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Water requirements for growth and survival of Swietenia macrophylla and Tabebuia heterophylla juvenile trees in relation to water production capacity of dew condensers1

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Water requirements for growth and survival of *Swietenia macrophylla* and *Tabebuia heterophylla* juvenile trees in relation to water production capacity of dew condensers[1,2]

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ABSTRACT

Drought mortality of juvenile trees is a major cause for failure of reforestation projects. Portable devices such as passive radiative dew condensers can often provide 0.15 L/day of water in situ, possibly sufficient for tree survival until roots can access groundwater, allowing self-sustainability. To evaluate growth and survivability of juvenile trees of *Tabebuia heterophylla* Britton and *Swietenia macrophylla* King under such low water amounts, juvenile trees received approximately 0.033, 0.067, 0.134, 0.201 and 0.268 L/tree/day, representing fractions (relative evapotranspiration or RET) of 0.125, 0.25, 0.50, 0.75 and 1.00 of the evapotranspiration demand (ET_o). The experiment lasted 60 days for *S. macrophylla* and 90 days for *T. heterophylla*. All *T. heterophylla* juvenile trees survived even at the lowest irrigation rate. However, *S. macrophyll*a juvenile trees began dying at RET < 0.5, with only 60 percent surviving at RET = 0.25 (0.067 L/day) and 100 percent mortality occurring at RET = 0.125 (0.033 L/day). Water requirements of 0.134 L/day, necessary for full survival of both species, were within the typical production capacity of 1-m^2 dew condensers. However, a greater safety factor is obtained using drought tolerant species such as *T. heterophylla,* which can survive under water application rates as low as 0.03 L/day.

Key words: reforestation, evapotranspiration, water management, drought mortality

RESUMEN

Requerimientos de agua para el desarrollo y supervivencia de plántulas de *Swietenia macrophylla* y *Tabebuia heterophylla* con relación a la capacidad de producción de agua de condensadores de rocío

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La mortalidad por sequía de las plántulas de árboles es una causa importante del fracaso de los proyectos de reforestación. Dispositivos portátiles como los condensadores de rocío pueden proporcionar ≥ 0.15 L/día de agua in situ, posiblemente suficiente para lograr supervivencia de las plántulas hasta que las raíces puedan acceder a las aguas subterráneas permitiendo así la autosostenibilidad. Para evaluar el crecimiento y la supervivencia de plántulas de *Tabebuia heterophylla* Britton y *Swietenia macrophylla* King bajo cantidades de agua tan bajas como aquellas producidas por condensadores de rocío, las plántulas fueron regadas con aproximadamente 0.033, 0.067, 0.134, 0.201 y 0.268 L/día, representando fracciones (evapotranspiración relativa o RET) de 0.125, 0.25, 0.50, 0.75 y 1.00 de la demanda de evapotranspiración (ETo). El experimento duró 60 días para *S. macrophylla* y 90 días para *T. heterophylla*. Todas las plántulas de *T. heterophylla* sobrevivieron incluso a la tasa de riego más baja. Sin embargo, las plántulas de *S. macrophylla* comenzaron a morir a RET < 0.50, observándose solo 60 por ciento de supervivencia a RET = 0.25 (≈0.067 L/día) y una mortalidad del 100 por ciento a RET = 0.125 (≈0.033 L/día). Los requerimientos mínimos de agua de ≈ 0.134 L/día, necesarios para la supervivencia total de ambas especies, estuvieron dentro de la capacidad de producción típica de condensadores de rocío de 1 m^2. Sin embargo, se obtuvo un mayor factor de seguridad en el caso de especies tolerantes a la sequía como *T. heterophylla*, que pudo sobrevivir a tasas de aplicación tan bajas como 0.03 L/día.

Palabras clave: reforestacón, evapotranspiration, manejo de agua, mortalidad por sequía

INTRODUCTION

Drought mortality of juvenile trees is a major cause for failure of reforestation projects in arid and semi-arid regions with limited access to irrigation water (Gindaba et al., 2004; Villagra and Cavagnarob, 2006; Chirino et al., 2008). A management challenge in these cases is to provide the minimum amount of water required for tree survival in the first few months after planting, until roots develop sufficiently for trees to become self-sustaining between rainfall events. The amount of water required depends in general on tree species and evapotranspiration demand under prevailing climatic conditions.

