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# MEASURING AND MODELING TREE AND STAND LEVEL TRANSPIRATION

*J. M. Vose, G. J. Harvey, K. J. Elliott, and B. D. Clinton*

## SUMMARY OF PRACTICAL IMPLICATIONS

Transpiration is a key process in the application of phytoremediation 'to soil or groundwater pollutants. To be successful, vegetation must transpire enough water from the soil or groundwater to control or take up the contaminant. Transpiration is driven by a combination of abiotic (climate, soil water availability, and groundwater depth) and biotic (leaf area, stomatal functions, root amount and distribution, and hydraulic characteristies) that need to be evaluated when considering appropriate site and species combinations. The protocols are not trivial, but transpiration can be measured at a variety of scales using techniques such as direct measurements of sap flow on individual trees, eddy flux gradient analyses, or gauged watersheds. Alternatively, models can be used to estimate transpiration, but these usually require on-site calibration or parameterization to produce accurate predictions. Case study analyses across a range of site conditions and species indicate a maximum transpiration capacity of approximately 7.5 x $10^6$ liters of water per hectare per year (8 x $10^5$ gallons of water per acre per year), with a range of $1.5 \times 10^6$ to $7.5 \times 10^6$ liters per hectare per year (1.6 x $10^5$ to 8x $10^5$ gallons per acre per year). Variation among sites is related to species, tree size, and stocking (*i.e.*, vegetation density) differences. Application of a physiologically based and site-specific parameterized model suggests reasonable agreement between measured and predicted transpiration estimates for the Air Force Plant 4 site in central Texas.

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## IMPORTANCE OF ACCURATE MEASUREMENTS OF TRANSPIRATION

Transpiration-the amount of water used by a tree or stand of trees-is one of the key processes in the application of phytoremediation of soil water or groundwater pollutants. To be successful, native or planted vegetation must transpire enough water from the soil or groundwater layer containing the pollutant to control the transport or decrease the mass of contaminant. Hence, quantifying current and future transpiration and determining the principal location of water uptake by native and planted vegetation on the site must be the evaluation criteria for applying. phytoremediation. Quantifying transpiration requires a thorough and accurate assessment of water use patterns such as, transpiration rates, depth of soil water uptake, interactions with climate, and soil water availability. Measuring current transpiration or predicting future transpiration is not trivial. Because transpiration is an integrated response of the atmosphere–plant–soil continuum, measurements and predictions of transpiration capacity must account ‘for.(l) variation in climatic driving variables (*i.e.*, solar radiation, water vapor saturation deficit, precipitation, wind speed, and temperature), (2) structural and physiological (leaf stomatal function) characteristics of the vegetation (leaf surface area, and root area and extent), and (3) soil ‘water dynamics (water-holding capacity, and permeability).

Evapotranspiration and transpiration are often used interchangeably, but these processes are different. Evapotranspiration includes the amount of water transpired by the vegetation, and losses due to evaporation of intercepted precipitation and soil surface evaporation. In forests, interception evaporation is a function of rainfall intensity and leaf and branch surface area, ranging from about 10 to 50 percent (Helvey 1971, Myers and Talsma 1992, Vose and Swank 1992). In closed canopied forests, soil evaporation is a minor component of the overall water budget (Vose and Swank 1992), but ‘may become increasingly important in open stands. From a phytoremediation perspective, transpiration is the key factor to consider because interception evaporation does not involve soil water or groundwater.

The process of transpiration involves water movement through the soil, roots, stems, and leaves into the atmosphere in response to water potential gradients--always moving in the direction of smaller potential or negative gradients. Water potential is near *zero* when water is freely available and decreases to negative values when water becomes more limiting. The movement of water from the leaf interior to the atmosphere occurs through small openings in the leaf called stomata, which open and close in response to external (e.g., climatic factors) and internal (e.g., water potentials of leaves) driving variables. Species vary considerably in stomatal responses to these driving variables and provide opportunities for selecting species to optimize transpiration in different climatic environments.

Five methods are used to quantify transpiration: (1) precipitation minus runoff on gaged watersheds, (2) energy balance (e.g., Penman-Monteith equation), (3) eddy covariance, (4) hydrologic models, and (5) direct sap-flow measurements. The first three methods are integrated estimates for the entire vegetation-soil complex and provide estimates of evapotranspiration not transpiration. Hence, those methods do not directly partition water losses based on transpiration versus evaporation and provide no information on the source of water (Le., shallow *versus* deep soil layers) for transpiration. Estimating transpiration with methods 1, 2, and 3 requires an independent analysis of the contribution of interception and soil surface evaporation. Hydrologic models vary considerably in complexity, ranging from very simple models [e.g., Thomthwaite (1948) indices of potential evapotranspiration] to detailed physiologically based models that link vegetation, soils, and the atmosphere (Vose and Swank 1992). In contrast, sap-flow measurements provide a direct measure of transpiration (after correcting for time lags) under field conditions at the individual tree level (Hinckley *et al.* 1994, Martin *et al.* *1997,* Vose *et* al. 2000). However, modeling or other scaling approaches are required to extrapolate tree-level measurements to the stand.

