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CROP WATER STRESS INDEX OF ORNAMENTAL PLANTS

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CROP WATER STRESS INDEX OF ORNAMENTAL PLANTS

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ABSTRACT

Water requirements were determined for eighteen species of ornamental plants produced under non-limiting water conditions at Las Cruces, New Mexico. Baseline equations were determined from regression analysis of canopy-air temperature differential versus air vapor pressure deficit. Canopy temperature was measured using an infrared thermometer. Air temperature and air vapor pressure deficit were measured using an Assmann psychrometer. Regressions for Salt Cedar, Sycamore, Ash, and Aleppo Pine had statistically equivalent slopes and intercepts ($P < 0.05$); all others were unique in their responses. Canopy and aerodynamic resistance were calculated from the baseline equations and the noontime and daily transpiration rates were calculated. Daily transpiration ranged from 12.5 mm d^{-1} (0.49 in. d^{-1}) (alfalfa) to 3 mm d^{-1} (0.12 in. d^{-1}) (Barberry). Relative transpiration was calculated using alfalfa as a standard. Redbud exhibited a relative transpiration of 0.78 and Mulberry showed a relative transpiration of 0.42.

KEYWORDS. Evapotranspiration, Water conservation, Water stress.

INTRODUCTION

In the western United States, a sizeable amount of urban water demand is for irrigating ornamental vegetation. City recreation departments and landscape horticulturists who care for ornamental plants need information about the water requirements of these plants to help these managers schedule the amount and timing of irrigation, and to help them determine which plants use water most efficiently. The crop water stress index (CWSI), based on canopy temperature (T_c), air temperature (T_a), and vapor pressure deficit (VPD) determined from relative humidity measurements, can be used to schedule irrigation of lawns, shrubs, and trees in an urban environment. The CWSI is determined from a measurement of the relative difference between the lower and upper baselines; a "baseline" being the relationship between $T_c - T_a$ and VPD. The lower baseline represents a non-limiting moisture condition for the plant (i.e., non-moisture stress). The upper baseline is constant over a range of vapor pressure deficits and represents the canopy temperature when transpiration is zero.

The rate of water application for non-limiting moisture conditions can be determined by deriving the aerodynamic and canopy resistance from the lower baseline of the CWSI and then, using Fick's Law, calculating the transpiration rate at noon. Assuming clear sky conditions exist, the daily transpiration rate can be calculated using a method described by Jackson et al. (1983). Using estimated water requirements of ornamental plants from the lower baseline of the CWSI, landscape designers can select plants that use the least amount of water per unit area.

The goal of this research was to determine the noontime and daily water requirements of selected ornamental plants. There were two specific objectives: 1) to determine the upper and lower baselines for calculating the CWSI for different ornamental plants, and 2) to determine the aerodynamic and canopy resistance of those plants.

THEORY

Jackson et al. (1981) developed CWSI theory based upon the energy balance equation. O'Toole and Real (1986) took the linear relationship between ($T_c - T_a$) and VPD and Jackson's solution to the energy balance equation, rearranged the two equations, and solved for the aerodynamic and canopy resistance:

$$\bar{r}_{ap} = \frac{\rho C_p a}{\bar{R}_n b(\bar{\Delta} + 1/b)} \qquad (1)$$

where

$\bar{r}_{ap}$ = average aerodynamic resistance, s m^{-1}

and

ρ = density of air, kg m^{-3}
C_p = heat capacity of air, Jkg^{-1} $°C^{-1}$
$\bar{R}_n$ = mean net radiation, W m^{-2}
a = intercept of regression of $T_c - T_a$ vs. vapor pressure deficit, °C
$\bar{\Delta}$ = average slope of the relation between the water saturation vapor pressure and air temperature, kPa $°C^{-1}$
b = slope of the regression equation of $T_c - T_a$ vs. vapor pressure deficit °C kPa^{-1}

and

$$\bar{r}_{cp} = -\bar{r}_{ap}\left[\frac{\bar{\Delta} + 1/b}{\gamma} - 1\right] \qquad (2)$$

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where

$\bar{r}_{cp}$ = average canopy resistance, s m^{-1}
γ = psychrometric constant, kPa $°C^{-1}$.