By examining data from a large number of experiments, Pereira et al. (2006) found that the transpiration demand (T_o) of fully watered individual trees widely separated from each other was given by

$$T_o = E_o A_f / 2.88 \qquad [1]$$

Here A_f is total leaf area (m^2 per tree), and E_o is the evapotranspiration demand in liters per day per m^2 of ground surface (or equivalently mm/day) estimated by the Penman-Monteith method for a fully watered grass reference crop with leaf area index of 2.88. According to Eq. [1], for a "typical" value of E_o = 5 mm/day, a small tree with leaf area of 0.02 m^2 would have a transpiration demand of only 0.034 L/day. Assuming that the minimum transpiration rate required for plant survival is about half the demand T_o (Doorenbos and Kassam, 1979), the demand for survival would be 0.017 L/day. Considering furthermore that water applied to the soil surrounding juvenile trees is generally lost both by transpiration and evaporation through the soil surface, and assuming that transpiration and evaporation are approximately equal, then the estimated transpiration requirement of 0.017 L/day in the above example would need to be doubled to yield an *evapotranspiration* demand (ET_o) of 0.034 L/day.

This estimate, although only approximate, is consistent with results of Kumsopa et al. (1997), who reported that only 0.035 to 0.05 L/day of irrigation water was sufficient for field survival of *Acacia* juvenile trees in a saline soil in Thailand in the absence of rain. Water in this case was provided by rudimentary solar stills installed next to the juvenile trees, which condensed soil water vapor and dripped it near the tree stem where it was used efficiently. In another study in Kenya, Mng'omba et al. (2011) found that species of *Persea americana* and *Vangueria infausta* survived on only 0.05 L/day under greenhouse conditions, whereas over 60% mortality occurred when water application was reduced to 0.013 L/day.

Low water requirements such as these, on the order of 0.05 L/day, can in principle be supplied in-situ by small water vapor condensation devices, such as dew condensers or solar earth-water stills, eliminating the need for transporting irrigation water to reforestation sites. Extensive research on dew condensers during the past decade (Berkowisz et al., 2004; Beysens et al., 2007; Clus et al., 2008) indicates that ≥0.1 L/day of water per square meter of condenser surface is typically collected on clear nights. Other in situ water production devices, such as earth-water stills, may also be used for tree irrigation (Rajvanshi and Zende, 1991; Kumsopa et al., 1997). Condensation rates of these devices are often initially high (on the order of ≥1 L/m^2/day) but tend to decrease rapidly due to a sharp reduction of soil water evaporation rate as the soil dries (Jackson and Van Bavel, 1965; Peralta et al., 1984).

Commercially available dew condensers (Liu et al., 2014) and systems designed to condense both dew and soil water vapor (Tal-Ya, 2014) are currently promoted by the respective manufacturers for reforestation purposes. The systems are designed so that dew or condensed soil water is dripped onto a small soil area near the tree stem, maximizing water use efficiency. The technologies are scalable, i.e. the amount of water condensed is proportional to the condenser surface area. Consequently, the dimensions of a condenser can be tailored to specific juvenile trees, provided the minimum water requirement of those juvenile trees is known. Tomaszkiewicz et al. (2016) have strongly advocated increased attention to dew condenser technologies for agriculture and reforestation.

To implement these technologies, it is crucial to know the minimum amount of water required for survival of different tree species. Correspondingly, as supplement to parallel research on dew condensation at UPR-AES (Snyder et al., 2018), the purpose of this study was to evaluate seedling performance of two tropical tree species, *Tabebuia heterophylla* Britton and *Swietenia macrophylla* King, under different water deficit intensities. Specific objectives were to: 1) evaluate growth and survival of juvenile trees of *Tabebuia heterophylla* Britton and *Swietenia macrophylla* King under different daily irrigation volumes determined as specific fractions (0.13, 0.25, 0.5, 0.75 and 1.0) of the daily evapotranspiration demand; and 2) determine if the minimum water requirements for seedling survival of the two species were within the typical water production range of 1 m^2 dew condensers.

