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ESTIMATION OF WATER USE OF LANDSCAPE TREES

by A.J. Vrecenak[1] and L.P. Herrington

Abstract. The use of a computer model of transpiration from individual tree crowns is discussed as it relates to the reciprocal effects of plants on the environment and the environment on plants. The model is shown to be useful in estimating a plant's contribution to local energy budgets as well as its water use under various environmental conditions. Model estimates of hourly transpiration rates for container-grown sugar maple *(Acer saccharum)* and Norway maple *(Acer platanoides)* saplings ranged from 6.8 $g/m^2/hr$ to 55.5 $g/m^2/hr$, while lysimetric determinations ranged from 10.4 $g/m^2/hr$ to 63.4 $g/m^2/hr$ over a range of soil moisture conditions. The significant contribution of latent heat transfer via transpiration to the overall tree energy budget is shown by the model results as well. The model results, its areas of weakness and further research needs are discussed.

The phenomenon of plant water use can be looked at in two ways. The first involves the effects of the environment on the plant. In this case, the primary concern is plant growth and survival and the adequacy of the environment to provide the necessary conditions for this. The second view looks at the effects of the plants on the surrounding environmental conditions, and is concerned with the plant's function as a physical component of a larger system. As the disciplines of urban forestry and urban horticulture have evolved, this aspect of plant water use has gained more attention, and work continues in assessing the capabilities and limitations of plants in their role as environmental modifiers.

In an attempt to look at both of these issues, there has been a substantial amount of work done on modeling the processes of mass and energy exchange of plants (3,5,14,17,20,22). Unfortunately, these efforts have been primarily directed toward simulations of closed crop canopies (3,5,20,22). The characteristic lack of surface homogeneity of the urban forest makes the closed canopy system an unacceptable model for use in urban energy budget work. We have thus been left to extrapolate from these canopy modeling results or to intuitively accept the notion that individual trees have a significant impact on the overall urban energy budget (8,18).

The objective of this study was to determine the effectiveness of a mechanistic model of the transpirational process in predicting the water and energy use of two species of ornamental landscape trees under varying soil moisture conditions. There are several ways that water use of trees can be measured or estimated (6,26) and two methods were used in this study. The most obvious method was to weigh the amount of water lost from each tree, a practical solution on the small scale with containerized trees, but not so in the landscape situation. The second method was to use the computer model to predict transpirational water use for each tree. The model's ability to predict plant water use could then be checked by comparing the results of the two methods over all the trees. If plant water use can be estimated by the model, then it can be assumed that the model's estimates of the crown energy budget parameters are reasonably accurate as well, due to its mechanistic nature . (At this point, it would be instructive to define "mechanistic" as it is used here. A mechanistic model is one that simulates the mechanisms of the physical and physiological

1. Currently Assistant Professor of Horticulture, P.O. Box 231, Rutgers University, New Brunswick, New Jersey 08903.

processes that lead to the results observed. This differs from empirical models, in which the observed results determine the form of the model. Mechanistic models can reasonably be applied to any system, while empirical models must be adjusted to accomodate new situations.) When the model can reliably do its job, then it will be useful as a predictive tool in landscape tree management situations, where measuring the water and energy use of trees is currently impractical, at best.

Materials and Methods

Six trees each of *Acer platanoides,* Norway maple, and *Acer saccharum,* sugar maple were planted in 75 liter trash cans using a screened silt loam soil as the planting medium. Within each species, three levels of soil moisture conditions were established, with soil moisture ranges corresponding to those reported as having little, moderate, or severe effects on transpiration (13,15). Soil water potential in each tree was allowed to drop to within its assigned range before the plant was rewatered. Measurements for modeling purposes were made while the soil water potential for each tree was within its assigned range.

