Black Locust Transpiration Responses to Soil Water Availability as Affected by Meteorological Factors and Soil Texture

WU Yuan-Zhi1,2, HUANG Ming-Bin2,∗ and David N. WARRINGTON2

1 Shandong Provincial Key Laboratory of Water and Soil Conservation and Environmental Protection, Linyi University, Linyi 276000 (China)
2 State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest A&F University, Yangling 712100 (China)

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ABSTRACT

On the Loess Plateau of China, a dry soil layer may form due to excess transpiration, leading to degradation of black locust (Robinia pseudoacacia) stands. In order to better manage projects involving black locust, this study was intended to investigate the response of black locust transpiration rate to soil water availability as affected by meteorological factors using two representative soils (loamy clay and sandy loam) on the Loess Plateau. Four soil water contents were maintained for black locust seedlings grown in pots initially outdoors and then in a climate-controlled chamber, by either drying or irrigating the pots. In both environments, daily transpiration rates were related by a power function to air temperature and by a logistic function to reference evapotranspiration (ET0). Transpiration rates were more susceptible to changes in the meteorological conditions in the sandy loam than in the loamy clay soil. The transpiration rate in the well-watered treatment was greater for black locust grown in the sandy loam than in the loamy clay soil. Normalized transpiration rates were unaffected by ET0 until a critical value of soil water content (θc) was attained; the θc value decreased significantly for the loamy clay soil but increased significantly for the sandy loam soil when ET0 increased. These suggested that the effect of the meteorological condition on the transpiration characteristics of black locust was dependent on soil texture.

Key Words: dry soil layer, evaporative demand, loamy clay, Loess Plateau, reference evapotranspiration, sandy loam, temperature, vapor pressure deficit

INTRODUCTION

In the semi-arid Loess Plateau region of China, aridity and severe soil erosion are two important environmental issues. Large-scale vegetation restoration projects have been implemented by the government since the 1950s as part of the measures to control soil erosion (Fu et al., 2002). However, planting non-indigenous vegetation, especially black locust (Robinia pseudoacacia), has resulted in the development of a permanent “dry soil layer” at depth, which may have adverse effects on the trees that are dependent in part on deep soil water (Wang et al., 2005). The dry soil layer is formed as a result of the excessive depletion of deep soil water by vegetation evapotranspiration combined with long-term insufficient amounts of rainfall that would facilitate soil water recharge (Chen et al., 2007). Severe water limitations during seedling establishment are also problematic and have been related to soil texture (Ceacero et al., 2012). Therefore, knowledge of the transpiration properties of black locust in response to soil water deficits in different soils, which in turn may be exacerbated by the trees’ behavior, is essential when managing vegetation restoration projects that include this species.

Plant transpiration responses to soil drying have been studied extensively, and several studies have found a consistent relationship whereby plant transpiration does not decrease until a threshold or critical value of soil water content (θc) is attained (Sadras and Milroy, 1996), below which transpiration declines more or less linearly with further soil drying. Either a linear-plateau equation with a turning point (the threshold value) or a logarithmic function has been used to represent the response of plant transpiration to soil drying (Soltani et al., 2000; Wahbi and Sinclair, 2007).

The response of plant transpiration to soil water deficit is influenced by many factors, such as plant type, soil texture, and meteorological conditions (Sadras and Milroy, 1996). Based on studies on the
effect of soil water content on gas exchange, Robertson and Fukai (1994) found that for *Sorghum bicolor* (L.) Moench, $\theta_e$ was higher for a clay soil than for a sandy soil, and Wahbi and Sinclair (2007) found that for *Arabidopsis thaliana*, maize (*Zea mays*), and soybean (*Glycine max* L.), $\theta_e$ was much higher for a peat moss mixture than for a sandy loam soil. However, in experiments using either a pot mix or a clay loam soil, Muchow and Sinclair (1991) reported that $\theta_e$ was not affected by soil texture. Denmead and Shaw (1962) found that $\theta_e$ increased with evaporative demand for maize grown in a silty clay loam. However, although evaporative demand might be related to other factors including vapor pressure deficit (VPD), Ray et al. (2002) and Fletcher et al. (2008) found that the response of plant transpiration to declining fraction of transpirable soil water was consistent for maize grown in a sandy loam soil and soybean grown in a loam soil regardless of VPD. Using a mathematical model for water transfer in the soil-plant-atmosphere continuum, Bailey and Spackman (1996) and Novák et al. (2005) showed that the value of $\theta_e$ was influenced by both the evaporative demand and soil texture. Experiments on winter wheat were consistent with these findings (Wu et al., 2011). Specific and genotypic differences may also affect the transpiration response to meteorological conditions. Stomatal control of species exhibiting anisohydric behavior (sunflower, wheat, and barley) is independent of evaporative demand and leaf water status; in contrast, stomatal control of species exhibiting isohydric behavior (maize and poplar) is dependent on both evaporative demand and leaf water status (Tardieu and Simonneau, 1998). Moreover, Hacke et al. (2000) and Ewers et al. (2005) showed substantial differences in the hydraulic properties of *Pinus taeda* trees growing in a loamy soil as compared with a sandy soil, which were due to the differences in water extraction from the two soils. Therefore, water extraction was mainly affected by soil texture and evaporative demand.

Traver et al. (2010) found that VPD rather than pedologic conditions had a greater influence on the spatial variability of tree transpiration. Engel et al. (2004) found that the transpiration responses of *Populus deltoides* to VPD were different for high ($>0.35$ cm$^3$ cm$^{-3}$) and low water ($<0.30$ cm$^3$ cm$^{-3}$) contents at the 20-cm soil depth. Perez-Martin et al. (2009) investigated the interactive effects of soil water deficit and air VPD on the mesophyll conductance ($g_m$) and stomatal conductance ($g_s$) of CO$_2$ and found that changes in $g_m/g_s$ were more related to VPD for *Olea europaea* and to soil water deficit for *Vitis vinifera*. Furthermore, results of Schulze et al. (1973) showed that the transpiration of three wild plants and one cultivated plant grown under desert conditions increased with temperature at low water stress, but decreased with temperature at high water stress, both cases being independent of atmospheric humidity. Sellin et al. (2008) showed that the leaf hydraulic conductance of *Betula pendula* depended on both light duration and density. Transpiration decreased with light density for soybean (Fay and Knapp, 1998), but increased with light density for citrus trees (Cohen et al., 1997). Therefore, the responses of transpiration to meteorological factors may be different under different soil water conditions.