The fraction of daily evapotranspiration demand, or *relative evapotranspiration* (RET), was used as the water availability measure instead of the absolute volume of water (L/day), because plants placed in environments with different evapotranspiration demands tend to respond identically (on a relative growth basis) to the same RET values (Doorenbos and Kassam, 1979). This facilitates extrapolating growth results from one experimental environment to another.

MATERIALS AND METHODS

Overview of evaluated tree species T. heterophylla *and* S. macrophylla

Tabebuia heterophylla Britton, known as White Cedar or 'Roble Blanco', is a medium sized tree endemic to the Greater Antilles and the Lesser Antilles from the Virgin Islands to Grenada and Barbados (Weaver, 1990). In Puerto Rico, it occurs commonly in both humid and dry secondary forests that have covered much of the island since the 1950s. The wood, strong and hard, is used for many products, although it is susceptible to termite attack. White cedar has also been widely used in urban reforestation projects, due to the large, showy pink flowers that cover the tree completely. Root architecture is deep rather than shallow thus causing no damage to nearby infrastructure and making it more resistant to falling during storms and hurricanes. In recent years it has been affected by an invasive thrip species (*Holopothrips tabebuia*), which makes the leaves curl (Cabrera-Asencio, 2008).

Big leaf mahogany or "Honduran mahogany" (*Swietenia macrophylla* King) is the most widely studied and exploited of the tropical

Meliaceae. The tree can reach heights of up to 50 m, with a straight trunk up to 3 m in diameter with few branches in the first 18 to 20 m (Brown et al., 2003). It is not endemic to Puerto Rico or the other Antilles but has been found to grow well in the region even in poor soils (Grogan et al., 2008). It is termite-resistant and is used extensively in the manufacture of furniture, cabinetry, molding and paneling. It is also used in smaller amounts for arts and crafts, coffins, turnery and musical instruments. It requires higher moisture conditions than *T. heterophylla* and therefore grows best in humid environments (Little et al., 1974).

Water application experiments

Two separate greenhouse experiments were carried out during the period from March 2011 to July 2012. The first experiment evaluated the growth of mahogany (*S. macrophylla* King) juvenile trees during a 60-day period beginning March 2011. The juvenile trees were provided by the Cambalache nursery facility of the Puerto Rico Department of Natural and Environmental Resources (DNER) and were approximately 50-cm tall at the beginning of the experiment. A second experiment, conducted for three months beginning April 2012, evaluated juvenile trees of *T. heterophylla* provided by the DNER nursery facility at Arecibo, Puerto Rico. These juvenile trees were approximately 25 cm in height at the beginning of the experiment. In both experiments the juvenile trees were planted in 10-L pots (one plant per pot), filled with a mixture of alluvium soil and compost. The mix was taken from a large batch of material being used for plant propagation at Finca Alzamora, which experience had indicated produced healthy plants. Since the water application experiment was short term, no fertilizer was deemed necessary.

The experiment with *S. macrophylla* was conducted in an open-sided, plastic-roofed greenhouse at the Alzamora experimental farm of the University of Puerto Rico at Mayagüez. The structure of the greenhouse prevented wetting with rain but at the same time allowed air circulation and a high rate of evapotranspiration. In the second experiment with *T. heterophylla*, the juvenile trees were grown for the first 30 days in the same Mayagüez greenhouse that had been used for the *S. macrophylla* experiment. Due to a temporary labor shortage associated with a general strike at Mayagüez, the juvenile trees were then moved to another open-sided greenhouse at the Río Piedras Research Center of the University of Puerto Rico Agricultural Experiment Station, to receive adequate care and maintenance for the next 40 days. After this period they were transported back to the original greenhouse at Mayagüez, where they were allowed to grow another 30 days until harvest.

The experimental treatments in both studies consisted of different amounts of water applied daily to the juvenile trees, determined as fractions of evapotranspiration demand (ET_o) of fully watered juvenile trees. The imposed fractions, termed *relative evapotranspiration rates* (RET) were 0.13, 0.25, 0.5, 0.75 and 1.0. In the case of *S. macrophylla*, the RET treatments were applied with five replications (five pots, each containing one seedling) in a randomized complete block arrangement. The experiment with *T. heterophylla* was similar except that it involved six replicate pots per treatment.