Model inputs include environmental parameters, plant water status information and plant descriptive parameters. In addition to site location data such as latitude and longitude, the following information is required for input to the model:

- soil water potential
- soil surface temperature
- leaf temperature
- air temperature
- dew point temperature
- shortwave radiation (0.3 to 4.0μm)
- photosynthetic photon flux density (0.3 to 0.7μm)
- wind speed
- crown dimensions
- leaf azimuth and inclination angle distributions
- mean and total leaf area

For the purpose of this study, leaf resistance to water vapor diffusion and leaf water potential were measured and compared to model estimates of these same quantities.

Model Operation

This model computes crown water use by reconciling the energy budget equation for the tree crown:

$$R_{net} = H + C + \lambda E$$

where R_{net} is the net flux density of radiation incident on the leaves, H is the energy flux density lost from the leaves through convection, C is the energy flux density lost through conduction, which is minimal for a tree crown, is the latent heat of vaporization for water, and E is the mass of water lost via transpiration from the leaves. By rearranging the above equation to read:

$$\frac{R_{net} - H - C}{\lambda} = E$$

the mass of water lost via transpiration can be determined. Although it seems relatively straightforward as a mathematical equation, the model is actually quite complex in its simulation of the interactions between the physical and physiological responses of the plants to the input of energy and the loss of water.

The crown model program is written in Fortran and consists of a relatively short main program that executes calls to subroutines that perform the calculations. There are four types of subroutines in the model program: data input, physical calculations, physiological calculations, and output. These correspond to the four major component sections of the model. Data input includes static conditions that characterize both the tree and the site as well as hourly inputs of environmental parameters that drive the physical and physiological calculations of the model. The information is then output on an hourly basis so the results of both water and energy use determinations can be studied.

The model's strength, as well as its weakness, lies within the physical and physiological calculations and their interactions. These require that certain information is available for the species or cultivar that is being tested. Of major importance are the stomatal and water potential responses of the plants. Some information exists on these parameters (11,12,23,24), but much more is needed to expand the usefulness and specificity of the model.

Results

Of the ten trees studied, five showed model results within 30% of lysimetrically determined transpirational water use, one was within 35%, and four were over 50% in error (Table 1). All three trees in the "wet" soil moisture range, and two in the "moist" range, showed agreement within 30%, while the three "dry" and the remaining two "moist" trees were outside that range. It appeared that the model functioned best when the modeled trees were under relatively low levels of soil moisture stress. It showed mixed success at moderate levels of soil moisture stress and it was only minimally successful when the plants were under severe soil moisture stress.

Both the measured and modeled transpiration rates determined in this study (Table 1) agreed well with those reported by other workers for similar species (12). On the basis of an observation period lasting from 0700 until 1800 EDT, lysimetrically determined transpiration rates ranged from 10.4 to 63.4 g/m^2/hr. Model estimates ranged from 6.8 to 55.5 g/m^2/hr over the same period. All measurements were made on days with bright sunshine and minimal cloud cover, under conditions as standard as can exist in the field. When looking at whole tree water loss over the eleven hour period, values ranging from 200 to 618 grams were lysimetrically determined, while model estimates ranged from 104.4 to 660.0 grams.

At times of high air temperature and high net radiation, the model showed that the energy lost via transpiration ranged from 30-50% of the total net radiant input for sunlit leaves. Over the entire tree crown, latent heat transfer via transpiration accounted for up to 70% of the dissipation of net radiant energy at times when the stomata were open and solar radiation was high. When stomata were closed, however, latent energy loss via transpiration dropped to less than 10% of net radiant energy input. Accompanying this drop in the contribution of transpiration was an increase in leaf temperature over air temperature, to drive the convective loss of energy. As radiant energy loads decreased within the crown as a result of shading, convective heat loss was the predominant energy loss mechanism. Before any additional energy balance results can be reported, the model functions need to be strengthened to enable the model to better simulate the response of trees experiencing water stress conditions.

