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Studies on the relationships among moisture tension, microclimate and transpiration rate of container grown *Acer rubrum*

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Abstract

A comprehensive statistical analysis was done to determine the relationship between moisture tension, microclimate variables and transpiration rate of container grown *Acer rubrum* in field conditions using a weighing lysimeter. Multivariable, first and second order regression models with an R^2 of 0.883 and 0.899, respectively, adequately described the effects of climate factors on measured evapotranspiration (ET). Based on the first order linear multiple regression model, most highly correlated climate factors with ET at the 90% confidence level were leaf temperature, media-water tension, and solar radiation. Single-factor, one-way analysis of variance (ANOVA) showed that plant growth medium tension was not highly correlated with ET at the 95% confidence level. Tensions above 12 kPa may have reduced transpiration rate and initiated plant stress as indicated by canopy leaf temperature which temporarily exceeded ambient air temperature during high radiation periods.

Key words:Transpiration, evapotranspiration, tension, *Acer rubrum*, microclimate

Introduction

Evapotranspiration (ET) is the combined total amount of water loss via transpiration and evaporation from the soil and plant surfaces. The transpiration process usually accounts for about 99 % of the water used by plants whereas only 1% of water taken up by the plant is used in metabolic activities (Salisbury and Ross, 1992).

One method of determining water requirements of plants is to measure or predict ET as the major parameter affecting water uptake. When there is sufficient moisture in the soil and stomata are fully open, atmospheric conditions control the transpiration rate. In most ET equations, all microclimate factors (such as ambient temperature, relative humidity, solar radiation, and wind speed) are included in the formula directly or indirectly except moisture conditions since it is normally assumed that there is always available moisture in the root zone for transpiration process (Kirnak, 1998). There is some controversy about effects of soil tension on transpiration process. One thought is that as soil moisture in the root zone is depleted, soil tension will increase and the rate of the transpiration will decrease. The opposing idea is that the rate of water use by plants is independent of the amount of available moisture as long as there is enough moisture above the permanent wilting point (PWP). According to the second concept, the ET occurs at an equal rate until the soil moisture level drops to PWP (Smith, 1985).

In container nurseries, where plants are grown in a small volume of potting medium, root development is highly restricted and frequent irrigation is essential. Because irrigation scheduling is basically done based on depleted moisture in the root zone, the rate of water use by plants and factors affecting this usage should be determined clearly to supply enough irrigation water for an optimum benefit to plants.

In container grown nursery plants, the ET process is assumed to be affected mostly by plant related factors (stage of growth, root zone depth, density), medium characteristics (texture, hydraulic characteristics), and microclimate conditions (vapour pressure deficit (VPD), wind speed, solar radiation) (Kirnak, 1998; Eagleman, 1963). This research was conducted in the field conditions to determine the physical relationship among microclimate conditions (especially medium tension) and transpiration rate of container grown *Acer rubrum.*

Materials and methods

This study was conducted at the Ohio Agricultural Research Development Center (OARDC), Wooster, Ohio, in August and September 1997. The nursery plant used was *Acer rubrum* (Red Maple) acquired as 1.25 m tall "whips" and potted in 26.5 L containers. The trees were at 1.8 x 1.8 m spacing in the gravel surfaced experiment area. The height and diameter of the container were 30 and 35 cm, respectively and the medium depth of soil mix in the container was 20 cm. The schematic of experimental setup is shown in Fig.1.

The potting medium used in the experiment, Metro Mix 510 (The Scotts Company, Marysville, OH), is common to the nursery industry and recommended for its good physical and chemical characteristics. It is especially noted for excellent aeration and rapid water percolation. It is also compatible with drip emitters and the microirrigation systems. The general ingredients of the growing medium are composted pine bark (20-45%), horticultural vermiculite (15-30%), Canadian sphagnum peat moss (25-35%), and processed bark ash (5-25%). The dry bulk density of the medium is estimated by the manufacturers to be 0.24 – 0.32 g/cm^3. A slow release fertilizer called Osmocote (8-9 month) was used to fertilize the plants and the N-P-K ratio of the Osmocote was 18:6:12.