Although there have been some studies on water-use characteristics of black locust (*e.g.*, Sinclair et al., 2005b; Wang et al., 2010), little work has been carried out on the effects of meteorological conditions such as VPD and temperature on its transpiration responses to soil water availability. Thus, the mechanism of the transpiration response to VPD of black locust under drought conditions is currently unclear. Therefore, the objective of this study was to evaluate the adaptability of black locust grown on the Loess Plateau by investigating its transpiration rate responses to soil water availability as affected by air temperature, VPD, and evaporative demand when grown in two soils of different textures, in order to provide important information for the management of vegetation restoration in this region.

**MATERIALS AND METHODS**

**Experimental site and soils**

This study was conducted at the Institute of Soil and Water Conservation, Chinese Academy of Sciences & Ministry of Water Resources, in Yangling County of Shaanxi Province, China. The institute is located at $34^\circ 20'\ N$ and $108^\circ 24'\ E$, at an elevation of 521 m above mean sea level. The climate is sub-humid with a mean annual daily temperature of 12.9 °C and a mean annual precipitation of 630 mm, falling mainly during July through September. The maximum and minimum temperatures are 41.6 and $-16.7$ °C, respectively. The maximum and minimum relative humidities are 99% and 14%, respectively. The mean frost-free period is 221 d and the annual potential evaporation is 750 mm (Kang et al., 2003).

Soils used were a Lou soil (Anthrosol, FAO, 2006) and a Huangmian soil (Calcaric Cambisol, FAO, 2006) collected from Yangling and Shenmu counties, Shaanxi Province, respectively. These two soil series are representative of the soils on the Loess Plateau (Zhu, 1989).
Soil particle-size distribution and texture (Table I) were determined according to the FAO classification system (FAO, 2006).

Water desorption curves of the two soils were determined by the pressure plate method (Smith and Mullins, 1991) at increasing pressures of 10, 20, 40, 60, 80, 100, 400, 600, 800, 1000, 1200, and 1500 kPa. Disturbed soils were first passed through a 2-mm sieve and then packed into a ring, which was placed on the pressure plate, to obtain bulk densities of 1.35 and 1.30 g cm\(^{-3}\) for the loamy clay and sandy loam soils, respectively. Corresponding soil water contents were determined by mass loss that was measured once equilibrium was reached. Saturated hydraulic conductivity, \(K_s\), was determined by the constant head method (Stolte, 1997) with disturbed soils. Unsaturated soil hydraulic properties were characterized using the model of van Genuchten (1980). For each of the two soils, the model was fitted to the experimental data and the model parameters were obtained using the RETC software (van Genuchten et al., 1991). The relationships between the unsaturated hydraulic conductivity and soil water content (\(\theta\)) are shown in Fig. 1.

**Pot experiment**

A pot experiment was conducted using black locust seedlings initially grown in nursery beds in the institute in three sequential steps: outdoors beneath a glass-roofed rain shelter, which isolated the plants from rainfall, then in a climate-controlled chamber, where temperature and humidity could be regulated, and finally under the outdoor shelter again. Black locust seedlings were grown individually in 24 plastic pots with a hole in the base for drainage. Twelve pots were packed with 10 L of the loamy clay soil at a bulk density of 1.35 g cm\(^{-3}\) and another 12 pots were packed with 10 L of the sandy loam soil at a bulk density of 1.30 g cm\(^{-3}\). In order to avoid soil crusting, irrigation water was provided through a tube (20 mm inner diameter) inserted in the surface soil to a depth of 17 cm. Twenty five grams of NPK fertilizers (18:12:20) were mixed with the soil before packing to supply enough nutrients for the tree seedlings, and the soil surface was covered with a 2.5-cm thick layer of perlite (80 g) to reduce soil water evaporation. Two-year old black locust seedlings with similar heights were selected from the nursery and were transplanted into the pots on June 9, 2009 and all the branches and leaves were removed. The field capacities (\(\theta_{fc}\)) of the loamy clay and sandy loam soils were determined by the modified Wilcox method (Hanks et al., 1954). Permanent wilting point (\(\theta_{pwpl}\)) values were determined by growing and wilting black locust seedlings in each of the two soils, in three replicates (pots). These values are given in Table I.

### Table I

<table>
<thead>
<tr>
<th>Soil</th>
<th>Sand (&gt; 20 µm)</th>
<th>Silt (2–20 µm)</th>
<th>Clay (&lt; 2 µm)</th>
<th>Bulk density</th>
<th>Field capacity</th>
<th>Permanent wilting point</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lou (Anthrosol)</td>
<td>460</td>
<td>285</td>
<td>255</td>
<td>1.35</td>
<td>0.287</td>
<td>0.109</td>
<td>Loamy clay</td>
</tr>
<tr>
<td>Huangmian</td>
<td>783</td>
<td>149</td>
<td>68</td>
<td>1.30</td>
<td>0.224</td>
<td>0.057</td>
<td>Sandy loam</td>
</tr>
</tbody>
</table>

![Fig. 1](image-url)  
Fig. 1 Soil suction (a) and hydraulic conductivity (b) as a function of soil water content for loamy clay and sandy loam soils. \(\theta_{fc}\) and \(\theta_{pwpl}\) represent the field capacities, and \(\theta_{pwpl}\) and \(\theta_{pwpl}\) represent the permanent wilting points of the loamy clay and sandy loam soils, respectively.
in Table I. Available soil water content (ASW) remaining in the soil was calculated by:

\[
\text{ASW} = \frac{\theta - \theta_{\text{prp}}}{\theta_{\text{fc}} - \theta_{\text{prp}}} \tag{1}
\]

All the pots placed randomly beneath the rain shelter had been irrigated regularly to keep the soil water content above 60% of field capacity for almost one year since June 9, 2009 and were irrigated to field capacity on May 24, 2010. Then, four water treatments, in three replications, were applied by either drying or irrigating different pots for the first and second steps of the experiment. The maximum established soil volumetric water contents were 100% (W1), 80% (W2), 65% (W3), and 50% (W4) of field capacity for the loamy clay soil and 100% (W1), 80% (W2), 65% (W3), and 40% (W4) of field capacity for the sandy loam soil. This resulted in ranges in soil water contents during the drying periods of 72%–100% (W1), 62%–80% (W2), 54%–65% (W3), and 37%–50% (W4) of field capacity for the loamy clay soil and 64%–100% (W1), 55%–80% (W2), 39%–65% (W3), and 25%–40% (W4) of field capacity for the sandy loam soil. The black locust plants grown in either soil often wilted in Treatment W4. On June 2, 2010, all the desired water contents were attained and were subsequently maintained by adding water to compensate for water losses at intervals ranging from one to three days until July 11, 2010.