			WATER LOSS (G)		TRANSPIRATION RATE (G/M^2/HR)		% DIFF. IN WATER LOSS
TREE[A]	SOIL Ψ (MPA) [B]	LEAF AREA (M^2)	LYSIMETER	MODEL	LYSIMETER	MODEL	(M-L)/L
1S	-1.06 (M)	0.884	280	256.5	28.8	26.4	-8
4S	-1.70 (D)	0.884	224	104.4	23.0	10.7	-53
5S	-0.08 (W)	0.878	405	334.0	41.9	34.6	-18
6S	-0.91 (M)	1.010	227	427.5	20.4	38.5	88
1N	-2.28 (D)	0.804	260	116.2	29.4	13.1	-56
2N	-0.08 (W)	1.203	508	660.0	38.4	49.9	30
3N	-0.87 (M)	1.219	377	437.2	28.1	32.6	16
4N	-0.08 (W)	0.886	618	540.9	63.4	55.5	-12
5N	-1.40 (D)	1.751	200	131.6	10.4	6.8	-34
6N	-0.98 (M)	1.092	371	602.0	30.9	50.1	62

[A] "S" STANDS FOR SUGAR MAPLE, "N" FOR NORWAY MAPLE

[B] W=WET, M=MOIST, D=DRY SOIL CONDITION

Table 1. Summary table of model and lysimetric determinations of transpirational water loss.

Discussion

The model needs further testing and refinement to make it available as a tool for the management and culture of landscape trees. As mentioned previously, the model does not function reliably under less than optimal soil moisture conditions. This deficiency may stem from either or both of two problems. The model cannot account for the natural variability that exists between individual plants in their responses to environmental factors. At this point in model development, it is unlikely that plant to plant variability is solely responsible for the confounding results seen, although it may play a part. A more reasonable explanation is that there are deficiencies in model functions and assumptions that lead to the variable results seen.

Modeling any system involves making assumptions and utilizing mathematical functions to represent component processes. Sound base information is required to produce good model results. A data base needs to be developed to catalog this information over a range of species. The assumptions and functions currently incorporated within the model are generally applicable, and are not cultivar or even species specific. Sensitivity analyses need to be run to determine the level of detail required for some of these functions. Some may require quite detailed information, while others may be made even more general than they currently exist. In the following section the deficiencies of the model as they are currently perceived will be described.

The physical submodels are important in determining the levels of radiation present within the crown volume. Radiation drives both the energy budget and some physiological responses of the plant that feed back and affect the energy budget parameters. It is obvious that the radiation regime within the crown needs to be accurately simulated because of the basic importance of radiation to the crown energy balance.

Leaf optical properties vary greatly among plants (1,10,16,25). Goudriaan (5) suggests values of 0.1 and 0.4 as good approximations of reflection and transmission coefficients for many leaves in both the visible and near infra-red wavebands, respectively, while Monteith (16) showed these properties as being quite variable, depending on plant species. Gates (4) and Goudriaan (5) suggest an infra-red emmissivity of 0.96 for an average leaf, while Idso et al. (10) have reported emmissiveities ranging from 0.938 to 0.995 for 34 plant species. The values used in the model for this study are those considered representative of the general case, but it would be more effective to characterize individual taxa under varying conditions and to utilize this information within the model.

The assumption of random distribution of leaves within the crown volume may be another source of error. A more valid approach would be to incorporate a probability density function to locate leaf surface area within the ellipsoid representing the tree crown. Horn (9) has described trees as having either "monolayer" or "multilayer" arrangements of leaves. These two distinct types would have very different leaf area distributions and probably ought to be represented differently within the crown model.

In our view, the simulative capabilities of the physiological submodels are probably more critical to crown model success than the problems mentioned previously. Specifically, the simulations of stomatal response and leaf water potential response are not reliably adequate (figures 1 and 2). The generalized stomatal response function used in the model obviously cannot represent all taxa under all conditions. In the instances where model estimates of leaf diffusion resistance approximated measured values (figure 1), model estimates of water use more closely matched lysimetric determinations than in those instances where such approximations were not evident (figure 2). The lack of information existing on the stomatal response characteristics of individual taxa makes rapid improvement of the model in this area quite difficult. Perhaps an adequate data base can be built if this is identified as a valuable and valid research area.