The daily evapotranspiration demand (ET_o) was measured directly using a water balance approach. In each of the replicate pots corresponding to the RET = 1.0 treatment, 0.4 L of water was added in the evening after a full day of evapotranspiration. This volume of water was always sufficient to ensure some percolation of excess water through the bottom of the pot during the night. The percolate was collected in a drainage pan and measured the next morning. The difference between added and percolated water was taken as the water volume consumed by evapotranspiration (ET_o) the previous day. The average ET_o for a given day was calculated as the mean of the measured values. Daily volume per pot (L/day) was converted to a depth basis (mm/day) by dividing the daily volume of transpired water by the cross sectional area of each pot ($0.053\ m^2$), making use of identity $1\ L/m^2 = 1\ mm$.

The daily volume of water per pot (L/pot/day) applied in each of the RET treatments was determined by multiplying the corresponding RET value times the previous day's ET_o value. For example, given a value of $ET_o = 0.1$ L/pot/day for a given day, the volumes of water applied the next day were 0.0125, 0.0250, 0.05, and 0.075 L/pot/day, corresponding to RET values of 0.125, 0.25, 0.50 and 0.75, respectively. This procedure was followed every day in the experiment with *S. macrophylla*. However, during some periods in the *T. heterophylla* experiment, the evening applications of excess water and early morning measurements of percolated water were not performed, therefore, daily ET_o data were not available and had to be estimated. During those periods, an average daily ET_o was estimated by extrapolating from the measured data cluster immediately before the estimation period. This value was used to determine the daily amounts of water added in the different RET treatments.

For all RET treatments, the respective amount of water was placed in a plastic cup with a wick (mop string) inserted into the soil through a hole in the bottom of the cup (Figure 1), which allowed the water to drip slowly into the soil near the seedling stem, where the seedling could efficiently utilize it. The idea was to mimic the slow dripping

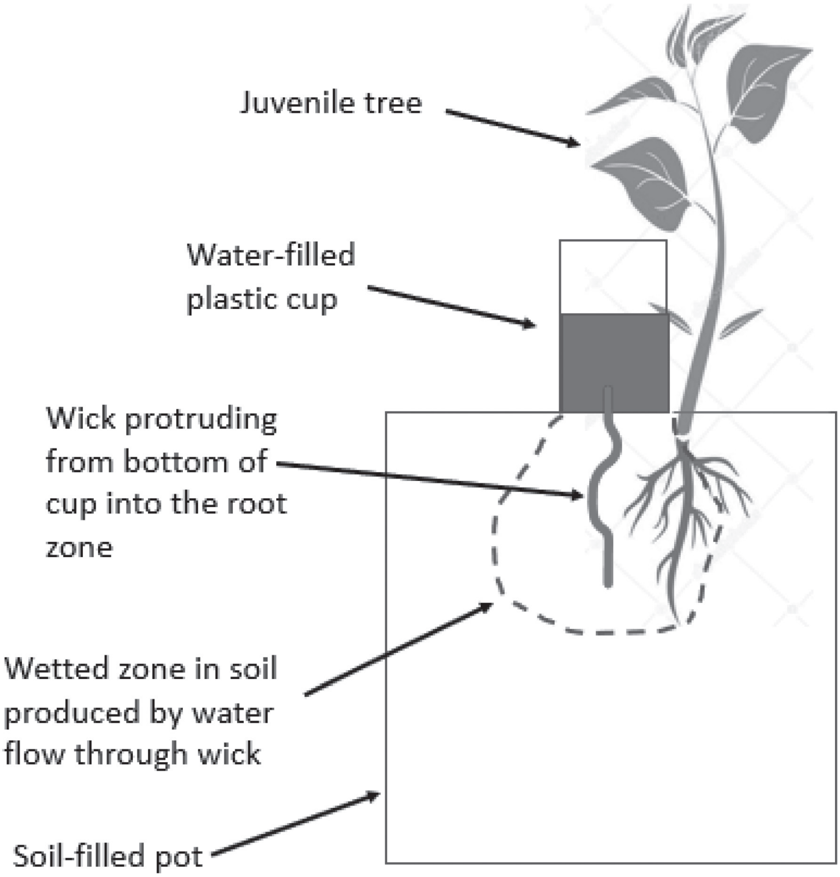


FIGURE 1. Diagram of wick system used to irrigate juvenile trees in greenhouse experiment.

provided to juvenile trees irrigated with water vapor condensation systems (Kumsopa et al., 1997; Liu et al., 2014).