Since salinity levels of irrigation water and potting medium may affect ET, the nutrient content of the growing medium was analyzed and results show that the salinity level of the medium was normal based on its pH (pH=7.2) and electrical conductivity (EC=3.0 mmho/cm). According to normally accepted standards, a normal soil must have a pH between 6.5 and 7.2 and an EC value less than 4 mmho/cm (Brady, 1990). The water source for irrigation was local city water with a pH and soluble salts (electrical conductivity) of 7.2 and 0.53 mmhos/cm, respectively. This range of pH and EC for the irrigation water was within acceptable water quality standards with a pH between 6.5 - 8.4 and an EC value less than 0.75 mmhos/cm (Hoffman, 1983).

Meteorological data (ambient temperature, wind speed, wind direction, relative humidity, barometric pressure, and radiation) were obtained from an automatic recording weather station located adjacent to the nursery growing area. All measurement sensors on the weather station were connected to a Q-COM control system and stored into GEM3V2 software at 15 minutes interval continuously. Rainfall was measured manually using rain gages located at three different places in the experimental area.

A Q-COM Inc., Irvine, CA computer controlled micro-irrigation system with GEM3V2 software was used to sense the medium tension. In the experiment, potting media tension was allowed to go up to 21 kPa in seven different tension increments (0-3, 3-6, 6-9, 9-12, 12-15, 15-18, and 18-21 kPa). Irrigation was done manually by considering the tension levels and observing cumulative water loss with the weighing lysimeter. Sampling interval for medium tension was 15 minutes. Hourly average values were used to represent medium tensions in the statistical analysis.

In order to measure ET, A SATORIUS F330S automatic weighing scale with an accuracy of ±1 g was placed beneath one of the tree containers. The lysimeter readings were recorded in print and cassette by using a Kaye DIGISTRIP III datalogger. Instantaneous weight readings were also displayed digitally in grams by the SATORIUS A/D converter. Besides climate variables and potting medium tension, soil temperature and leaf temperature were also collected to evaluate the potential effects of each on transpiration rate. The leaf temperature was measured from upper, middle and bottom parts of the plant and averaged. Each leaf temperature was measured using type T thermocouples of 0.127 mm diameter inserted into the central veins at the underside of the leaf. Since the thermocouples were easily pulled from the vein due to the effect of wind, an adhesive band was used for holding them in place. The datalogger recorded leaf and medium temperature readings in 15 minutes intervals.

The potting medium temperature was measured at two different depths within the root volume. Two potting medium temperature sensors were 9 ± 0.5 cm deep and 18 ± 0.5 cm deep and averaged. The soil temperature sensors were type T ungrounded, 1/8² stainless steel probes. These sensors were calibrated with ice in the lab before the experiment. Each tensiometer was calibrated before use by using a long plastic u-tube, and a meter stick using a C-clamp (Fig.2). After the u-tube was filled with water, one end was attached securely to the pressure transducer in order to prevent leakage in the seal between the tube and the transducer. Then, the differential water head readings from u-tube and Q-COM controller were matched to each other. If there was no match between these two readings, adjustments were made on the Q-COM software or the tensiometer was discarded.

In order to determine leaf area index (LAI), a total of 10 leaves were removed from different parts of the plant and then measured as a basis for determining the average leaf area. An electronic areameter was used to measure each sample leaf. The areameter was calibrated based on known areas of metal plates. The horizontally projected area of the plant was calculated assuming a rectangular shape, resulting in a LAI of 1.58.

Results and discussion

Multiple linear regression analysis: In order to evaluate individual and combined effects of climatic factors on the measured ET, linear multiple regression analyses were done with Minitab (Release 12.1, by Minitab Inc.). Since there were three different levels of leaf temperature and two levels of potting medium temperature, average values were used to represent leaf and potting medium temperatures in the statistical analysis.