On July 12, 2010, all the pots were moved into the climate-controlled chamber and placed randomly within it for the second step of the pot experiment. Overhead lighting, a humidifier, a dehumidifier, and an air-conditioner regulated the environmental conditions in the climate-controlled chamber in order to keep the temperature and humidity at a prescribed level. An air circulator blower fan ensured the uniformity of conditions in the chamber. The overhead lighting provided 12 hours of simulated sunlight each day, with a quantum flux density (400–700 nm) of 900 ± 100 μmol mm⁻² s⁻¹ at the top of the plants. Temperature and relative humidity were both set at two different levels to create four combinations of meteorological conditions that were applied sequentially. The day/night temperatures were 35/28 °C (high) or 27/22 °C (low) and the relative humidity during the whole day was 40% (low) or 80% (high). The sequence of applied meteorological conditions was: high temperature and low humidity (HL) (July 17 to 21); high temperature and high humidity (HH) (July 21 to 27); low temperature and low humidity (LL) (July 27 to August 1); and low temperature and high humidity (LH) (August 2 to 6). Every day, between 16:30 and 17:00 during the first and second steps of the experiment, all the pots were weighed and irrigated to maintain the water regimes; pan evaporation during the drying interval was also determined at that time from a pan (20 cm inner diameter) placed near the pots. Temperature, relative humidity, and VPD in the climate-controlled chamber were measured by a temperature and humidity sensor mounted at a height of 1.5 m above the base of the chamber. All the pots were returned to the rain shelter on August 7, where they were weighed and watered daily for five days to maintain the water content close to field capacity as the third step of the experiment.

Data calculation and statistical analysis

Volumetric water contents (θ_v) of each pot for each drying interval were calculated by multiplying the known bulk density (D) by the gravimetric water contents (θ_g). θ_v was obtained by dividing the mass of water (M_w) by that of the dry soil (M_s) in a pot. M_w in a pot was calculated by subtracting the mass of the fresh plant material and the known masses of the empty pot, layer of perlite, water supply tube, and dry soil from the weight of the pot with its contents. The mass of the fresh plant material was estimated at the end of the experiment. The daily increase of plant mass in each pot was negligible compared with the variation in the soil water content. The mean volumetric water content for each water treatment was calculated from the θ_v of the three replicates. The volumetric water content of each water treatment was calculated by:

\[
\theta_v = \theta_g \times D = \frac{M_w}{M_s} \times D \tag{2}
\]

For any drying interval, water consumption (W) was calculated as the product of the difference between the mass of the pot at the beginning (M_i) and that at the end (M_i+1) of the i'th interval and the mass of water added at the beginning of the interval (M_w).

\[
W = M_i - M_{i+1} + M_w \tag{3}
\]

The daily transpiration rate (TR) was calculated as the mean daily water consumption over each drying period; i.e., the daily transpiration rate for each drying period was calculated by dividing water consumption (W) by the days (d) in the drying period:

\[
\text{TR} = \frac{W}{d} \tag{4}
\]

The mean daily transpiration rate was determined from the three replicates for each water treatment. The reference evapotranspiration (ET₀) in the first part
of the experiment was calculated using the Penman-Monteith equation with alfalfa as the reference crop (Allen et al., 1998). The climatic factors such as temperature, relative humidity, sunshine hours, and VPD were obtained from a meteorological station situated about 200 m from the pots. The relationship between pan evaporation and ET₀ was determined using regression analysis. ET₀ in the climate-controlled chamber was estimated from the derived relationship between the pan evaporation and calculated ET₀ from the first step of the experiment.

The relationships between the various climatological factors and the daily transpiration rate of black locust grown under four water treatments in the two soils were determined by regression analysis. Differences in daily transpiration rate among the water treatments were analyzed by one-way analysis of variance (ANOVA) using a significance level of $P < 0.05$.

As proposed by Ray and Sinclair (1997), daily transpiration was normalized to account for changing meteorological conditions and differences in initial plant sizes among the water treatments. Thus, for a given water treatment and soil, the relative transpiration rate of the three replicates was estimated by dividing the measured transpiration rate of that treatment by the measured transpiration rate of the well-watered treatment (W1) for that soil for a given time. The normalized transpiration rate (NTR) was obtained by dividing the relative transpiration rate by the mean relative transpiration, which had been determined during the period when all treatments were well-watered in the beginning of the first step of the experiment and in the third step of the experiment. Following the method of Denmead and Shaw (1962), the NTR values of all pots were grouped in classes of ET₀, which included those calculated by the Penman-Monteith equation (Allen et al., 1998) and those estimated from the relationship between pan evaporation and the calculated ET₀. When the plants were grown outdoors, the ET₀ values ranged from 1.27 to 5.19 mm d⁻¹, and the results for this step of the experiment were analyzed considering ET₀ as an evaporative demand class variable at three levels: low (ET₀ < 3 mm d⁻¹), medium (3 mm d⁻¹ ≤ ET₀ < 4 mm d⁻¹), and high (ET₀ ≥ 4 mm d⁻¹). In the climate-controlled chamber step of the experiment, the ET₀ values ranged from 2.17 to 3.57 mm d⁻¹ and the results were analyzed considering ET₀ as a class variable at two levels: low (ET₀ < 3 mm d⁻¹) and medium (3 mm d⁻¹ ≤ ET₀ < 4 mm d⁻¹). These facilitated the evaluation of the effects of soil type, soil water content, and ET₀ on NTR.

For each soil, the relationship between NTR and the mean volumetric soil water content during each drying period was evaluated using the equations of Muschow and Sinclair (1991):

\[
\begin{align*}
NTR &= 1 & \theta & \geq \theta_c & \quad (5a) \\
NTR &= 1 + k(\theta - \theta_c) & \theta & < \theta_c & \quad (5b)
\end{align*}
\]

where $\theta$ is the measured mean soil water content of each water treatment; $\theta_c$ is the critical soil water content below which NTR begins to decrease; and $k$ is the slope of the relationship for $\theta$ values below $\theta_c$.

Parameters $k$ and $\theta_c$ of Eq. 5 were derived by fitting the model to the measured data using the SAS NLIN procedure (SAS Institute, 1998). The coefficient of determination ($R^2$) and the root mean square error (RMSE) between observed and predicted NTR values were used to evaluate the goodness of fit of the model. RMSE was given by:

\[
RMSE = \left[ \frac{1}{n} \sum_{i=1}^{n} (S_i - M_i)^2 \right]^{1/2}
\]

where $S$ and $M$ are the predicted and measured NTR values for the ith drying period, respectively, and $n$ is the total number of observed NTR values. The fitting procedure provided the 95% confidence intervals for all fitted parameters, which were used for comparisons between soil textures and among evaporative demand classes.