Plant parameter measurements

At the end of the experiment, just prior to harvesting, plant height was measured with a ruler; stem diameter at 10 cm above the soil was measured with an electronic caliper, and the leaves on each tree were counted. The number of dead and surviving trees was also recorded. The living trees were then harvested and separated into stem, leaf and root fractions, for which dry weights were measured after oven drying for 48 hours at 75° C.

Data Analysis

Effects of different RET treatments on plant parameters were examined using both ANOVA and linear regression analysis. The type of analysis used in a given case will be described in the caption of the corresponding table or figure in the results section.

For statistical analysis of seedling survival data, each RET treatment for a given species was considered as a Bernoulli experiment with n trials. This is the same type of statistical model used to estimate the possibility of achieving n heads and N-n tails in a coin toss experiment involving N coin tosses. In the experiments described here, the number of trials or "coin tosses", N, was the number of replications in a given experimental treatment (six for *T. heterophylla* and five for *S. macrophylla*), and the two possible outcomes in each trial were plant survival or death, analogous to "heads" or "tails" in a coin toss trial. The null hypothesis assumed in each experiment was that the seedling in each pot was sampled from a large parent population of healthy juvenile trees, each with probability of survival (p) of 0.95 and a death probability of $1 - p = 0.05$. (In the coin-toss analogy, the null hypothesis assumes a probability $p = 0.5$ for "heads" and an equal probability of $1 - p = 0.5$ for "tails"). The probability $P(s)$ that the observed number (s) of surviving juvenile trees out of N replications conformed to the null hypothesis was calculated from the binomial distribution as (Bury, 1999)

$$P(s) = \binom{N}{s} \times (p)^{s} \times (1 - p)^{n-s} \qquad [2]$$

where $\binom{N}{s}$ is the binomial coefficient defined by

$$\binom{N}{s} = \frac{N!}{s!\,(N - s)!} \qquad [3]$$

The criterion for rejecting the null hypothesis was $P(s) \leq 0.05$. Whenever this criterion was satisfied, the alternate hypothesis was accepted, namely that seedling survival rate was significantly less than in a healthy population.

RESULTS AND DISCUSSION

Evapotranspiration demand measurements

Evapotranspiration demand values for *S. macrophylla* generally ranged from 3 to 7 mm/day (Figure 2A). Values for *T. heterophylla* were