In the first order regression model, there were seven input parameters with an $R^2 = 88.4\%$ where:

Measured ET = -3.78 + 0.370 (ambient temperature) – 0.0798 (relative humidity) + 0.186 (radiation) + 1.04 (average leaf temperature) – 0.233 (tension) – 0.274 (average potting medium temperature) – 1.07 (windspeed) (1)

Table 1 shows the result of this statistical analysis and indicates that the average leaf temperature, soil temperature, ambient temperature, and relative humidity were nonsignificant at 90%

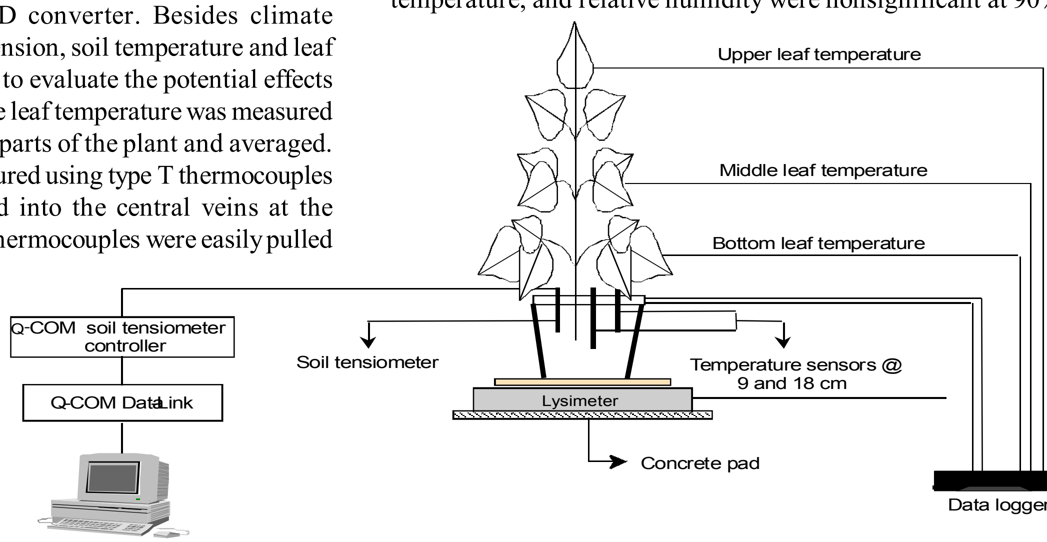


Fig. 1. Schematic drawing of instrumental setup for Red Maple

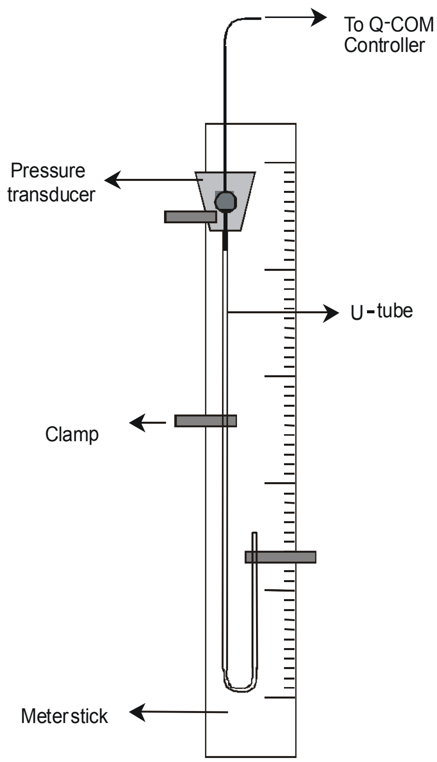


Fig. 2. Calibration of the tensiometer by aid of Q-COM controller

Table 2. Partial regression coefficients for a first order model including possible input variables related to measured ET.