**RESULTS**

**Variations in soil water contents and meteorological factors**

Fig. 2 shows the variations in the mean volumetric soil water content and the mean daily transpiration rate per plant during the drying intervals for each water treatment under both the outdoor and climate-controlled chamber conditions. The large variations in soil water content were likely due to fluctuations in the transpiration rate occurring in these treatments. The mean soil water content in each water treatment was maintained around the desired value. One-way ANOVA of all the soil water content data showed that the differences in the mean soil water content among different water treatments during the experimental period were all significant ($P < 0.05$). Differences in the daily transpiration rate among different water treatments during the experiment period were also all significant ($P < 0.05$).

The relevant meteorological factors varied during the experiment (Fig. 3). When outdoors, daily hours of
Fig. 2 Variations in volumetric soil water content of the loamy clay soil (a) and the sandy loam soil (b) and variations in daily transpiration for the loamy clay soil (c) and the sandy loam soil (d) with black locust grown outdoors and in a climate-controlled chamber experiments under various water treatments (72%–100% (W1), 62%–80% (W2), 54%–65% (W3), and 37%–50% (W4) of field capacity for the loamy clay soil and 64%–100% (W1), 55%–80% (W2), 39%–65% (W3), and 25%–40% (W4) for the sandy loam soil).

Fig. 3 Variations in daily sunshine hours and daily mean temperature (a) and variations in relative humidity (RH) and vapor pressure deficit (VPD) (b) for black locust grown outdoors and in climate-controlled chamber.

of sunlight, temperature, and VPD followed similar trends; however, the changes in relative humidity followed an opposite trend. Zero sunshine hours occurred on rainy days when the relative humidity was high. In the climate-controlled chamber, daily hours of sunlight were controlled and were, therefore, the same (12 h) during the whole period. For the four applied meteorological conditions, the mean daily temperature and the mean relative humidity were 30.1 °C and 41.5% (HL), 30.2 °C and 77.9% (HH), 23.6 °C and 43.7% (LL), and 23.6 °C and 79.1% (LH), respectively. The mean VPD values were 2.49, 0.88, 1.65, and 0.61 kPa for HL, HH, LL, and LH, respectively. As shown in Fig. 3, the values of temperature and relative humidity used in the climate-controlled chamber were within the ranges of those occurring outdoors; this was
Also true of the VPD values.

**Effect of temperature on transpiration rate**

There was a direct relationship between the transpiration rate and the air temperature regardless of whether the black locust was grown outdoors or in the climate-controlled chamber, as indicated by the positive correlation coefficients (Table II). The relationship was also true for plants grown in either soil and under each water treatment outdoors (Fig. 4a, b) or in the climate-controlled chamber (Fig. 5a, b). Furthermore, the relationship between air temperature and transpiration rate for each water treatment was well explained by the power function as indicated by the $R^2$ and RMSE values presented in Tables III and IV. In the climate-controlled chamber, the transpiration rates of the plants under each water treatment for the higher temperatures (HH and HL) were significantly higher than those for the lower temperatures (LH and LL) ($P < 0.05$) (Table V).

**Effect of vapor pressure deficit on transpiration rate**

Transpiration rates of black locust plants grown outdoors were inversely related to relative humidity and directly related to VPD; however, when the plants were grown in the climate-controlled chamber, these relationships were insignificant except for the W1 treatment for the sandy loam soil (Table II). No significant

### TABLE II

<table>
<thead>
<tr>
<th>Environment</th>
<th>Soil Treatment</th>
<th>Temperature</th>
<th>Relative humidity</th>
<th>VPD</th>
<th>ET$_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoors Loamy clay</td>
<td>W1</td>
<td>0.719**</td>
<td>-0.822**</td>
<td>0.784**</td>
<td>0.870**</td>
</tr>
<tr>
<td></td>
<td>W2</td>
<td>0.698**</td>
<td>-0.818**</td>
<td>0.781**</td>
<td>0.877**</td>
</tr>
<tr>
<td></td>
<td>W3</td>
<td>0.740**</td>
<td>-0.822**</td>
<td>0.783**</td>
<td>0.835**</td>
</tr>
<tr>
<td></td>
<td>W4</td>
<td>0.855**</td>
<td>-0.856**</td>
<td>0.874**</td>
<td>0.798**</td>
</tr>
<tr>
<td>Sandy loam W1</td>
<td>W1</td>
<td>0.807**</td>
<td>-0.869**</td>
<td>0.864**</td>
<td>0.903**</td>
</tr>
<tr>
<td></td>
<td>W2</td>
<td>0.736**</td>
<td>-0.879**</td>
<td>0.846**</td>
<td>0.910**</td>
</tr>
<tr>
<td></td>
<td>W3</td>
<td>0.711**</td>
<td>-0.804**</td>
<td>0.777**</td>
<td>0.847**</td>
</tr>
<tr>
<td></td>
<td>W4</td>
<td>0.717**</td>
<td>-0.688**</td>
<td>0.698**</td>
<td>0.786**</td>
</tr>
<tr>
<td>Climate-controlled chamber Loamy clay W1</td>
<td>W1</td>
<td>0.960**</td>
<td>-0.004</td>
<td>0.383</td>
<td>0.921**</td>
</tr>
<tr>
<td></td>
<td>W2</td>
<td>0.986**</td>
<td>-0.051</td>
<td>0.336</td>
<td>0.885**</td>
</tr>
<tr>
<td></td>
<td>W3</td>
<td>0.962**</td>
<td>-0.045</td>
<td>0.323</td>
<td>0.913**</td>
</tr>
<tr>
<td></td>
<td>W4</td>
<td>0.963**</td>
<td>-0.064</td>
<td>0.319</td>
<td>0.885**</td>
</tr>
<tr>
<td>Sandy loam W1</td>
<td>W1</td>
<td>0.965**</td>
<td>-0.085</td>
<td>0.450*</td>
<td>0.872**</td>
</tr>
<tr>
<td></td>
<td>W2</td>
<td>0.973**</td>
<td>-0.015</td>
<td>0.394</td>
<td>0.864**</td>
</tr>
<tr>
<td></td>
<td>W3</td>
<td>0.977**</td>
<td>-0.055</td>
<td>0.432</td>
<td>0.850**</td>
</tr>
<tr>
<td></td>
<td>W4</td>
<td>0.951**</td>
<td>-0.064</td>
<td>0.423</td>
<td>0.839**</td>
</tr>
</tbody>
</table>