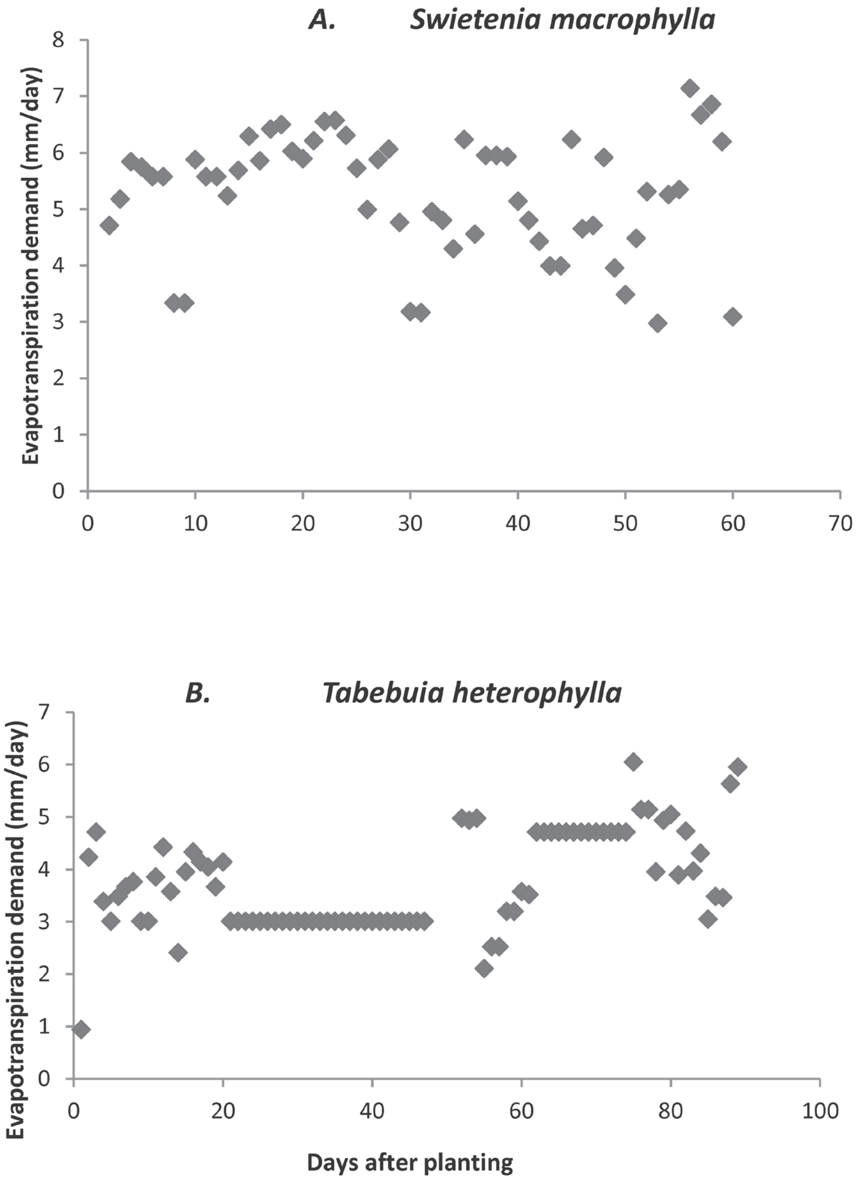


FIGURE 2. Daily evapotranspiration demand (ET_o) for *S. macrophylla* (A) and *T. heterophylla* (B). The scattered data correspond to direct measurements of ET_o by adding an excess amount of water each evening and subtracting the percolate the next morning. The straight-line segments for *T. heterophylla* correspond to estimated ET_o values.

generally lower, ranging between about 2 and 6 mm/day (Figure 2B). In both cases the ET_o ranges were within ranges of reference evapotranspiration reported for field conditions in Puerto Rico (Harmsen et al., 2004). Therefore, evapotranspiration conditions in the greenhouse experiments were considered representative of field conditions in Puerto Rico. Light intensity and wind speed inside the greenhouses were generally lower than in the field, which tended to reduce ET_o, but this was compensated by higher greenhouse temperatures that increased $ET_{o.}$

As noted earlier for the *T. heterophylla* experiment, during two time intervals it was not possible to measure ET_o directly, in which case ET_o was estimated. These two time periods and the corresponding estimated values are indicated by the straight dotted segments in Figure 2B.

Survival of Swietenia macrophylla King and Tabebuia heterophylla under different relative evapotranspiration (RET) treatments

All *S. macrophylla* juvenile trees survived at RET values of 0.5 and higher (Table 1), but only 60 percent survived at RET = 0.25 and all died at RET = 0.125. This means that the minimum RET value required for survival of *S. macrophylla* occurred somewhere between 0.25 and 0.5 (approximately in the range between 0.07 and 0.14 L/tree/day). By contrast, the *T. heterophylla* juvenile trees showed a 100 percent survival rate even at the lowest RET value of 0.125 (approximately 0.03 L/tree/day). Even though the *T. heterophylla* juvenile trees at RET = 0.125 had become completely defoliated by the end of the experiment, they were all still alive as indicated by vigorous sprouting of new leaves within two days after re-irrigating.

In terms of average daily water volumes, as little as 0.03 L/tree/day sufficed to maintain all *T. heterophylla* juvenile trees alive. By contrast,

TABLE 1.—*Number of surviving juvenile trees of T.* heterophylla *and* S. macrophylla *under different water management (RET) treatments in greenhouse experiments.*

	Number of surviving juvenile trees	
RET	*S. macrophylla* (n=5)	*T. heterophylla* (n=6)
1.0	5 (P=0.77)	6 (P=0.74)
0.75	5 (P=0.77)	6 (P=0.74)
0.50	5 (P=0.77)	6 (P=0.74)
0.25	3 (P < 0.02)*	6 (P=0.74)
0.125	0 (P<0.0001)*	6 (P=0.74)

The parameter P in parenthesis indicates the probability of encountering the observed number of surviving trees under the null hypothesis. Numbers followed by an asterisk are those for which $P \leq 0.05$.