Predictor	Coefficient	Stdev	t-ratio	P value
Constant	-50.80	27.58	-1.84	0.066
Ambient temp.	-7.06	2.678	-2.64	0.008
Relative humidity	0.47	0.281	1.66	0.097
Radiation	0.19	0.021	9.06	0.000
Windspeed	-17.55	5.448	-3.22	0.001
Av. leaf temp.	7.72	2.768	2.79	0.005
Tension	-0.52	0.452	-1.16	0.246
Av. potting medium temp.	3.72	1.297	2.87	0.004
Ambient temp. * Windspeed	0.77	0.163	4.72	0.000
Ambient temp. * Tension	0.13	0.032	3.92	0.000
Ambient temp. * Av. potting medium temp.	0.28	0.128	2.20	0.028
Relative humidity * Windspeed	0.17	0.053	3.12	0.002
Relative humidity * Av. potting medium temp.	-0.03	0.012	-2.74	0.006
Radiation * Windspeed	-0.01	0.004	-3.32	0.001
Radiation * Tension	-0.01	0.000	-7.82	0.000
Radiation * Av. potting medium temp.	0.00	0.000	1.98	0.048
Windspeed * Tension	0.67	0.104	6.43	0.000
Windspeed * Av. potting medium temp.	-0.56	0.137	-4.09	0.000
Av. leaf temp. * Av. potting medium temp.	-0.32	0.133	-2.40	0.017
Tension * Av. potting medium temp.	-0.07	0.029	-2.44	0.015

confidence level. Beginning with ambient temperature, nonsignificant terms were eliminated one by one from the model and a new regression model was set up each time till all variables in the model became significant at a 90% confidence level. By doing this backward elimination, the final simple first order model was obtained in equation (2) with R^2 = 88.3%. The result of this reduced first order model is shown in Table 1. Since the R^2 value of equation (1) is only a little larger than the R^2 values of equation (2), it is preferred to use the equation (2), which is a much simpler model where:

Measured ET = -13.9 + 0.190 (radiation) + 1.19 (average leaf temperature) - 0.214 (tension) (2)

Eq. 2 indicates that a good multiple linear regression model can estimate ET using radiation, leaf temperature and potting medium tension. Since a second order regression analysis can show the interactions among the variables in the model, it was performed with a resulting regression coefficient of R^2 = 90.0%. A similar procedure for establishing a final model of second ordered measured ET was followed eliminating nonsignificant terms. The result of the backward elimination procedure for the second ordered model resulted in equation (3) with R^2 = 89.9%. The equation (3) represents the full model for ET and Table 3 shows the results of this procedure.

Measured ET = - 50.8 – 7.06 (ambient temp.) + 0.468 (relative humidity) + 0.191 (radiation) – 17.5 (windspeed) + 7.71 (av. leaf temp.) – 0.524 (tension) + 3.72 (av. potting medium temp.) + 0.769 (ambient temp. * windspeed) + 0.126 (ambient temp.* tension) + 0.282 (ambient temp. * av. potting medium temp.) + 0.165 (relative humidity * windspeed) - 0.0336 (relative humidity * av. potting medium temp.) - 0.0128 (radiation * windspeed) - 0.00519 (radiation * tension)+ 0.00169 (radiation * av. potting medium temp.) + 0.668 (windspeed * tension) - 0.560 (windspeed * av. potting medium temp.) - 0.319 (av. leaf temp.* av. potting medium temp.) - 0.0721 (tension * av. potting medium temp.) (3)

By comparing the R^2 values of the first and second order regression models, it was concluded that the effects of interactions to the model did not make the model better. Therefore, it was assumed to be better to use a simple first order regression model requiring less input variables.