### TABLE III

<table>
<thead>
<tr>
<th>Soil Treatment</th>
<th>TR = $A \times T^B$</th>
<th>TR = $A/[1 + B \times \exp(-C \times VPD)]$</th>
<th>TR = $A/[1 + B \times \exp(-C \times ET_0)]$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A$</td>
<td>$B$</td>
<td>$R^2$</td>
</tr>
<tr>
<td>Loamy clay W1</td>
<td>0.000502</td>
<td>2.278</td>
<td>0.483</td>
</tr>
<tr>
<td>W2</td>
<td>0.000352</td>
<td>2.279</td>
<td>0.547</td>
</tr>
<tr>
<td>W3</td>
<td>0.000323</td>
<td>2.135</td>
<td>0.520</td>
</tr>
<tr>
<td>W4</td>
<td>0.000004</td>
<td>3.202</td>
<td>0.727</td>
</tr>
<tr>
<td>Sandy loam W1</td>
<td>0.000044</td>
<td>3.074</td>
<td>0.597</td>
</tr>
<tr>
<td>W2</td>
<td>0.000086</td>
<td>2.756</td>
<td>0.517</td>
</tr>
<tr>
<td>W3</td>
<td>0.000271</td>
<td>2.342</td>
<td>0.465</td>
</tr>
<tr>
<td>W4</td>
<td>0.000006</td>
<td>3.131</td>
<td>0.552</td>
</tr>
</tbody>
</table>

---

*,$ **Significant at the 0.05 and 0.01 levels, respectively.

$\text{VPD}$ = vapor pressure deficit; $\text{ET}_0$ = reference evapotranspiration.
Fig. 4 Transpiration rates of black locust grown outdoors under various water treatments, 72%–100% (W1), 62%–80% (W2), 54%–65% (W3), and 37%–50% (W4) of field capacity for the loamy clay soil (a, c, and e) and 64%–100% (W1), 55%–80% (W2), 39%–65% (W3), and 25%–40% (W4) for the sandy loam soil (b, d, and f), as a function of different meteorological factors, air temperature (a and b), vapor pressure deficit (VPD) (c and d), and reference evapotranspiration (ET$_0$) (e and f).

Differences in transpiration rate were observed between the controlled conditions with low and high humidity for a given temperature regime in the climate-controlled chamber for any water treatment (Table V). Since VPD was determined from both temperature and relative humidity (VPD = $e_s - e_a$, where $e_s$ is the saturated water vapor pressure and $e_a$ is the actual water vapor pressure), only the relationship between VPD and transpiration is shown in Fig. 4c and d and this relationship was logistic for each water treatment for both soils outdoors (Table III). When VPD was greater than 1.0 kPa for the loamy clay soil and greater than 1.5 kPa for the sandy loam soil, the transpiration rate fluctuated within the range of 85% of its maximum value in each water treatment. Therefore, these VPD values were considered to be the turning points where further increases in VPD induced little change in outdoor daily transpiration.

**Effect of evaporative demand on transpiration rate**

Evaporative demand, which was indicated by ET$_0$, was significantly related to the transpiration rate of black locust whether growing outdoors or in the climate-controlled chamber (Table II) ($P < 0.05$). Since
Fig. 5 Transpiration rates of black locust grown in a climate-controlled chamber under various water treatments, 72%–100% (W1), 62%–80% (W2), 54%–65% (W3), and 37%–50% (W4) of field capacity for the loamy clay soil (a and c) and 64%–100% (W1), 55%–80% (W2), 39%–65% (W3), and 25%–40% (W4) for the sandy loam soil (b and d), as a function of different meteorological factors, air temperature (a and b) and reference evapotranspiration ($ET_0$) (c and d).

Table IV

<table>
<thead>
<tr>
<th>Soil</th>
<th>Treatment</th>
<th>$TR = A \times T^B$</th>
<th>$TR = A/[1 + B \times \exp(-C \times ET_0)]$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$A$</td>
<td>$B$</td>
</tr>
<tr>
<td>Loamy clay</td>
<td>W1</td>
<td>0.00000016</td>
<td>3.856</td>
</tr>
<tr>
<td></td>
<td>W2</td>
<td>0.0000011</td>
<td>3.910</td>
</tr>
<tr>
<td></td>
<td>W3</td>
<td>0.0000034</td>
<td>3.468</td>
</tr>
<tr>
<td></td>
<td>W4</td>
<td>0.0000033</td>
<td>3.160</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>W1</td>
<td>0.0000033</td>
<td>2.767</td>
</tr>
<tr>
<td></td>
<td>W2</td>
<td>0.0000033</td>
<td>3.466</td>
</tr>
<tr>
<td></td>
<td>W3</td>
<td>0.0000029</td>
<td>3.393</td>
</tr>
<tr>
<td></td>
<td>W4</td>
<td>0.0000031</td>
<td>3.047</td>
</tr>
</tbody>
</table>

* $A$, $B$, and $C$ are the coefficients of the fitted functions; $R^2$ is the coefficient of determination; RMSE is the root mean square error.

The actual transpiration rate was a function of both soil water content and $ET_0$ (Allen *et al.*, 1998), the relationship between transpiration rate and $ET_0$ was analyzed separately for each water content. When grown both outdoors and in the climate-controlled chamber, the transpiration rate of black locust under each soil water treatment was related by a logistic function to $ET_0$ (Figs. 4e, f and 5c, d; Tables III and IV). Once $ET_0$ increased to 3.2 mm d$^{-1}$ for the loamy clay soil and to 4.0 mm d$^{-1}$ for the sandy loam soil, the transpiration rates did not change significantly in any water treatment in the outdoor environment. Similarly, once $ET_0$ increased to 3.6 mm d$^{-1}$ for the sandy loam soil and 3.9 mm d$^{-1}$ for the loamy clay soil in the climate-controlled chamber, the transpiration rates did not change significantly in any water treatment. The
of the two soils with different textures. Since the sandy could be explained by the different heat conductivity clay soil in both the experimental environments. This was greater for the sandy loam soil than for the loamy rate with temperature in the well-watered treatment ber (Fig. 5). The reduction rate of the transpiration and loamy clay soils in the climate-controlled cham- difference in transpiration rate between the sandy loam soils (Fig. 4). However, there was no significant dif- factors occurred for each water treatment for both fferences in the various meteorological soils (Table W1 W2 W3 W4)