In summary, there are numerous approaches to quantifying transpiration in native or plantation-derived vegetative ecosystems. However, these methods vary considerably in accuracy, in data and measurement requirements, and in the capability to predict future transpiration rates as stands develop. In this chapter, we review approaches to quantifying forest transpiration from the leaf level to the stand and discuss the pros and cons of &f&rent approaches. We then provide applications of a subset of these approaches from phytoremediation case studies in Texas, Colorado, and Florida.

## OVERVIEW OF CONTROLS ON TRANSPIRATION

Transpiration rates vary considerably among species and geographic regions (Figure 8-l). Which factors contribute to this variation? At large scales (i.e., regions), climate is an overriding control. The strong relationship between evapotranspiration and precipitation (Figure 8-1) suggests that transpiration is principally limited by soil water supply. However, other climatic factors such as temperature, atmospheric vapor pressure deficit, and solar radiation also play important roles and interact with soil water availability and physiological status of the plants (Figure 8-2). For example, one of the key effects of temperature is through the influence on the length of growing season, in which longer periods with temperatures above freezing promote longer leaf area duration and hence, surface area available for transpiration. Frozen or cold soils also restrict -transpiration (Fahey 1979) by limiting the permeability of cell membranes (Kaufmann 1977, Kozlowski et *al.* 1991). Solar radiation provides the energy for transpiration and regulates stomatal opening. As a

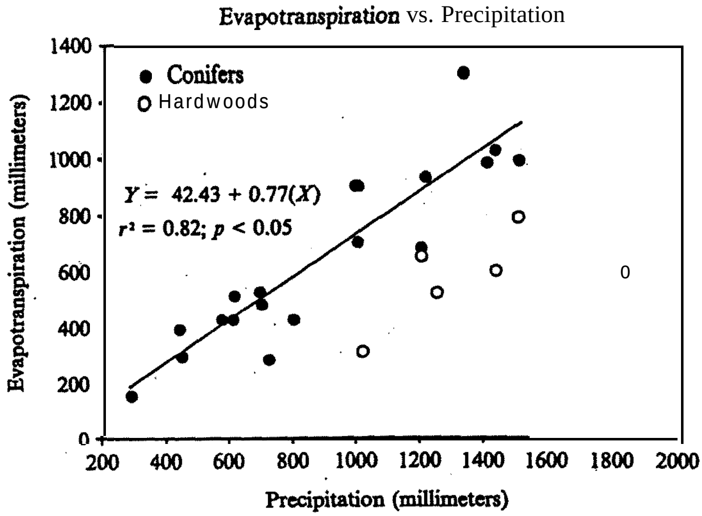


Figure 8-1 Relationship between annual evapotranspiration ($Y$) and precipitation ($X$) for hardwood and confier species (redrawn from Vose and Swank 1992, Knight *et* al. 1994 and data from this chapter). The regression line represents the data for the conifer species only. Note that $r^2$ is the correlation coefficient and $p$ is probability.

result, a strong relationship generally occurs between solar radiation and transpiration, estimated as sap flow in Figure 8-2. Atmospheric vapor pressure deficit provides the gradient to which leaf-water vapor responds through the leaf stomata (Figure 8-2), and wind speed has a direct influence on the leaf boundary layer (Gates 1980). Optimal climatic conditions for transpiration include high soil water availability, high solar radiation, high vapor pressure deficits, warm temperatures for extended periods, and high wind speed. In most cases, these conditions do not occur simultaneously because increased soil water availability is usually a result of high rainfall that decreases solar radiation (due to increased cloud cover) and vapor pressure deficit (due to higher humidity). Species that have the ability to utilize deeper sources of soil or groundwater [i.e., phreatophytic vegetation such as poplar (*Populus* spp.). and willow (*Salix* spp.)] are an especially attractive option in hot, dry, and windy environments in the southwestern U.S., because transpired water can be derived from groundwater (Dawson and Ehleringer 1991, Busch et al. 1992). Several studies have evaluated the influence of phreatophytes on surface and groundwater (e.g., Robinson 1970, Van Hylckama 1980, Allen et *al.* 1999) from the perspective of negative impacts on streamflow and groundwater recharge. From a phytoremediation standpoint however, the high water consumption of phreatophytes has a positive effect to decrease aquifer recharge and influence the movement of contaminated shallow groundwater.

The structure, morphology, and physiological characteristics of the vegetation are also important regulators of transpiration. For example, at equal