Correlation (r) among the variables presented in Table 3 show that there was high correlation (0.989) between leaf temperature and ambient temperature indicating that the ambient temperature can be used instead of leaf temperature for similar conditions. Table 3 also shows that there were significant correlations among VPD, radiation and measured ET making a VPD and radiation model a very practical solution for ET estimates. For this purpose,

Table 1. A first order model with seven variables

Predictor	Coefficient	Stdev	t-ratio	P value
Constant	-3.78	6.707	-0.56	0.573
Ambient temp.	0.37	0.763	0.48	0.628
Relative humidity	-0.08	0.061	-1.31	0.191
Radiation	0.19	0.005	39.85	0.000
Av. leaf temp.	1.04	0.738	1.41	0.158
Tension	-0.23	0.093	-2.51	0.012
Av. medium temp.	-0.27	0.177	-1.55	0.122
Windspeed	-1.07	0.513	-2.09	0.037
A reduced first order model with three variables				
Constant	-13.89	2.476	-5.61	0.000
Radiation	0.19	0.013	60.29	0.000
Av. leaf temp.	1.20	0.143	8.39	0.000
Tension	-0.25	0.089	-2.40	0.017

Table 3. Partial regression coefficients for a reduced second order model with seven variables related to measured ET.

	Measured ET	Ambient temp.	Relative humidity	Radiation	Wind speed	Leaf temp.	Tension	Medium temp.
Ambient Temp.	0.682							
Relative humidity	-0.708	-0.526						
Radiation	0.935	0.660	-0.752					
Windspeed	0.383	0.295	-0.373	0.424				
Leaf temp.	0.698	0.989	-0.532	0.678	0.306			
Tension	0.028	0.026	-0.185	0.056	-0.044	0.040		
Medium temp.	0.129	0.586	-0.185	0.087	0.006	0.550	0.091	
VPD	0.827	0.707	-0.922	0.850	0.362	0.716	0.158	0.318

equation (4) was obtained with an R^2 = 87.8% by performing a multiple regression analysis where:

Measured ET = 2.16 + 0.185 (radiation) + 0.0125 (VPD) (4)

In order to compare regression models using only VPD-measured ET and radiation-measured ET, a simple linear regression analysis was performed where:

Measured ET = -0.17 + 0.0898 (VPD) (5)

Measured ET = 4.05 + 0.207 (radiation) (6)

The equations 5 and 6 predicted the ET with a R^2 = 68.4% and R^2 = 8.5% respectively. The statistical analysis results of these linear regression models are shown in Table 4.

Table 4. Correlation coefficients between input variables and measured ET

Statistical result of a multiple linear regression model that relates solar radiation, and VPD to measured ET.

Predictor	Coefficient	Stdev	t-ratio	*p* value
Constant	2.17	0.778	2.78	0.006
Radiation	0.19	0.004	41.51	0.000
VPD	0.01	0.002	5.73	0.000

Statistical result of the simplified linear regression model that relates only solar radiation to measured ET.

Predictor	Coefficient	Stdev	t-ratio	*p* value
Constant	4.05	0.715	5.66	0.000
Radiation	0.21	0.002	86.74	0.000

Statistical result of the simplified linear regression model that relates only VPD to measured ET.

Predictor	Coefficient	Stdev	t-ratio	*p* value
Constant	-0.17	1.251	-0.14	0.892
VPD	0.09	0.002	48.28	0.000

In general, the second order multiple regression analysis did not make the model significantly better according to the R^2 values. So, for simplicity, it was assumed better to use a first order, multiple regression model instead of the second order multiple regression model.

Table 3 shows that tension levels used in this experiment did not show significant correlation with transpiration. However, the results of a multiple linear regression analysis (Eq. 2) showed that tension was a significant variable as part of the overall system. Devore and Peck (1993) stated that since the correlation was done by comparing only two variables, the correlation coefficient alone may not always show the significant level of an input variable in a model. The correlation simply shows the strength of association between two variables. There is no prediction from one variable to another and there is no distinction between dependent and independent variable in the correlation. However, the multiple regression analysis shows the partial contribution of each variable in the model to the system response. So, a nonsignificant variable in the correlation could be potentially a significant variable in the multiple regression analysis since the multiple regression analysis considers each possible variable in the system and its partial contribution to the model response.