<table>
<thead>
<tr>
<th>Soil</th>
<th>Meteorological conditions</th>
<th>W1</th>
<th>W2</th>
<th>W3</th>
<th>W4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loamy clay</td>
<td>HH</td>
<td>0.760a</td>
<td>0.461a</td>
<td>0.304a</td>
<td>0.101a</td>
</tr>
<tr>
<td></td>
<td>HL</td>
<td>0.746a</td>
<td>0.465a</td>
<td>0.296a</td>
<td>0.102a</td>
</tr>
<tr>
<td></td>
<td>LH</td>
<td>0.396b</td>
<td>0.195b</td>
<td>0.131b</td>
<td>0.049b</td>
</tr>
<tr>
<td></td>
<td>LL</td>
<td>0.359b</td>
<td>0.195b</td>
<td>0.124b</td>
<td>0.044b</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>HH</td>
<td>0.805b</td>
<td>0.622a</td>
<td>0.433a</td>
<td>0.150a</td>
</tr>
<tr>
<td></td>
<td>HL</td>
<td>0.814a</td>
<td>0.649a</td>
<td>0.474a</td>
<td>0.160a</td>
</tr>
<tr>
<td></td>
<td>LH</td>
<td>0.299b</td>
<td>0.230b</td>
<td>0.196b</td>
<td>0.067b</td>
</tr>
<tr>
<td></td>
<td>LL</td>
<td>0.319b</td>
<td>0.257b</td>
<td>0.190b</td>
<td>0.074b</td>
</tr>
</tbody>
</table>

a) HH = high temperature and high humidity; HL = high temperature and low humidity; LH = low temperature and high humidity; LL = low temperature and low humidity.
b) Values followed by the same letter in a column for a given soil are not significantly different (P < 0.05).

ET0 value where the transpiration rates began to decrease significantly was higher for the sandy loam soil in the outdoor environment, but was higher for the loamy clay soil in the climate-controlled chamber.

Moreover, the transpiration rates of black locust were significantly different among the different water treatments in both experimental environments (P < 0.05). The changes of transpiration rates with changing temperature, VPD, and ET0 in the well-watered treatment (W1) were notably larger than in the treatment with the greatest water deficit (W4). Therefore, soil water content had a direct impact on the transpiration rates. Evaporative demand has been related to VPD and air temperature (Allen et al., 1998), and therefore, evaporative demand also directly affected transpiration, while temperature and VPD indirectly affected transpiration rates.

**Effect of soil texture on transpiration rate**

The transpiration rate in the well-watered treatment (W1) outdoors was greater for black locust grown in the sandy loam soil than in the loamy clay soil, although similar responses of the transpiration rates to the changes in the various meteorological factors occurred for each water treatment for both soils (Fig. 4). However, there was no significant difference in transpiration rate between the sandy loam and loamy clay soils in the climate-controlled chamber (Fig. 5). The reduction rate of the transpiration rate with temperature in the well-watered treatment was greater for the sandy loam soil than for the loamy clay soil in both the experimental environments. This could be explained by the different heat conductivity of the two soils with different textures. Since the sandy loam soil had the higher heat conductivity (Jury and Horton, 2004), transpiration of the plants grown in it decreased more rapidly because soil temperatures fell faster with reductions in air temperatures. For each water treatment, the values of VPD and ET0 above which transpiration rates fluctuated within 85% of the maximum value for the sandy loam soil (1.0 kPa and 3.0 mm d−1, respectively) were higher than those for the loamy clay soil (1.5 kPa and 4.0 mm d−1, respectively) when black locust was grown outdoors, and the values were about 3.7 and 4.0 mm d−1, respectively, for ET0 when black locust was grown in the climate-controlled chamber. Therefore, soil texture could affect the responses of transpiration rate to both VPD and ET0.

**Transpiration responses to soil water availability**

There were differences in the transpiration response of black locust, when grown outdoors, to soil water availability among the three defined ET0 levels (Fig. 6). The θc values below which the NTR decreased were generally significantly different among the ET0 levels for a given soil (P < 0.05), with the only exceptions being the differences between the θc value of the loamy clay soil for the medium ET0 level and that of either the high or low ET0 level (Table VI; Fig. 6). The θc values ranged between 0.213 and 0.222 cm3 cm−3 for the loamy clay soil and between 0.125 and 0.145 cm3 cm−3 for the sandy loam soil. Notably, when ET0 decreased, θc increased for the loamy clay soil but decreased for the sandy loam soil. The slope (k) values for the different ET0 levels ranged from 7.85 to 8.27 (cm3 cm−3)−1 for the loamy clay soil, and from 9.97 to 12.51 (cm3 cm−3)−1 for the sandy loam soil (Table
TABLE VI

Parameters for the linear-plateau model relating normalized transpiration rate (NTR) to soil water content for three levels of the reference evapotranspiration rate (ET)<sub>0</sub>