After $\bar{r}_{ap}$ and $\bar{r}_{cp}$ are calculated from the regression of the lower baseline, the transpiration rate (LE) can be calculated for an assumed radiation, relative humidity, and temperature condition using equation 3 (Campbell, 1977):

$$LE = \rho C_p (e_c^* - e_a) / \gamma (\bar{r}_{ap} + \bar{r}_{cp}) \qquad (3)$$

where

LE = Latent heat flux, W m^{-2}
e_c^* = Saturated vapor pressure at canopy temperature (kPa)
e_a = Vapor pressure of the air (kPa).

Canopy temperature is calculated from air temperature and $T_c - T_a$, which is derived from equation 4 (O'Toole and Real, 1986).

$$T_c - T_a = \frac{r_{ap} R_n}{\rho C_p} \times \frac{\gamma (1 + r_{cp} / r_{ap})}{\Delta + \gamma (1 + r_{cp} / r_{ap})} - \frac{e^*_a - e_a}{\Delta + \gamma (1 + r_{cp} / r_{ap})} \qquad (4)$$

where ea* represents Saturated vapor pressure at air temperature (kPa).

MATERIALS AND METHODS

The study was conducted at New Mexico State University in Las Cruces during the summers of 1986 and 1987. Canopy temperature, air temperature, vapor pressure deficit, and net radiation were determined for the ornamental horticultural plants listed in Table 1. Alfalfa data in Table 1 were reported by Abdul-Jabbar et al. (1985). Most plants were located in open areas; some were within 10 m (30 ft) of a building. The soil type at the different locations is classified bluepoint loamy sand (mixed, thermic Typic Torripsamment). An infrared thermometer (Everest Interscience Model 210) with the emissivity set at 0.98 was used to measure canopy temperature from 10 A.M. to 4 P.M. Tree temperatures were measured at all four quadrants by aiming the thermometer into the center of the canopy. Shrub temperatures were measured east and west, holding the thermometer at a 35° angle below horizontal. The thermometer was connected to an Interface (Inst Model ADC71A) datalogger system, which in turn was connected to a Hewlett Packard 71 personal computer. The data acquisition system sampled canopy temperatures every second for 30 s and recorded the mean and standard deviation of the 30 readings for later analysis. Two, 30-s measurements were taken in the east-west direction and the data averaged.

Canopy temperatures were measured two days after the ornamental shrubs had been irrigated and one day after irrigation for larger trees. To determine vapor pressure deficit, an Assmann psychrometer was used to measure wet and dry bulb temperatures 1 m (3 ft) above the ground and adjacent to the canopy. For all crops lower than 2 m (6 ft) a Fritchen net radiometer was placed 1 m (3 ft) above the top of the canopy. For the large tree crops, net radiation was measured 1 m (3 ft) above an adjacent patch of grass. The upper baseline, representing the temperature of non-transpiring plants, was determined using a branch cut from a shrub or tree and tied in place early in the morning. Measurements of the canopy temperature were taken the next day between noon and 2 P.M. when solar radiation was a maximum. Again, 30 1-s measurements were taken and an average calculated. A single tensiometer was installed next to each plant species, and in all cases it read less than 50 kPa (50 cbar).

TABLE 1. Results of the linear regression of canopy – air temperature and vapor pressure deficit

Name	Scientific Name	Obs #	Slope $°C\,kP_a^{-1}$	Intercept °C	r^2	Statistical Test*
Alfalfa	*Medicago Sativa,L.*		– 1.930	0.96	0.700	
Pecan	*Carya illinoensis*	27	– 0.606	0.429	0.764	a
Red Leaf Plum	*Prunus cerasifera*	19	– 1.140	1.050	0.613	b
Mulberry	*Morus alba*	30	– 0.423	0.332	0.806	c
Honey Locust	*Gleditsia triachanthos inermis*	26	– 0.972	0.947	0.862	d
Modesto Ash	*Fraxinus velutina glabra*	12	– 2.020	2.360	0.932	c
Redbud	*Cercis canadensis*	16	– 1.390	1.770	0.927	f
Bolleana Poplar	*Populus alba 'Pyramidalis'*	8	1.980	2.690	0.944	g
Vitex	*Vitex angus-castus*	25	– 0.960	1.560	0.912	h
Salt Cedar	*Tamarix gallica*	29	– 0.712	1.550	0.666	i
Sycamore	*Platanus acerifolia*	11	– 0.772	1.990	0.677	i
Ash	*Fraxinus*	29	– 0.712	1.550	0.666	i
Aleppo Pine	*Pinus halepensis*	25	– 0.949	2.220	0.824	i
Rosemary	*Rosemarinus officinalis*	23	– 1.410	3.630	0.877	j
Mimosa	*Albizia julibrissin*	25	– 0.377	1.010	0.610	k
Atlas Cedar	*Cedrus atlantica*	30	– 0.604	1.600	0.745	l
Afghan Pine	*Pinuse eldarica*	23	– 0.666	2.470	0.324	m
Hollywood Juniper	*Juniperus chinensis 'Tolurosa'*	30	– 0.543	2.020	0.588	n
Barberry	*Berberis mentorensis*	19	– 0.906	6.610	0.433	o

* Regressions for plants followed by the same letter were not statistically different ($P \leq 0.05$).