The simulation of leaf water potential presents a similar problem within the model. Since leaf water potential both affects and is affected by leaf diffusion resistance, accurate simulation of the phenomenon is important to the estimation of plant water use. A major factor affecting the change in leaf water potential is the hydraulic conductivity of the tree. Hydraulic conductivity, as it is used in the model, is the amount of water passing through a unit cross-sectional area of xylem per *unit time per unit potential gradient* (Kg m^{-2} S^{-1} $(10^5 Pa)^{-1}$). This differs from conductivities reported by other workers (7,19) and it needs to be determined experimentally for a range of taxa.

It is widely known that tree stems shrink as transpirational water loss exceeds root uptake of soil water (13), indicating that water is being removed from tissues to replace that lost through the stomata at these times. The hydraulic capacitance, as this is called, modifies the water potential response of the tree to transpirational water loss. It slows the drop in leaf water potential that results as transpiration exceeds root water uptake. The model's water potential response function does not contain this capacitance term because there is very little published information on this subject.

The leaf temperature response function is greatly dependent on the stomatal and water potential response functions. Once the radiation levels at the leaf surface and the water relations characteristics are adequately simulated, then leaf temperatures can be determined by application of the energy budget equation.

Deciduous trees generally have leaf area index values ranging from 3 to 8 (13). The trees in this study were very young and had an average LAI of approximately 3. Taking the results of this study and extrapolating, a table of water use estimates for well-watered, deciduous trees of various sizes can be constructed, using the following equation:

water use	= ground area	× LAI	× water loss rate	× .0011
(qts/hr)	(sq. meters)		(g/sq. meter/hr)	(g to qt)

Assuming a water loss rate of 60 grams per square meter per hour, the values in table 2 are generated and are applicable to those trees generally similar in characteristics to Norway and sugar maples.

gallons of water in a 12 hour day. This is a significant amount of water, but it is certainly not beyond the soil's supply capability. Assume for the sake of conservatism that the roots of that tree are confined beneath the crown volume and within the upper 0.5 meter of soil. This has been shown not to be the case (21), but these estimates will serve to illustrate a point. Given the above parameters, the soil volume available to the plant's roots is 157.08

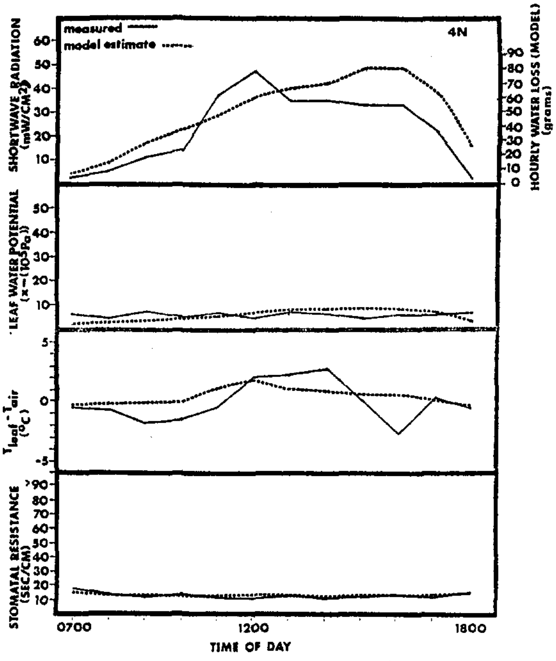

Figure 1. Model estimates and measured water status parameters for a non-drought stressed Norway maple (soil water potential greater than −0.8 MPa).