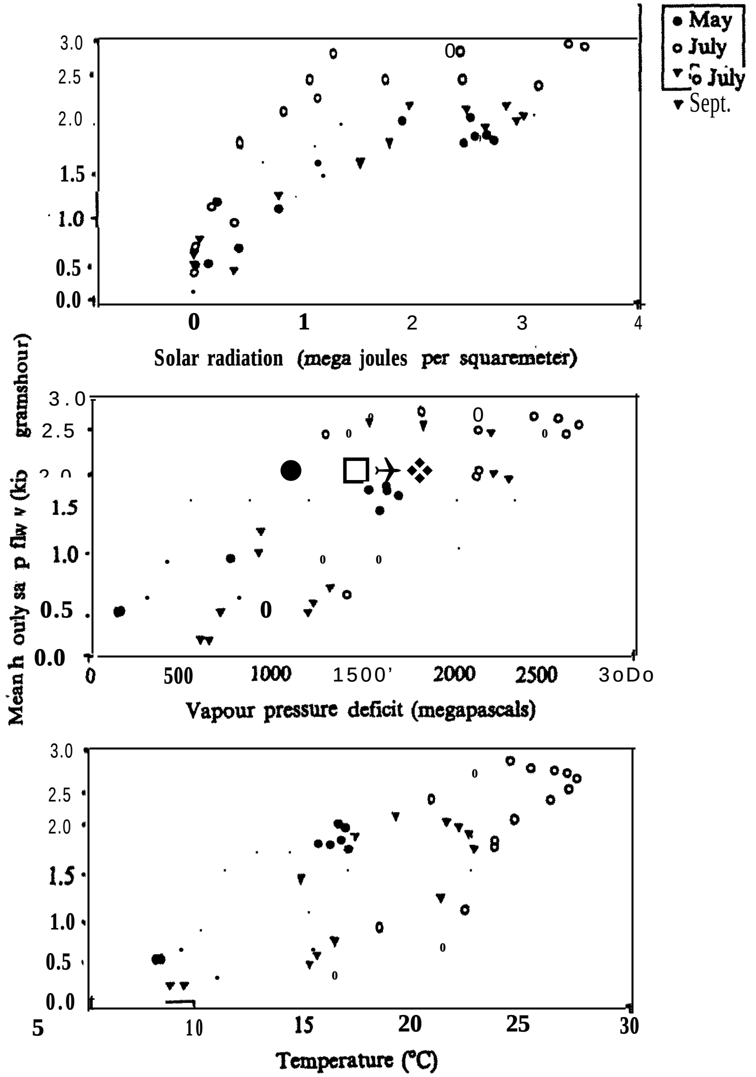


**Figure 8-2** Mean hourly sap flow *versus* climatic driving variables for three seasonal measurement (May, July, and September) periods in central Colorado.

precipitation inputs, there are large differences in transpiration between conifer and hardwood species (Figure 8-1), with hardwoods generally lower than conifers. Causes for these coarse scale differences are generally well known. The single greatest controlling factor is the quantity of leaves, expressed as leaf area index (in square meters per square meter). Site water availability and leaf area are related in that, sites with the greatest water availability typically have the highest leaf area index (Gholz 1982, Long and Smith 1990), although nutrient availability (Vose and Allen 1988, Colbert et *al.* 1990) and temperature also play a role (Gholz 1986, Cropper and Gholz 1994) in determining the maximum leaf area index, Watershed studies have documented strong relationships between leaf area and streamflow, with streamflow increasing exponentially as leaf area decreases (Douglass and Swank 1975, Swank *et al.* 2000). Because precipitation minus streamflow is an estimate of evapotranspiration at watershed scales, the implication is a direct control of stand-level transpiration by leaf area. Other structural and physiological factors regulating transpiration include the amount and permeability of sapwood and stomatal characteristics such as conductance and responsiveness to climatic variation and overall plant water status (*i.e.*, water potential of leaves). Differences among species in leaf area, the rate of attainment of maximum leaf area, and physiological characteristics regulating the rate of water movement through the plant (sapwood amount and permeability, and stomatal conductance) provide opportunities for manipulating vegetation composition and structure to optimize transpiration. Optimal structural and physiological conditions for high transpiration amounts include rapid development of high leaf area, high stomatal conductance and sapwood permeability, and physiological characteristics that facilitate rapid responses to climatic conditions promoting transpiration.

Because transpiration is a function of root uptake from the soil and groundwater, soil characteristics are an important factor determining transpiration. Root growth and volume of soil occupied by roots are also important because water movement is slow when soils are drier than field capacity. Several factors determine soil water availability. First, the amount of precipitation entering the soil is a function of infiltration rate. Soils with low infiltration rates due to factors such as compaction or fme texture will have lower soil water availability because some precipitation may move across the soil surface in overland flow. Once in the soil, soil water availability is a function of water holding capacity and unsaturated hydraulic conductivity, both of which are determined by soil texture. Texture impacts water availability in different ways. Heavy clay soils (e.g., pore size less than 0.2 micrometer) have limited soil water availability because of very low rates of movement in the soil (i.e., conductivity) due to the fine pore space. In contrast, coarse textured sandy soils (e.g., pore size greater than 50 micrometers) have low water availability because of rapid drainage. Rooting volume and ‘the presence or absence of restrictive layers are also important soil factors determining transpiration. For example, compacted soils provide a physical. barrier to root growth, limiting root extension (Heilman 1981).

## QUANTIFYING TRANSPIRATION

### Leaf Level

Because water exits the plant primarily through leaf stomata (a small amount of cuticular transpiration may also occur in stems of some species), leaf-water relations are a key factor determining whole-plant transpiration (Schulz 1991). The concentration gradient of water vapor between the interior of the leaf and the atmosphere at the leaf boundary layer defines the maximum transpiration rate. Vapor exchange is also determined by the opening size of the stomata. When stomata are wide open, transpiration occurs at about 20 percent to 40 percent of the rate of evaporation of open water (Waring and Schlesinger 1985), whereas closed stomata limit transpiration to less than 1 percent of open water. Stomatal opening is controlled by guard cell turgor, which responds to light, temperature, vapor pressure, and water potential of the leaves. The rate of movement of water through the stomata is the stomatal conductance. The rate of stomatal response to climatic conditions varies by species, but generally reflects responses to current conditions, whereas stomatal responses to water potential in leaves may reflect previous climatic and environmental conditions.