RESULTS AND DISCUSSION

Table 1 presents the slopes and intercepts of the linear regressions of vapor pressure deficit versus the differential temperature between the plant canopy and air. A three-point running average was used to compute the regression line (Sammis et al., 1988).

The slopes and intercepts for the lower baseline (Table 1), representing plants under no moisture stress, were analyzed statistically to search for differences in lower baselines between plant types (Ames and Sammis, 1990). Salt Cedar, Sycamore, Ash, and Aleppo Pine showed statistically equal slopes and intercepts (Table 1). Each of the other crops showed a unique non-stressed baseline. There was no grouping of plant materials that exhibited a common baseline. These results are similar to those observed by Idso (1982) for 25 agricultural crops. Idso's baseline data for alfalfa indicates a canopy resistance of 6.47 s m^{-1} using equation 2, with an aerodynamic resistance of 1.96 s m^{-1} using equation 1, assuming a 30° C average temperature and radiation at 600 Wm^{-2} (0.86 Cal cm^{-2} min^{-1}). The baseline data (Table l) from Abdul-Jabbar et al. (1985) indicate alfalfa has canopy resistance of 13.1 s m^{-1} and aerodynamic resistance of 3.6 s m^{-1} at 30° C and radiation at 600 Wm^{-2} (0.86 Cal cm^{-2} min^{-1}) (Table 2). Alfalfa canopy resistance, as would be expected, is lower than that for all of the horticultural crops measured. Salt Cedar, a phreatophyte that would be expected to transpire at a high rate, had a canopy resistance of 69 s m^{-1}. However, the Salt Cedar in this study was growing where the water table was at 30 m (100 ft). Consequently, its transpiration rate was not as high as would be expected under conditions where the ground water level was at or near the root zone.

Measurements have shown pecan trees use 1300 mm (51.1 in.) of water during the growing season, compared to a potential evapotranspiration of 1380 mm (54.3 in.), (Miyamoto, 1983). They represent a high water-use crop and should have a low resistance. The pecan trees in this study had a canopy resistance of 25 s m^{-1} and a low aerodynamic resistance of 1 s m^{-1} (Table 2). These measurements were taken on isolated pecan trees. The lower baseline reported previously by Sammis et al. (1988) for pecans grown in orchards, had a slope of – 0.59° C kPa^{-1}, compared to one of – 0.606° C kPa^{-1} measured in this study (Table 1). However, the intercept measured by Sammis et al. (1988) was 0.03° C, compared to 0.42° C for the pecan trees in the study. Because the data reported by Sammis et al. (1988) were made only at noon, the net radiation was 596 W m^{-2} (0.85 Cal cm^{-2} min^{-1}) and the average temperature was 41.4° C. Using equations 1 and 2, these measurements yield a canopy resistance of 1.63 s m^{-1} and an aerodynamic resistance of 0.08 s m^{-1}. Both are lower than the value measured for the pecan trees grown in the study. Higher resistances for the trees grown in a typical horticulture environment (Sammis et al., 1988) indicate that the trees may be adjusting osmotically to their micro-environment. Future experiments will help to determine whether separate baselines are needed for crops grown as isolated plants.

The Barberry canopy had the highest resistance of 250 s m^{-1}, and was the only plant canopy whose temperature was always above air temperature.