<table>
<thead>
<tr>
<th>Environment</th>
<th>Soil</th>
<th>ET&lt;sub&gt;0&lt;/sub&gt; level</th>
<th>θ&lt;sub&gt;c&lt;/sub&gt;</th>
<th>S</th>
<th>ASW</th>
<th>k</th>
<th>R&lt;sup&gt;2&lt;/sup&gt;</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>cm&lt;sup&gt;3&lt;/sup&gt; cm&lt;sup&gt;-3&lt;/sup&gt;</td>
<td>kPa</td>
<td>%</td>
<td>cm&lt;sup&gt;3&lt;/sup&gt; cm&lt;sup&gt;-3&lt;/sup&gt;-1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outdoors</td>
<td>Loamy clay</td>
<td>ET&lt;sub&gt;0&lt;/sub&gt; &lt; 3</td>
<td>0.222±0.004</td>
<td>205</td>
<td>63.5</td>
<td>7.92±0.44</td>
<td>0.982</td>
<td>0.042</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ET&lt;sub&gt;0&lt;/sub&gt; &lt; 4</td>
<td>0.219±0.005</td>
<td>220</td>
<td>61.8</td>
<td>8.27±0.65</td>
<td>0.970</td>
<td>0.054</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ET&lt;sub&gt;0&lt;/sub&gt; ≥ 4</td>
<td>0.213±0.003</td>
<td>250</td>
<td>58.4</td>
<td>7.85±0.50</td>
<td>0.967</td>
<td>0.054</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>ET&lt;sub&gt;0&lt;/sub&gt; &lt; 3</td>
<td>0.125±0.006</td>
<td>47</td>
<td>40.7</td>
<td>12.5±1.51</td>
<td>0.959</td>
<td>0.063</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ET&lt;sub&gt;0&lt;/sub&gt; &lt; 4</td>
<td>0.139±0.004</td>
<td>38</td>
<td>49.1</td>
<td>10.4±0.93</td>
<td>0.967</td>
<td>0.059</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ET&lt;sub&gt;0&lt;/sub&gt; ≥ 4</td>
<td>0.145±0.003</td>
<td>35</td>
<td>52.7</td>
<td>9.97±0.56</td>
<td>0.980</td>
<td>0.046</td>
<td></td>
</tr>
<tr>
<td>Climate-controlled chamber</td>
<td>Loamy clay</td>
<td>ET&lt;sub&gt;0&lt;/sub&gt; &lt; 3</td>
<td>0.260±0.011</td>
<td>95</td>
<td>84.8</td>
<td>4.51±0.54</td>
<td>0.885</td>
<td>0.080</td>
</tr>
<tr>
<td></td>
<td>ET&lt;sub&gt;0&lt;/sub&gt; &lt; 4</td>
<td>0.233±0.005</td>
<td>162</td>
<td>69.7</td>
<td>5.25±0.35</td>
<td>0.955</td>
<td>0.047</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ET&lt;sub&gt;0&lt;/sub&gt; ≥ 4</td>
<td>0.134±0.006</td>
<td>41</td>
<td>46.1</td>
<td>7.30±0.88</td>
<td>0.958</td>
<td>0.044</td>
<td></td>
</tr>
<tr>
<td>Sandy loam</td>
<td>ET&lt;sub&gt;0&lt;/sub&gt; &lt; 3</td>
<td>0.144±0.004</td>
<td>35</td>
<td>52.1</td>
<td>7.48±0.60</td>
<td>0.971</td>
<td>0.044</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>θ<sub>c</sub> is the critical soil water content; S is the soil suction corresponding to critical soil water content; ASW is the remaining available soil water corresponding to critical soil water content; k is the slope gradient; R<sup>2</sup> is the coefficient of determination; RMSE is the root mean square error; values of θ<sub>c</sub> and k are presented as the mean±confidence interval at the 95% level.

VI); however, these differences among the k values for a given soil were not significantly different (P > 0.05).

In the climate-controlled chamber, where the plants were under weaker illumination than under natural sunlight, ET<sub>0</sub> could not attain a level higher than 4 mm d<sup>-1</sup>, which could occur in the outdoor environment. The transpiration responses of black locust to soil water availability were also different between the medium and low ET<sub>0</sub> levels as represented by the fitted lines (Fig. 7). For the loamy clay soil, the transpiration responses to soil water availability at both ET<sub>0</sub> levels were well represented by the linear-plateau model. The θ<sub>c</sub> value for the medium ET<sub>0</sub> level (0.233 cm<sup>3</sup> cm<sup>-3</sup>) was significantly (P < 0.05) lower than that for the low ET<sub>0</sub> level (0.260 cm<sup>3</sup> cm<sup>-3</sup>) (Table VI). However, in the case of the sandy loam soil, where the linear-plateau model was also well fitted, the θ<sub>c</sub> value for the low ET<sub>0</sub> level (0.134 cm<sup>3</sup> cm<sup>-3</sup>) was significantly (P < 0.05) lower than that for the medium ET<sub>0</sub> level (0.144 cm<sup>3</sup> cm<sup>-3</sup>) (Table VI). For either soil, no significant differences were found between the k values (P > 0.05). Moreover, the θ<sub>c</sub> values were lower for the plants grown outdoors than for those grown in the climate-controlled chamber; however, the k values were in the opposite order.

It was shown in Table VI that NTR began to decrease at higher θ<sub>c</sub> in the loamy clay soil (0.213–0.260 cm<sup>3</sup> cm<sup>-3</sup>) than in the sandy loam soil (0.125–0.145 cm<sup>3</sup> cm<sup>-3</sup>) both outdoors and in the climate-controlled chamber. In terms of soil suction, the critical water contents increased within the range of 95–250 kPa for the loamy clay soil, and decreased from 47 to 34.5 kPa for the sandy loam soil, with increases in ET<sub>0</sub>. While for the remaining available soil water content (ASW),
Fig. 7 Normalized transpiration rates (NTR) of black locust grown in a climate-controlled chamber as a function of soil water content for the loamy clay soil (a) and the sandy loam soil (b). Symbols represent data measured daily at two reference evapotranspiration ($\text{ET}_0$) levels (medium: $3 \text{ mm d}^{-1} \leq \text{ET}_0 < 4 \text{ mm d}^{-1}$; low: $\text{ET}_0 < 3 \text{ mm d}^{-1}$) while lines represent fitted values.

the critical values occurred within the range of 58%–85% for the loamy clay soil and 40%–55% for the sandy loam soil.

When the soil water content was lower than $\theta_c$ in the outdoor environment (Fig. 6), the NTR was less when $\text{ET}_0$ was low than when it was high in the case of the loamy clay soil; however, the relationship of NTR with $\text{ET}_0$ was the opposite in the case of the sandy loam soil. Similarly, in the climate-controlled chamber (Fig. 7), the NTR of the plants grown in the loamy clay soil was higher for the medium than for the low $\text{ET}_0$ level when the soil water content was lower than $\theta_c$, but the effect of $\text{ET}_0$ was the opposite for the NTR of plants grown in the sandy loam soil.

DISCUSSION

Increasing temperatures, as one of the studied meteorological factors, were found to have significant effects on the response of black locust transpiration under the various water treatments when grown both outdoors and in the climate-controlled chamber. Similarly, Downes (1969) reported that the transpiration rates of both sorghum and winter wheat increased with temperature rises from 17 to 27 °C with an air VPD of about 1.4 kPa. Thus, a warmer climate with reduced precipitation would likely increase water losses due to black locust transpiration. It has been reported that the Loess Plateau is currently becoming warmer and drier (Duan et al., 2009), so that soil drying may be aggravated by the presence of black locust stands in this region. Du et al. (2011) and Yan et al. (2010) have shown that black locust consumes about 1.0 kg m$^{-2}$ d$^{-1}$ of water, for a given leaf area, which is greater than that of Syringa oblata or Quercus liaotungensis, and has notably quite different sapflows during pre- and post-rainfall periods. This finding indicated that black locust is both a high water consumer and a drought-sensitive plant species as compared with indigenous plants. Pratt and Black (2006) and Li et al. (2010) also showed that as a non-indigenous tree species, black locust does not have a hydrologically advantage over indigenous trees. Therefore, decisions to plant black locust on the Loess Plateau should only be made with caution, taking into account the disadvantages as well as the advantages of doing so.