Because of the tight linkage between transpiration, leaf stomatal conductance (hereafter referred to as leaf conductance), and water potential of leaves, knowledge of all three parameters is useful for evaluating transpiration capacity. For example, species that exhibit high leaf-level transpiration and conductance, and maintain high water potential in the leaves have the capacity to transpire large quantities of water. Similarly, the relationship between water potential in the leaves and conductance is often threshold dependent; *i.e., species* that maintain high leaf conductance at low water potential have the capacity to transpire more water under dry conditions (Zhang *et* al. 1997). Because of the importance of factors such as leaf area index and distribution, sapwood amount and permeability, and the difficulty in extrapolating spatially and temporally from the leaf to stand level, there may be no direct correspondence between leaf-level transpiration and overall stand transpiration, Typically, leaf conductance and tree and stand-level transpiration are most highly related in young stands with simple canopy architecture (Vose *et al.* 2000), such as closely spaced, even-aged monocultures. However, as stands develop, the linkage between leaf conductance and tree or stand-level sap flow declines due to shifts in the importance of stomatal *versus* boundary layer conductance to total vapor phase conductance (Heilman *et al.* 1996, Martin *et al.* 1999). Hence, leaf-level measurements should only be used as an indicator of transpiration capacity.

## Tree Level

Transpiration at the whole-tree level represents the integrated movement of water vapor from all the leaves in the crown of the tree. As mentioned in the previous section, spatial and temporal variation severely limits extrapolation of individual leaf measurements to the tree, so more direct measurements at the tree level are required. Two approaches have typically been used. In a few instances, entire trees have been enclosed in a cuvette and the flux of water vapor calculated based on the rate of increase in humidity within the enclosure. This approach is severely limited by methodological constraints such as the size of trees, heat buildup within the cuvette, and alterations in the boundary layer and vapor pressure gradients.

Sap-flow rate and volume have also been used as an estimate of transpiration (Steinberg et al. 1989). Because of lags between water movement in the stem and leaf-level transpiration, sap flow is not a direct measure of transpiration, but can be corrected after accounting for lags (Schulze *et al.* 1985, Philips *et al.* 1997). Typically, a 1- to 2-hour lag correction is applied to real time sap-flow data to account for this temporal difference (Philips et *al.* 1997, Vose et *al.* 2000).

Two sap-flow techniques have been utilized; heat balance and heat pulse. For the heat-balance approach, collars consisting of a heating element and thermocouples above and below the heating element are placed around the stem and the entire stem section is heated. Sap flow is calculated using the heat-balance principle based on the difference in temperature between thermocouples above and below the heated stem section, after subtracting for heat loss due to conduction by stemwood (Baker and van Bavel 1987). An advantage of this approach is that it integrates sap flow along the entire stem and does not require an independent estimate of sapwood area. For larger trees, paired probes are inserted vertically into the sapwood (Granier 1987). The upper probe is heated and both contain thermocouples. The probes measure heat dissipation, which increases with sap flow and the resultant cooling of the heat source, as the apparent thermal conductance of sapwood increases with sap velocity. To convert sap velocity to sap flow rate, the cross-sectional area of sapwood must also be determined. Typically, trees are cored and sapwood to heartwood ratios quantified. Because sap-flow probes measure sap flow velocity at only one location, multiple probes are required to adjust for the variation in sapwood thickness and permeability in the stem section. Despite this, unaccounted for variation in horizontal and vertical variation in sapwood thickness and permeability introduces some error into sap-flow estimates obtained with probes. The magnitude of error can be determined experimentally and corrected for in small trees by comparing sap flow with actual transpiration using procedures such as weighing lysimeters. In large trees, corrections are much more difficult and hence, predictions have more uncertainty. In contrast to the heat-balance method, the heat pulse method estimates sap flow based on the time lag between pulses of heat and the distance between the sensors (Swanson 1962).

## Stand Level

While it is informative to understand transpiration at the leaf and tree level to help evaluate species and environments suitable for phytoremediation, stand-level transpiration ultimately determines how much soil water and groundwater are removed. However, unlike leaf and tree measurements, no methods directly measure stand transpiration. Instead, three indirect measurement approaches have been utilized. These approaches involve gaged watersheds, extrapolation of individual tree measurements, and eddy flux estimates. Gaged watersheds require a combination of well-defined watershed boundaries, tight bedrock, and wellconstructed weirs or gages to provide accurate transpiration estimates. If these criteria are met, then evapotranspiration (*ET*) is estimated by the equation

$$ET = P - RO \pm \text{soil water storage} \quad (8\text{-}1)$$

where $P$ = precipitation and $RO$ = runoff, determined from weirs or gages. Because $P$ is a component of the equation, the accuracy of precipitation measurements will also influence evapotranspiration estimates. Changes in soil water storage are usually assumed to be negligible at annual time steps, although this is clearly not the case over shorter intervals. Hence, using this approach at time steps less than a year requires determining changes in soil water storage. Because evapotranspiration is estimated, interception evaporation must be determined and subtracted to estimate transpiration.

Extrapolating individual tree measurements to the stand can be done in a number of ways. For example, instruments that measure sap flow can be installed on trees representing the averaged sized tree and mean sap flow multiplied times the number of trees in the stand (*i.e.,* a "mean-tree" approach). Considerable uncertainty in stand-level estimates can accompany this approach where sites are variable. Alternatively, relationships between tree diameter, sapwood area, or basal area and sap flow at the individual tree level can be applied to all trees. In both approaches, repeated sampling is required to account for seasonal variability.