In order to evaluate the effects of different tension levels on measured ET, a single-factor, one-way analysis of variance test was performed excluding all night time transpiration data. The tension values had seven different ranges between 0 and 21 kPa as shown in Table 5 and statistical result of this analysis is shown in Table 6.

In the first order multiple linear regression analysis, it was found that the tension was significant at a 90% confidence level. The single-factor ANOVA analysis excluding all night time data indicated that the tension levels were not significant at a 95% confidence level. A plot of tension levels with measured ET is shown in Fig. 3 with related standard errors.

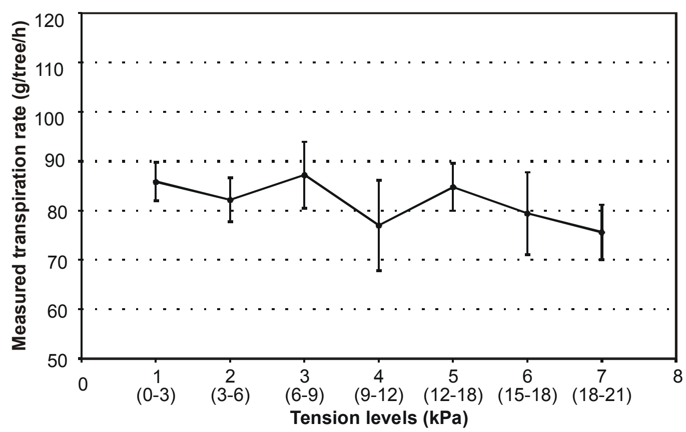


Fig. 3. Mean transpiration rate and standard error for different tension level treatments (excluding all night time data).

In the experiment, potting medium tension levels were maintained between 0-21 kPa values. The experimental results however show that these tension levels should have been beyond 25 kPa to potentially observe a negative effect of tension levels on transpiration. In order to further evaluate the effect of the tension levels on transpiration rates, data were selected for some specific days whose tension values and solar radiation were relatively high (Fig. 4 and 5). A visual observation from these figures showed that there was no apparent effect of high-tension values on transpiration rates during the early morning and late night. However, the effect of the high-tension on transpiration rate was observed by the canopy temperature rising above the ambient temperature in late afternoons. These figures indicate that effect of medium tension on transpiration rate under field conditions is directly related to the intensity of the microclimate factors. Negative tension slope in Fig. 5 shows the effect of

Table 5. Statistical results of the linear regression model that relates solar radiation, VPD and both to measured ET

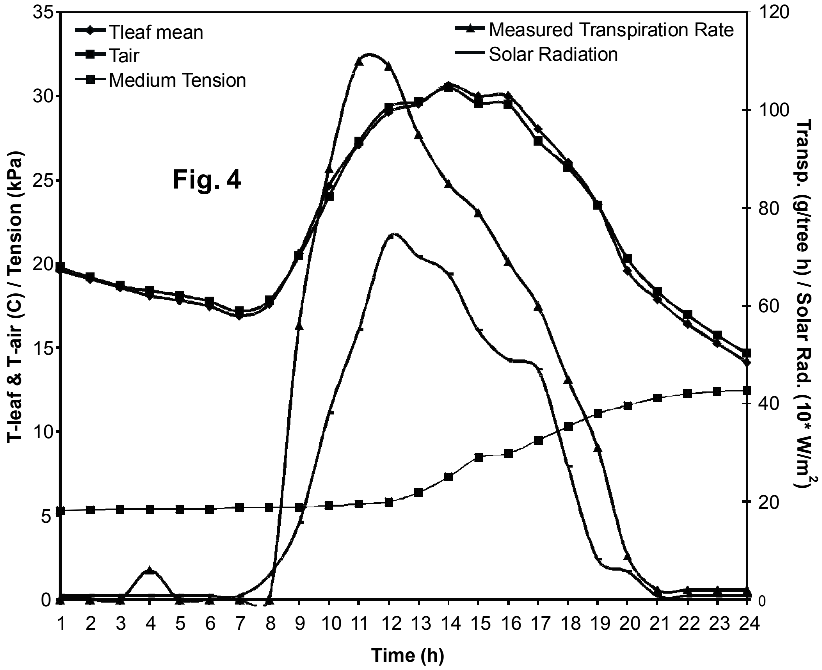
Tension Levels	Tension range (kPa)	N	Mean transpiration rate(g/tree h)	Standard Error
1	0-2.99	178	85.84	3.894
2	3-5.99	109	82.17	4.466
3	6-8.99	58	87.19	6.748
4	9-11.99	26	77.00	9.117
5	12-14.99	43	84.79	4.836
6	15-17.99	32	79.41	8.330
7	18-20.99	37	75.62	5.537