Because $\overline{r}_{ap}$ and $\overline{r}_{cp}$ are calculated from the slope and intercept of the regression of (T_c-T_a) versus VPD, there is some variability associated with the numbers. The higher the coefficient of determination of the lower baseline

TABLE 2. Calculated aerodynamic resistance (r_{ap}), canopy resistance (r_{ap}), net radiation, air temperature, and upper baseline calculated and measured

					Net Radiation			T_c-T_a			
Name	r_{ap} sm^{-1}	r_{ap}* sm^{-1}	r_{cp} sm^{-1}	r_{cp}* sm^{-2}	W m^{-2}	(Cal cm^{-2} min^{-1})	Air Temp °C	Calculated °C	Measured °C	Sd† °C	Ob
Alfalfa	3.6	7.4	13.1	26.8	600.00	0.86	30.00				
Pecan	1.1	3.7	25.5	85.0	539.00	0.77	28.55	0.49	3.03	1.76	8
Red Leaf Plum	2.7	5.3	28.4	55.9	597.88	0.86	1.35	3.10	3.10	1.48	5
Mulberry	0.8	3.3	29.0	116.3	534.07	0.77	0.36	3.01	0.93	0.93	9
Honey Locust	2.8	5.7	32.8	67.6	552.27	0.79	31.87	1.28	2.55	0.70	8
Modesto Ash	8.6	11.7	37.1	50.8	521.24	0.75	24.23	3.72	3.54	1.56	4
Redbud	5.3	4.9	38.8	49.0	585.08	0.84	28.66	2.59	3.08	0.66	6
Bolleana Poplar	13.0	16.9	40.0	55.7	519.81	0.75	30.52	5.62	4.56	1.56	5
Vitex	4.3	7.1	52.9	87.2	573.88	0.82	30.55	2.05	2.26		1
Salt Cedar	4.1	6.7	68.9	126.5	545.38	0.78	29.09	1.85	1.55	0.81	10
Sycamore	4.8	7.2	79.8	119.9	617.75	0.89	29.93	2.45	2.43	0.73	9
Ash	4.1	6.7	76.9	126.5	545.38	0.78	29.09	1.86	2.82	1.56	13
Aleppo Pine	6.8	9.8	84.7	122.8	518.28	0.74	30.48	2.91	2.00	0.15	5
Rosemary	13.4	13.4	85.8	85.6	524.78	0.75	31.96	5.80	3.88	0.15	15
Mimosa	2.4	4.8	95.3	190.0	555.92	0.80	29.32	1.10	1.50	0.44	3
Atlas Cedar	4.3	7.0	97.7	159.5	524.93	0.75	30.09	1.88	1.52	0.86	12
Afghan Pine	6.4	9.0	129.0	182.4	552.70	0.79	29.30	2.92	2.61	1.05	3
Hollywood Juniper	5.3	8.1	137.6	205.9	526.27	0.76	31.79	2.36	2.19	1.37	13
Barberry	17.8	20.7	250.0	291.9	553.68	0.79	27.16	8.17	6.70	1.82	6

* Calculated when 1.0° C was added to the canopy temperature data.

† Standard deviation.

regression equation, the higher the confidence in the calculated $\bar{r}_{ap}$ and $\bar{r}_{cp}$.

An independent test of $\bar{r}_{ap}$ was calculated from the upper baseline using equation 5:

$$T_c - T_a = \bar{r}_{ap} R_n / \rho C_p \qquad (5)$$

The calculated upper baseline was always within ± 3 S.D. of the average measured value for the data in Table 2. Canopy temperature measurements made on Weeping Willow, Cluster Pine, Tam Juniper, Mexican Elder, and Rose resulted in a calculated upper baseline that was substantially different than the measured value. Consequently, the data were assumed to be wrong. If the canopy of a tree is too sparse, then the infrared thermometer will "see" some sky when pointed up into the tree. Conversely, it will "see" some soil if pointed down from above the trees. Measuring the upper baseline and comparing it to the calculated value $\bar{r}_{ap}$ using equation 5 is a way to evaluate the validity of the lower baseline regression data.

Transpiration rates were calculated using equations 3 and 4, where net radiation was 600 W m^{-2} (0.86 Cal cm^{-2} min^{-1}), air temperature 30° C, relative humidity 40%, and the elevation was 1219 m (4000 ft). Under these conditions, the calculated alfalfa transpiration rate was 2018 Wm^{-2} (2.89 Cal cm^{-2} min^{-1}). This rate was unreasonable because it would have resulted in a daily transpiration rate of 23 mm d^{-1} (0.90 in. d^{-1}). It seemed unlikely that there was an error in the temperature data measured with the infrared thermometer, because the thermometer had been calibrated by Everest Inc. before measurements began. Also, after the measurements were made, the calibration was re-checked and showed no change, confirming the accuracy of the temperature measurements.