The eddy flux method uses water vapor gradients at fixed intervals above and below the canopy to calculate evapotranspiration. The technique is based on the assumption that water vapor flux is proportional to the vertical gradient of water vapor between two measurement points (averaged over several minutes). Typically, measurements are conducted from towers extending through the canopy. To be useful for estimating transpiration of a particular stand, the stand must be large enough to encompass most of the footprint measured by the sensors. In many phytoremediation applications conceived as of 2003, the stands are too small for an eddy flux approach to be appropriate.

## Modeling

The use of modeling provides a potentially powerful tool for predicting current transpiration of native or planted vegetation and for projecting future transpiration capacity as a function of stand development: At the coarsest level of forecasting, gross measures of plant water demand and use can be derived from empirical estimates of potential evapotranspiration (Thornthwaite 1948, Mongaran 1973). These approaches usually consider climate and soils to some extent, but do not consider vegetation effects such as leaf area index, rooting depth, or leaf-level physiological characteristics. Hence, empirical approaches are useful for gross estimates of transpiration, but have limited utility for evaluating actual effects on the groundwater. At the other extreme, detailed physiological models that link the soil-plant-atmosphere continuum provide much more accurate estimates of transpiration. Depending upon the structure, models may also provide estimates of specific uptake locations within the soil profile (Huff and Swank 1985, Vose and Swank 1992, Vose and Swank 1994). Using detailed physiologically based models results in significantly greater data requirements. The most accurate application of these models requires site-specific estimates of soils, climate; and physiological characteristics of the major species on the site. However, large-scale application of detailed models with generalized parameters may provide estimates sufficiently accurate to be used in evaluating phytoremediation applications.

## MEASURING AND MODELING TRANSPIRATION: CASE STUDY APPLICATIONS

### Study Site Descriptions

Sap flow was measured at sites in Texas, Florida, and Colorado as components of larger studies evaluating the efficacy of using phytoremediation technology to clean up shallow groundwater contaminants. The north-central Texas study site was located, about 15 kilometers west of Fort Worth. The climate of this area is characterized as subhumid, with mild winters and hot, humid summers. The average annual precipitation is 80 centimeters per year with most rainfall occurring between May and October. Average annual temperature is 18.6 °C. Study plots were located on the U.S. Naval Air Station, which adjoins U.S. Air Force Plant 4. A plume containing trichloroethylene was detected in the terrace alluvial aquifer in 1985. To demonstrate phytoremediation potential, eastern cottonwood (*Populus deltoides* Marsh.) trees were planted in two plantations over the TCE plume. One plantation was planted with vegetative cuttings (whips) and the other with l-year-old nursery grown seedlings. Each plantation was approximately 80 by 20 meters and located perpendicular to groundwater flow in the alluvial aquifer. Sap-flow measurements were conducted using the heat-balance method (collars) in the first and second year after plantation establishment.

The eastern Florida site was located in the city of Orlando. The climate of the area is humid, with mild winters and hot, humid summers. The average annual temperature is 22.6 °C and the average annual rainfall is 123 centimeters. Native vegetation of interest was located on the U.S. Naval Training Center. Trichloroethylene and tetrachloroethylene, which originated from a dry-cleaning facility that is no longer in operation, contaminate shallow groundwater. The plume extends under a 2-hectare forest and seepage wetland before reaching Lake Druid that borders the forest. A dense and diverse mix of overstory and understory species occur in the forest (density of 107 trees per hectare), with red bay [*Persea borbonia* (L.) Spreng.], camphor [*Cinnumomum camphora* (L.) Nees & Eberm.], slash pine and longleaf pine (*Pinus* spp.), sweet bay (*Magnolia virginiana* L.), and live oak and laurel oak

(*Quercus* spp.) most abundant in the overstory. The most abundant understory species are skunk vine (*Paederia foetida* L.), 'saw palmetto [*Serenoa repens* (Bartr.) Small], cinnamon fern (*Osmunda cinnamomea* L.), and Christmas fern [*Polystichum acrostichoides* (Michx.) Schott.].

The central Colorado site is located approximately 20 kilometers southwest of Denver,, The climate of the area is dry, with warm summers and cold winters. Annual precipitation averages approximately 44 centimeters, with 30 percent of this amount received in April and May. The average annual temperature is 12 "C. Study plots were located on the U.S. Air Force Plant PJKS. Trichloroethylene and dichloroethylene from a variety of sources contaminate the site. Measurements were conducted in two existing stands of natural vegetation: cottonwood-willow (*Populus* spp.–*Salix* spp.) and Gambel oak (*Quercus gambelii* Nutt.) The cottonwood-willow (*Populus* spp.–*Salix* spp.) stand is restricted to riparian areas (approximately 1 percent of the total land area of the site), while the Gambel oak (*Quercus gambelii*) stand is on more midslope locations (approximately 30 percent of the total land area of the site).