Black locust grown outdoors demonstrated a daily transpiration relationship to VPD that was logistic in which the transpiration did not significantly increase when the VPD values were higher than 1.0 and 1.5 kPa for the loamy clay and sandy loam soils, respectively. This result was similar to the finding of Anthoni et al. (1999), who reported that in a tall ponderosa pine stand, stomata started to close to restrict transpiration when VPD exceeded 1 kPa and evapotranspiration was almost constant for VPD > 1 kPa. Ewers et al. (2005) found that this regulation of VPD on transpiration is species-specific in boreal trees. Genotype was also an important factor as Fletcher et al. (2007) showed that the slow-wilting genotypes of soybean ($\text{Glycine max}$ L.) attained a maximum transpiration rate at a VPD of about 2.0 kPa with little or no further increase in the transpiration rate when VPD became greater than 2.0 kPa. A limitation on maximum transpiration rate could be a key trait in less humid regions when VPD is high and irrigation is
not available, which enables significant water saving early in the season (Sinclair et al., 2005a). Therefore, the different responses of transpiration to VPD could be attributed to the different regulation strategies of different plant species or genotypes for controlling water transpiration. Moreover, Du et al. (2011) showed that the sap flux density of black locust, which could represent the transpiration, remained constant for VPD > 2 kPa and began to decrease earlier than those of *Armeniaca sibirica* and *Quercus liaotungensis* grown in a loess soil with a texture of more than 50% silt (0.002–0.05 mm) and less than 20% clay (< 0.002 mm). The differences in the VPD value at which black locust transpiration was restricted between the two soils in our study and the loess soil in Du et al. (2011) could be attributable to the different soil textures. In some cases, the soil type does not lead to restrictions in evapotranspiration, such as that of peat soils where a linear relationship exists between evapotranspiration and VPD (Brümmel et al., 2011). Therefore, the results indicated that plants would present different phenotypes in the transpiration regulation for different soil textures.

Furthermore, the transpiration response of black locust plants to VPD differed when grown in the climate-controlled chamber from when grown outdoors. There was no significant correlation between VPD and the transpiration rate of plants grown in the climate-controlled chamber in this study. This could be attributed to the artificial light sources, which had a low and steady light density, used in the chambers. Light density has been reported to significantly affect stomatal opening (Sellin et al., 2008). Therefore, the changing light density in the outdoor environment may have an important effect on the relationship between transpiration and VPD.

Although the response of transpiration rate to ET$_0$ was similar in being fitted by a logistic function for all water treatments (Figs. 4e, f and 5e, f), water consumption by black locust subjected to the various water treatments differed among the different soils and meteorological conditions. The ET$_0$ values at which transpiration rates began to decrease significantly was higher for the sandy loam soil in the outdoor environment, but was higher for the loamy clay soil in the climate-controlled chamber. Furthermore, differences due to ET$_0$ were observed when relating NTR to soil water content (Figs. 6 and 7). Evaporative demand significantly affected the critical values of soil water content below which transpiration would be reduced, but had little influence on the rate of decline in transpiration that occurred with further drying of the soil. This was consistent with the findings of Novák et al. (2005) and Bailey and Spaakman (1996). For the loamy clay soil, the $\theta_c$ values for black locust decreased with increases in ET$_0$ outdoors and in the climate-controlled chamber. However, for the sandy loam soil, the $\theta_c$ values for black locust significantly increased as ET$_0$ increased in both environments. This phenomenon observed in the case of the loamy clay soil indicated that evaporative demand increased transpiration of black locust at soil water contents lower than the $\theta_c$ value at the higher ET$_0$ levels. In the sandy loam soil case, increased evaporative demand resulted in lowered transpiration when the soil water content was lower than the $\theta_c$ value at the lower ET$_0$ levels. Therefore, the evaporative demand influenced the transpiration response of black locust to soil drying in a different way for the two soils. The higher water content of the loamy clay soil at which NTR began to decrease accounted for the lower transpiration of black locust in the loamy clay soil than in the sandy loam soil.

The differences in transpiration response of black locust to increased evaporative demand when grown between the two different soils could be attributed to the different hydraulic properties of the soils. The hydraulic conductivity of the loamy clay soil declined almost linearly with the reduction in soil water content (Fig. 1). However, the decline in the hydraulic conductivity of the soils would induce reductions in stomatal conductance as reported by Saliendra and Meinzer (1989). However, the transpiration rate of the black locust grown in the loamy clay soil was generally lower and less influenced by meteorological conditions when compared to that in the sandy loam soil, even though transpiration was more likely to be reduced in the latter soil case due to the relatively lower critical water content (Figs. 6 and 7). It was also true of the critical values of soil suction. As the sandy loam soil had lower critical values of soil suction at which NTR began to decrease, water was easier to be transpired in it as compared to the loamy clay soil. For every ET$_0$ levels, at the critical soil water content, 58%–85% of the available soil water remained in the loamy clay soil whereas only 40%–55% of available soil water remained in the sandy loam soil. Therefore, the different effects of ET$_0$ on transpiration response to water availability were related to the remaining available soil water content.

In addition, proper light density which promotes stomatal opening would increase plant transpiration (Cohen et al., 1997). Higher light density in the outdoor environment would induce high plant transpiration at the same evaporative demand. Therefore, at
the same ET$_0$ level, the NTR began to decrease at lower soil water contents at greater rates in the outdoor environment than in the climate-controlled chamber.

CONCLUSIONS

Transpiration rates were related to air temperature by a power function and to ET$_0$ by a logistic function in each soil water treatment for plants grown both outdoors and in the climate-controlled chamber. The transpiration rate was more susceptible to changes in meteorological conditions for plants grown in the sandy loam soil than in the loamy clay soil in both environments. The NTR did not decrease until the critical value of the volumetric soil water content was between 0.213 and 0.260 cm$^3$ cm$^{-3}$ for the loamy clay soil and between 0.125 and 0.145 cm$^3$ cm$^{-3}$ for the sandy loam soil. These critical values corresponded to soil suctions of 95–250 and 34–55 kPa for the loamy clay and sandy loam soils, respectively. The critical soil water content was higher under the climate-controlled chamber than under the outdoor conditions, which may be related to the differences in light density. The critical values of volumetric soil water content for the sandy loam soil increased significantly with increased evaporative demand; however, the critical values for the loamy clay soil decreased significantly with increased evaporative demand. The different effects of ET$_0$ on transpiration response to water availability in the two soils were related to the remaining available soil water contents.

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