When Huband and Montieth (1986) made measurements with an infrared thermometer and compared them to the aerodynamic temperatures determined from air temperature profile data, they found that the radiative temperature determined using the infrared thermometer was on average one celsius degree cooler than the aerodynamic temperature. After elaborate testing, Huband and Montieth (1986) concluded: a) differences in temperature measurements were explained by changes in the determination of effective emissivity of a crop at differing viewing angles of the infrared thermometer; and b) with the thermometer held at a 35° angle below the horizon, the effective emissivity of the crop was 0.96 instead of 0.98. They also concluded that the infrared temperature, which represents the integrated temperature of the canopy, depends on the viewing angle of the instrument since the surface of the canopy is hotter than the deeper portions of canopy. However, the aerodynamic temperature represents only a surface temperature. Consequently, an infrared thermometer that senses the deeper portion of the canopy may underestimate the true surface temperature. To correct this, a one degree celsius temperature based on the Huband and Montieth (1986) recommendation was added to the canopy temperature and a new lower baseline determined. Equations 1 and 2 were used to calculate a new $\bar{r}_{ap}$ and $\bar{r}_{cp}$. Using the corrected value of $\bar{r}_{ap}$ and $\bar{r}_{cp}$, the transpiration rate was recalculated. Noontime transpiration rates of alfalfa were 1112 W m^{-2} (1.59 Cal cm^{-2} min^{-1}), Barberry was 272 W m^{-2} (0.39 Cal cm^{-2} min^{-1}) (Table 3).

Using this information in conjunction with day length, it was possible to use a technique by Jackson et al. (1983) to calculate the daily transpiration rate for a clear day. Based on a day length on 30 May, the range of daily transpiration rates varied from 12.9 mm d^{-1} (0.51 in. d^{-1}) for alfalfa to 3.2 mm d^{-1} (0.12 in. d^{-1}) for Barberry (Table 3). The calculated alfalfa transpiration rate was close to the 10.5 mm d^{-1} (0.41 in. d^{-1}) average rate measured for alfalfa using lysimeters during the month of June, which included both clear and cloudy days (Sammis et al., 1979).

The daily transpiration rate is estimated per unit plant area. The volume of water used by the isolated plants must be calculated by integrating the unit transpiration rate over the whole plant surface, which depends on the geometry of the plant and on its location with respect to structures that may shade the plant during part of the day. Table 3 reports transpiration rates from a nonshaded canopy.

The relative transpiration rate – plant transpiration divided by the transpiration of alfalfa – varied from 0.78 for Redbud to 0.24 for Barberry and was 0.38 for Ash-tree (Table 3).

CONCLUSIONS

Infrared thermometry offers a method to determine the canopy and aerodynamic resistance of isolated ornamental plants and to rank them in order of their potential rate of water consumption under non-limiting-moisture conditions. Evapotranspiration under nonsoil moisture

TABLE 3. Calculated midday and daily transpiration rates and relative transpiration using adjusted computed canopy and aerodynamic resistance

Name	Transpiration				
	Noon		Daily		Relative*
	$W m^{-2}$	(Cal cm^{-2}) min^{-1}	$mm D^{-1}$	(in. D^{-1})	
Alfalfa	1112	1.60	12.9	12.9	1.00
Redbud	862	1.24	10.0	10.0	0.78
Real Leaf Plum	780	1.12	9.0	9.0	0.70
Modesto Ash	730	1.05	8.5	8.5	0.66
Honey Locust	678	0.97	7.9	7.9	0.61
Bolleana Poplar	657	0.94	7.6	7.6	0.59
Pecan	584	0.84	6.8	6.8	0.53
Vitex	559	0.80	6.5	6.5	0.50
Rosemary	549	0.79	6.3	6.3	0.49
Mulberry	448	0.64	5.2	5.2	0.40
Sycamore	443	0.64	5.1	5.1	0.39
Aleppo Pine	439	0.63	5.1	5.1	0.39
Ash	425	0.61	4.9	4.9	0.38
Salt Cedar	424	0.61	4.9	4.9	0.38
Altar Cedar	354	0.51	4.1	4.1	0.31
Afghan Pine	326	0.47	3.8	3.8	0.29
Mimosa	297	0.43	3.5	3.5	0.27
Hollywood Juniper	291	0.42	3.4	3.4	0.26
Barberry	272	0.39	3.2	3.2	0.24

* Transpiration of plant / transpiration of alfalfa.

stress conditions can be estimated by using the canopy and aerodynamic resistance, determined from the lower baseline of the CWSI, a solution of Fick's Law, and the energy balance equations. However, adjustments must be made to the baseline by adjusting the infrared temperature to match that of the aerodynamic surface temperature, the true temperature governing the transpiration process at the canopy surface.

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