## Methods

The sampling approach and methods varied among the three studies based on study objectives, species composition, and tree sixes. For the Texas study, sap flow from saplings in the plantation was estimated using sap-flow gauges (Dynamax Inc., Houston, TX) on 14 to *16* trees (divided equally among whips and l-year-old trees) in May, June, July, August, and October over a Z-year period. During each measurement period, sap-flow measurements were taken every minute for 2 to 3 consecutive days. Data presented in this chapter represent averages of both plantations. In' addition, sap flow was measured on nine larger native trees growing near the plantations using thermal dissipation probes (Dynamax, Inc., Houston, TX). Species sampled were: eastern cottonwood (*Populus deltoides* Marsh.), American elm (*Ulmus americana* L.), black willow (*Salix nigra* Marsh.), sugarberry [or large hackberry, (*Celtis laevigata* Willd.)], Eastern red cedar (*Juniperus virginiana* L.), and mesquite (*Prosopis pubescens* Benth.). At the end of sampling, increment cores were taken from the nine large trees for determining sapwood area.

For the Orlando study, sap flow was estimated using thermal dissipation probes installed on nine trees representative of major canopy species. Species sampled were: slash pine (*Pinus elliottii* Engelm.), longleaf pine (*Pinus palustris* Mill.), live oak (*Quercus virginiana* Mill.), laurel oak (*Quercus hemisphaerica* Bartram ex. Willd.), sweet bay (Magnolia *virginiana* L.), and camphor [*Cinnamomum camphora* (L.) Nees & Eberm.]. Two probe sets were installed into the sapwood on the north and south sides of sample trees, and sampling was conducted in November, March, and July for 2 to 3 consecutive days over a l-year period. At the end of sampling, increment cores were taken and sapwood area determined.

For the Colorado study, sap flow was estimated using thermal dissipation probes on eight trees representing three species: eastern cottonwood (*Populus* *deltoides* Marsh.), narrow-leaf cottonwood (*Populus angustifolia* James.), and Gambel oak (*Quercus gambelii* Nutt.). Two probe sets were installed into the sapwood on the north and south side of sample trees and sampling was conducted in May, July, and September over a l-year-period. At the end of sampling, increment cores were collected and sapwood area determined.

For all three studies, data were summarized to provide average hourly sap flow rates (kilograms per hour) or daily totals (kilograms per day). In addition, climate was measured at all three studies with climate stations located on-site. Measurements included: hourly rainfall (centimeters), wind speed (meters per second), solar radiation (watts per square meter), temperature (°C), and relative humidity (percentage). Relative humidity and air temperature were used to. Calculate vapor pressure deficit (megapascals).

For the Texas plantation site, we parameterized and applied a mechanistic model of sap flow (PROSPER) and compared the results to sap flow measurements. Evapotranspiration at the Texas site was simulated because data were available to parameterize the model (Vose *et al.* 2000). The PROSPER model has been described in detail elsewhere (Goldstein *et al.* 1974, Huff and Swank 1985), so only a general description is provided here. The PROSPER code is a phenomenological, one-dimensional model that links the atmosphere, vegetation, and soils. Plant and soil characteristics are combined into a single evapotranspiration surface that is characterized by a resistance to water vapor loss. This resistance is analogous to the relationship between stomatal resistance and water potential of the leaves and is a function of the water potential of the evapotranspiration surface. Evapotranspiration is predicted by a combined energy balance-aerodynamic method (Penman-Monteith equation modified as described in Swift *et al.,* 1975) that is a function of the surface resistance to vapor loss described previously. The PROSPER model uses electrical network equations (Goldstein et al. 1974) to balance water allocation among vegetation and soil horizons. The flow of water within and between soil and plant is a function of soil hydraulic conductivity, soil water potential, root characteristics in each soil layer, and surface water potential. The PROSPER model predicts evapotranspiration, transpiration, and soil water distribution between soil layers daily, but monthly data are most accurate. The PROSPER model requires the following climatic data: solar radiation, precipitation, wind speed, air temperature, and vapor pressure. Initial model parameters include surface resistance to vapor loss, leaf area index, root distribution and surface area, soil moisture release, and several other parameters listed in Goldstein *et al.* (1974).

## Transpiration Estimates

Maximum transpiration rates for the study sites indicate large variation in transpiration potentials among sites (Table 8-l). On a per tree basis, rates ranged from 8 to 120 kilograms per tree per day. Much of this variation was related to differences in tree size that reflects differences in leaf area and sapwood area.

**TABLE 8-1 Midsummer Peak Sap-flow Rates Averaged across Species and Measurement Days**

| Site | Sapwood area (square centimeters per tree) | Sap-flow rates: Kilograms per day per square meter of sapwood | Kilograms per tree per day | Liters per hectare per year | Gallons per acre per year |
|---|---|---|---|---|---|
| **Texas** | | | | | |
| Plantation | 30 | 2600 | 8 | 3620000 | 387200 |
| Native trees | 820 | 1463 | 120 | 7551000 | 807600 |
| Colorado | 234 | 1043 | 24 | 1510000 | 161500 |
| Florida | 710 | 1535 | 109 | 6859000 | 733600 |

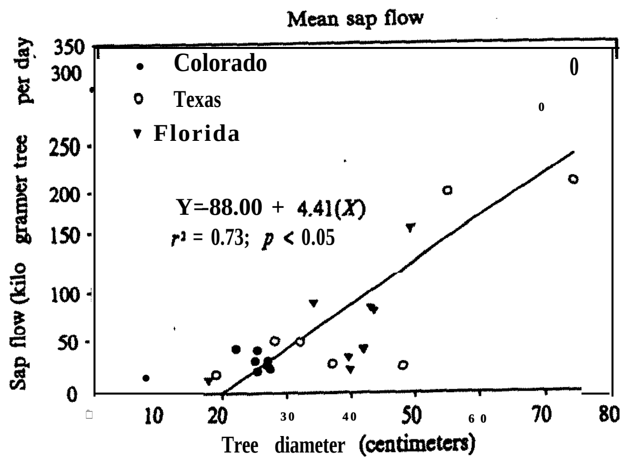


**Figure 8-3** Total **daily sap flows (*Y*) during peak transpiration periods (midsummer) *versus* tree** diameter (A') across a range of species and rite. Note that $r^2$ is the correlation coefficient and $p$ is probability.