Table 6. Mean, standard error of mean, and number of the observation values of different tension classes in the single-factor ANOVA analysis (excluding all night time data)

Source	DF	SS	MS	F	*p*
Tension levels	6	5958	993	0.44	0.851
Error	476	1069207	2246		
Total		482	1075165		

irrigation.

Using a first order linear regression model was more practical than using a second order model since the more complex second order model did not significantly improve the R^2 of the ET model. The first order linear regression analysis showed that at 90% confidence level, the most important input climate factors affecting ET were media-water tension, average leaf temperature, and solar radiation. The second order linear regression analysis showed that interactions between windspeed and ambient temperature, windspeed and medium tension, were the most significant factors affecting ET at 90% confidence level. Single-factor ANOVA and visual observation from data showed that the medium tension was not highly correlated with ET under available tension levels used in the experiment. The driving microclimate conditions for ET play an important role in the determination of the role of the medium tension on transpiration rate under near field capacity conditions.



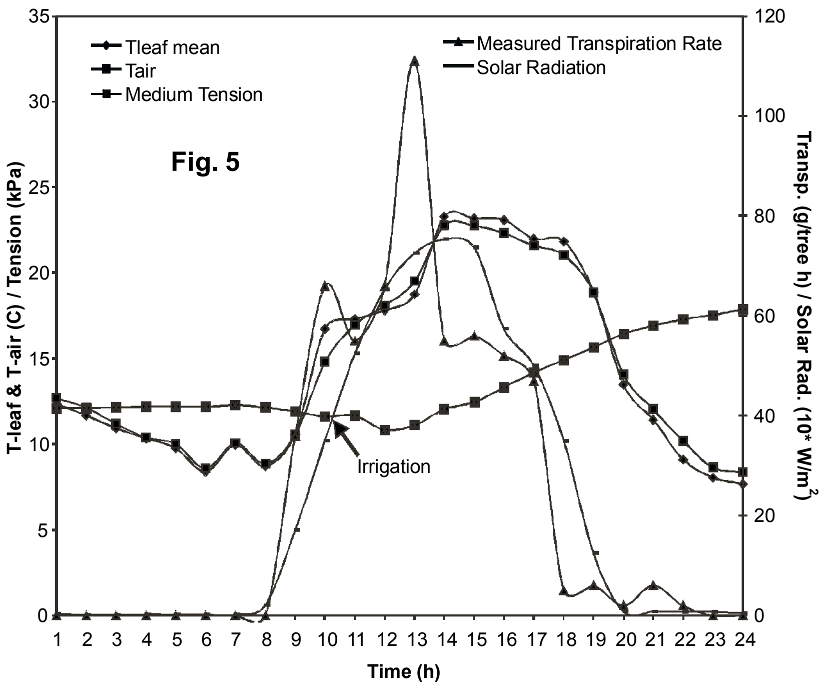


Fig. 4. Air and leaf temperature differences along with transpiration rate and relatively high-tension values for a clear day (8/27/97).

Fig. 5. Air and leaf temperature differences along with transpiration rate and relatively high tension values for a clear day (9/25/97).

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