8	15.6	64.3	12.9	3.5
15	11.8	11.2	6.2	11.2	13.2	53.6	10.7	2.7
16	12.5	15.1	6.9	11.8	17.9	64.2	12.8	4.1
17	20.0	10.2	9.1	15.8	15.6	70.8	14.2	4.5
18	22.0	15.8	15.6	18.6	21.0	93.0	18.6	2.9
19	11.8	16.8	9.9	18.0	12.8	69.3	13.9	3.4
20	19.4	17.1	11.4	14.0	19.1	80.9	16.2	3.4
21	10.8	22.0	9.1	15.8	14.8	72.6	14.5	5.0
22	16.4	11.5	12.1	14.3	14.8	69.1	13.8	2.0
23	15.4	12.2	8.9	12.4	19.9	68.8	13.8	4.1
24	9.9	9.2	7.2	11.5	18.3	56.0	11.2	4.3
25	17.4	16.8	5.7	14.6	11.7	66.1	13.2	4.8
26	11.5	14.5	11.9	14.9	15.6	68.3	13.7	1.9
27	15.1	11.5	9.4	8.7	12.5	57.1	11.4	2.6
28	9.5	19.7	8.2	7.4	13.6	58.5	11.7	5.1
29	14.4	16.1	8.2	13.0	14.4	66.1	13.2	3.0
30	24.0	15.1	21.3	16.1	23.0	99.5	19.9	4.0
31	15.4	15.1	13.1	26.4	17.9	87.9	17.6	5.2
32	33.2	16.1	6.7	15.8	21.8	93.6	18.7	9.7
33	12.8	15.8	13.6	21.7	18.3	82.2	16.4	3.6
34	13.1	12.2	11.4	15.8	17.9	70.4	14.1	2.7
35	20.0	14.1	11.4	11.5	23.8	80.8	16.2	5.5
36	16.4	14.5	7.4	16.8	18.7	73.7	14.7	4.4
37	12.1	12.5	8.4	13.0	18.3	64.4	12.9	3.5

Water use by coppice on cut area in liters per day.

Week Number	Tree 7	Tree 8	Tree 10	Tree 11	Tree 13	Total	Average	Standard Deviation
1	4.3	2.7	2.9	1.8	2.7	14.4	2.9	0.9
2	8.1	3.9	4.4	2.2	5.1	23.6	4.7	2.2
3	8.1	5.1	4.1	2.0	3.2	22.4	4.5	2.3
4	9.0	7.1	4.9	5.0	3.6	29.6	5.9	2.1
5	9.2	5.8	3.9	5.7	6.3	30.9	6.2	1.9
6	7.2	4.4	4.5	6.1	7.8	29.9	6.0	1.6
7	9.0	5.5	4.5	3.7	2.4	25.2	5.0	2.5
8	6.1	4.6	3.7	2.7	2.4	19.6	3.9	1.5
9	8.1	2.8	5.6	4.3	5.8	26.6	5.3	1.9
10	5.5	4.4	3.1	3.2	5.6	21.9	4.4	1.2
11	3.4	4.4	2.8	2.0	3.9	16.5	3.3	0.9
12	6.7	3.4	2.7	1.9	3.5	18.1	3.6	1.8
13	3.6	3.4	4.2	3.2	5.0	19.4	3.9	0.7
14	5.6	2.3	2.5	3.3	3.9	17.6	3.5	1.3
15	6.1	3.5	3.6	2.6	3.9	19.7	3.9	1.3
16	3.9	3.7	3.8	1.8	5.9	19.0	3.8	1.4
17	4.1	3.4	5.1	2.9	4.3	19.9	4.0	0.9
18	5.4	4.3	2.5	4.5	4.9	21.6	4.3	1.1
19	4.5	4.2	3.2	2.3	4.9	19.1	3.8	1.1
20	7.9	3.9	3.0	2.8	4.9	22.4	4.5	2.1
21	5.0	3.7	3.9	3.2	5.4	21.2	4.2	0.9
22	5.7	2.8	4.5	3.0	6.9	22.9	4.6	1.8
23	6.7	4.8	2.6	3.8	4.8	22.7	4.5	1.5
24	4.3	3.8	2.8	2.6	4.0	17.6	3.5	0.7
25	3.0	5.3	2.6	3.1	3.2	17.1	3.4	1.1
26	2.8	4.3	3.7	3.2	5.4	19.4	3.9	1.0
27	4.3	3.2	2.1	2.5	3.9	16.1	3.2	0.9
28	3.3	3.4	2.7	3.8	2.4	15.6	3.1	0.6
29	5.2	4.9	3.2	3.2	5.0	21.6	4.3	1.0
30	5.9	3.2	2.2	3.7	5.6	20.6	4.1	1.6
31	4.8	6.4	2.4	4.3	5.5	23.4	4.7	1.5
32	5.6	4.0	4.2	5.7	3.1	22.5	4.5	1.1
33	5.9	3.9	2.5	3.0	3.9	19.1	3.8	1.3
34	5.2	2.8	3.0	3.2	6.5	20.8	4.2	1.6
35	3.3	4.7	4.5	2.5	5.3	20.3	4.1	1.1
36	4.8	3.2	2.7	2.2	4.0	17.0	3.4	1.0
37	6.1	4.7	3.3	3.6	0.0	17.8	3.6	2.3

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IMAGE EVALUATION TEST TARGET (QA-3)

150mm

6"

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