For example, when pooling the data across the sites, a significant proportion of the variation in transpiration rates among and within sites can be explained by tree diameter (Figure S-3). Larger trees typically have greater sapwood volume resulting in more water transporting vessels (angiosperms) and tracheids (conifers) for sap-flow movement in the stems. Because leaf area is also related to sapwood area, larger trees will typically have greater leaf area index; and hence, greater surface area for transpiration.

When sap-flow rates are adjusted based on sapwood area (i.e., kilograms per day per square meter of sapwood), the variation in transpiration reflects species related differences in physiology (leaf, stem, and root), leaf area to sapwood area ratios, and site-dependent factors such as soil water availability and climate driving variables. Because species composition varies among sites and physiological and physical factors influence transpiration simultaneously, these studies cannot separate physiological and climatological effects; to do so requires an evaluation of transpiration rates of the same species and genotype in differing climatic and soil water availability conditions. For example, species sampled at the three sites represent a mixture of conifers, and ring porous and diffuse porous hardwood species, resulting in large differences in sapwood permeability and specific conductivity among sites and among species within sites (Figure 8-4). In general, sap-flow velocity is lower in conifers and diffuse-porous species because sap flow moves through a number of annual rings, whereas water moves through only one or two annual rings in ring-porous species (Kramer and Kozlowski 1979, Kozlowski et *al.* 1991). Despite the limitations of the current approach, some notable patterns emerge when evaluating transpiration after adjusting for differences in sapwood area. For example, the cottonwood (*Populus deltoides*) plantation in Texas had the highest transpiration rate per unit of sapwood area, followed by the Florida stand, large trees in Texas, and the Colorado stand (Table 8-l). Tire high transpiration rate for cottonwood (*Populus deltoides*) in the plantation is a function of species characteristics that promote high transpiration, high leaf area per unit sapwood in the developing canopy, and access to shallow groundwater. In contrast, transpiration rates per unit of sapwood area were lowest in Colorado, even though the site contained cottonwood (*Populus deltoides*) and several of the measured trees occurred in the riparian zone. The combination

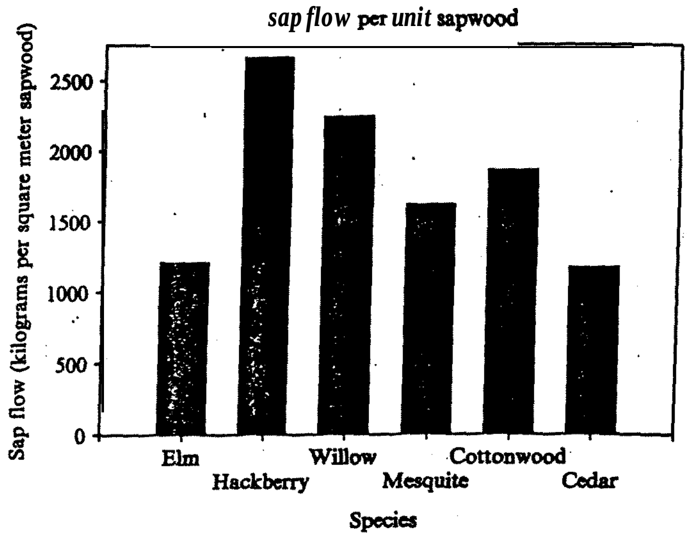


**Figure 8-4** Mean growing season sap-flow rate par unit sapwood for six species in north-central Texas. Black willow (*Salix nigra* March.), eastern cottonwood (*Populus deltoides* Marsh.), and eastern red cedar (*Juniperus virginiana*, L.) are diffuse porous species, while American elm (*Ulmus americana* L.), hackberry (*Celtis laevigata* Wiid.), and mesquite (*Prosopis pubescens* Benth.) are ring porous.

of species composition and climate characteristics were not as conducive to high sap-flow rates per unit sapwood area relative to the other sites.

Using sap-flow techniques to predict actual stand transpiration requires frequent sampling to account, for seasonal variation. Ideally, sap flow should be measured continuously for the entire growing season on a large number of trees. Because this approach is often impractical, an alternative is to measure sap flow at shorter frequencies and calculate bounds or maximum values as a tool to evaluate phytoremediation potentials. Because the sampling frequency varied among the case studies described here, we focused only on measurements during the highest transpiration period (midsummer). These estimates can be used as a "best-case scenario" approach-that is, if these rates occurred on the site, would transpiration be sufficient to control the plume? To estimate maximum potential transpiration at the stand level (i.e.., kilograms per hectare or gallons per acre), we extrapolated the tree transpiration data (kilogram per tree per day) assuming a 180 days transpiration period and a stem density of 350 stems per hectare, except for the plantation where actual tree density was used (Table 8-l). We emphasize that these data provide estimates of maximum transpiration capacity under in *situ* climate conditions because the peak sap-flow rates were used in the extrapolation and previous studies have shown considerable seasonal variation in sap flow (Vose *et al.* 2000). The 350 stems per hectare is representative of a fully stocked stand under most forest conditions and is consistent with full canopy closure and maximum leaf area index.