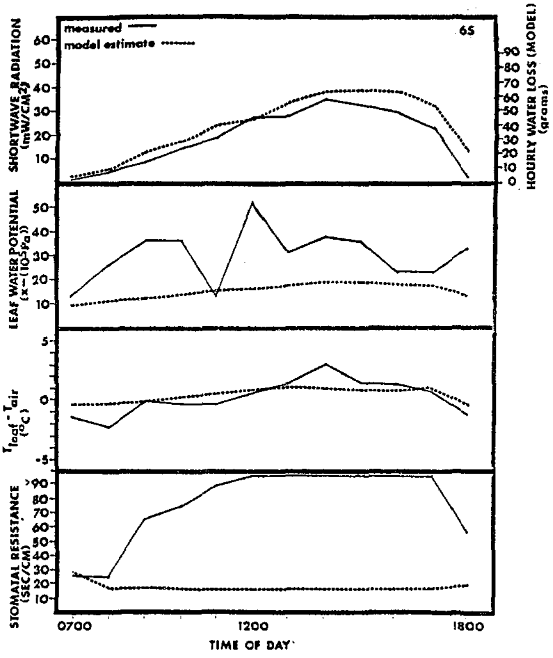

Figure 2. Model estimates and measured water status parameters for a moderately drought stressed sugar maple (soil water potential between −0.5 and 1.0 MPa).

cubic meters, or 157,080,000 cubic centimeters. According to Brady (2), the ideal silt loam surface soil is 50% pore space, of which 50% is water filled at field capacity. This leaves 25% of the total soil volume as water filled pore space, or 39,270,000 cubic centimeters of water at field capacity. Fifty percent of this is considered "available" water and is equal to 19,635,000 cubic centimeters, or 5400 gallons. This is a substantial reservoir of water, even within this conservative estimate of the rooting zone of a tree. Assuming that the stomates were open continuously for 12 hours every day, this supply of water would last approximately 23 days. Obviously, the stomatal closure mechanism would be in operation and the soil volume available for root water uptake would be more extensive. This would indicate that the soil can support a tree's water needs for a long period of time. We can also see that the replacement of water lost by a large tree requires more than a cursory ten minute soak with a garden hose.

Following further testing and development, the model will be described in terms of its energy balance determinations for shade trees under various conditions. This information will be useful in determining the capabilities of plants as environmental modifiers.

Conclusions

The modeling of transpiration from individual tree crowns can be an effective tool in the management of plants at any level, from production to landscape use. It can be used to predict water use, to schedule irrigation, to monitor plant water stress conditions, or to assess the whole plant energy balance. The model depends upon a great deal of background information that currently is not available in the literature. These areas need to be identified as valid research needs so that the information does become available for this use.

This kind of work is relatively new to the fields of horticulture and arboriculture. It will take some time for the answers supplied by research to catch up to the needs of further research. As more horticultural and arboricultural scientists begin to work in this area, the information will become available and progress will be made.

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	RADIUS (meters) DIAMETER (feet)					
LAI	0.5 (3)	1 (6)	2 (12)	3 (18)	5 (30)	10 (60)
2	.10 (94)	.41 (377)	1.66 (1508)	3.73 (3393)	10.37 (9425)	41.47 (37699)
3	.16 (141)	.62 (565)	2.49 (2262)	5.60 (5089)	15.55 (14137)	62.20 (56549)
4	.21 (188)	.83 (754)	3.32 (3016)	7.46 (6786)	20.73 (18850)	82.94 (75398)
6	.31 (283)	1.24 (1131)	4.98 (4524)	11.20 (10179)	31.10 (28274)	124.41 (113097)

Table 2. Estimates of water loss in quarts/hr (g/hr) from deciduous trees of various diameters and leaf area indexes, based on model results, assuming well-watered conditions and a water loss rate of 60 g/m^2 leaf area/hr.

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School of Forestry
323 Bray Hall
SUNY-ESF
Syracuse, NY 13210