When comparing results from the sites with mature trees, the variation in maximum transpiration capacity is considerable. The Texas site has a maximum transpiration capacity of approximately 7.5 x $10^6$ liters of water per he&-are per year (8 x $10^5$ gallons of water per acre per year) if the site was fully stocked with the sampled species. By contrast, the Colorado site has a maximum transpiration capacity of approximately 1.5 x $10^6$ liters per hectare per year (1.6 x $10^5$ gallons per acre per year). The plantation site in Texas currently has a maximum transpiration capacity of approximately 3.7 x $10^6$ liters per hectare per year (4 x $10^5$ gallons per acre per year). However, we anticipate that transpiration will equal or exceed the estimate from mature trees on the site (versus 7.5 x $10^6$ liters per hectare per year or 8.0 x Id gallons per acre per year) once the canopy develops and achieves the maximum leaf area.

## Comparison of Measured *versus* Modeled Transpiration

A critical need for phytoremediation is the development and application of a tool to provide species and site-based estimates of transpiration. While a powerful tool for measuring transpiration from vegetation already on-site or quantifying transpiration of planted vegetation, sap-flow measurements at every phytoremediation site may not be practical. One potential tool for application across sites is the development or application of models. In most cases, however, models need to be calibrated or parameterized for specific site and species conditions. To evaluate the use of such a tool, we parameterized

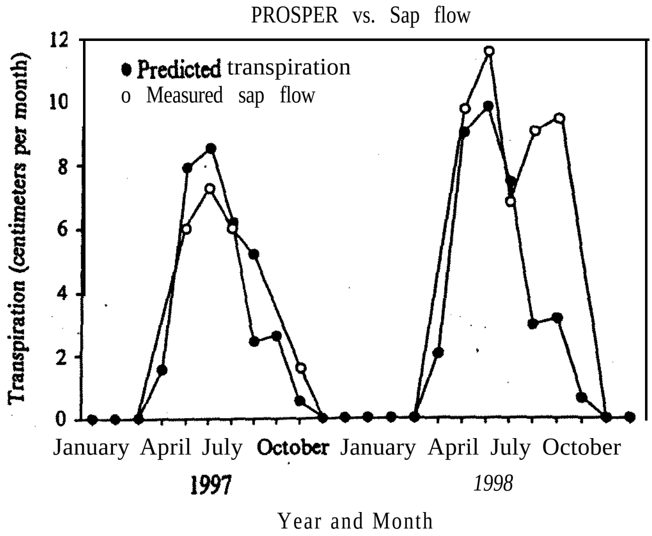


**Figure 8-5** Comparison of measured sap flow and **predicted transpiration** from PROSPER for cottonwood (***Populus deltoides*** *Marsh.)* plantations in north-central Texas.

PROSPER for the Texas plantation using intensive site (soils, climate, and root distribution) and leaf-level measurements (stomatal characteristics and leaf area index) (see Vose et al. 2000). We compared monthly transpiration estimates obtained with PROSPER to transpiration estimated from sap-flow measurements over a 2-year period (Figure 8-5). Comparisons indicated generally good agreement between predicted and measured values, except during the late summer that was coincident with some of driest and hottest periods (August and September 1998) in our study. During this period, PROSPER predicted a considerable decline in transpiration, while measured values showed an increase. We attribute this discrepancy to an inability of PROSPER to adequately simulate root uptake from shallow groundwater during drought conditions, since the original formulation of PROSPER was designed to only simulate surface and soil water dynamics (Goldstein et al. 1974, Huff and Swank 1985). The results of this comparison are consistent with other studies that have shown that PROSPER provides reasonable estimates of either evapotranspiration or transpiration (Vose and Swank 1992, Vose and Swank 1994). However, refinements in the subsurface water and groundwater hydrology and subsequent availability to tree roots might improve the predictive capability and usefulness, as a phytoremediation evaluation tool.

## CONCLUSIONS AND RECOMMENDA'I'IONS

The importance of transpiration to the success of phytoremediation applications suggests that accurate estimates of current and potential transpiration should be a high priority when considering this approach for site management. Both measuring and modeling transpiration are important. Assessments require a substantial sampling commitment for direct measurements or parameterizing physiologically based models. This requires detailed knowledge of local site conditions and physiological parameters' for the major species. For screening assessments, we recommend that published estimates be used to set the bounds for maximum transpiration capacity based on genera3 climate and vegetation characteristics of the location. If these general transpiration rates are great enough to influence groundwater hydrology, then evaluations of current, enhanced (e.g., manipulating the structure and species composition of current vegetation), or new vegetation transpiration capacity should proceed. Technology and models exist to provide reasonable estimates and predictions of transpiration. However, the accuracy of the estimates depends on the investment in accounting for the spatial and temporal variation or in providing site and species-specific estimates for physiologically based transpiration models.

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