species *S. macrophylla* required between 0.07 and 0.14 L/tree/day for complete survival. This shows a marked difference in the drought tolerance of the two species, which must be taken into account in formulating reforestation strategies. In the case of *T. heterophylla*, the required amount of water was well within the ‘typical’ range of 0.05 to 0.15 L/day produced by dew condensers with surface areas of 1 m^2 (Figure 3) indicating that dew condensers may be a viable technology for establishing this species in arid environments. By contrast, water requirements of *S. macrophylla* were very close to the upper bound of water supplying capacity of 1 m^2 dew condensers, indicating a greater risk of relying on dew condensers alone for water supply. For reforestation with such species, planting should probably be effected during periods of high rainfall probability or in conjunction with supplemental irrigation.

Figure 3 shows dew condensation data obtained with 1 m^2 condensers over a three-year period in a tropical humid environment in San Juan, Puerto Rico (Snyder et al., 2018). In this case a marked seasonal effect was observed, with more dew condensation occurring during the

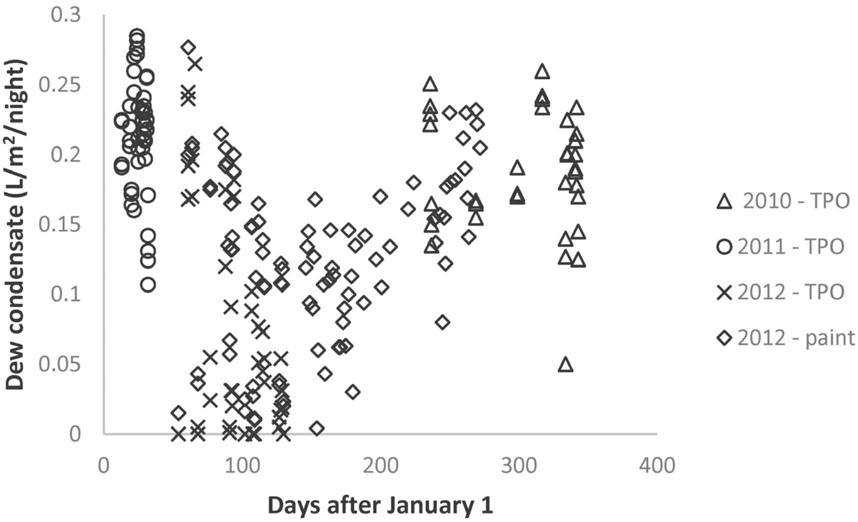


FIGURE 3. Nightly dew condensate measured over a 3-year period at Río Piedras, Puerto Rico. The dew condensers identified as “TPO” consisted of a 1 m^2 sheet of white thermoplastic polyolefin roofing material, with a rated infrared emissivity of 0.91, overlaying a 5-cm thick layer of foam insulation, with the whole assembly sloped at 30° relative to the horizontal to facilitate dew runoff. Condensers identified as “paint” were similar to the TPO condensers except that the infrared emitting surface was a coat of white roofing paint containing ceramic microspheres, with a rated infrared emissivity of 0.87. Source: Snyder et al. (2018).

longer, cooler and less cloudy winter nights that coincide with the dry season, and lower and highly variable amounts condensed during the shorter and often cloudier late spring and summer nights. Seasonal variations such as this, together with rainfall probability distributions, need to be considered in designing dew condensers for reforestation projects.

Effect of RET on biomass and spatial dimensions of plant components of S. macrophylla and T. heterophylla

Values of various plant parameters of *S. macrophylla* and *T. heterophylla* at different RET values are shown in Figures 4 through 7. The parameters shown are root biomass, stem biomass, leaf biomass, total above-ground plant biomass, stem diameter, plant height, number of leaves and leaf area. Each data point in the figures represents the mean of six replications in the case of *T. heterophylla* and five replications in the case of *S. macrophylla*. The figures generally include best-fitting linear regression lines together with the corresponding regression equations and R^2 values. Error bars are omitted from the figures in order to simplify visualization of trends in the data. However, means and standard deviations for all data points in the figures are presented in tabular form in Tables 2 to 5, together with ANOVA results indicating significant differences between means.

A linear relation between most plant parameters and RET was observed for both *S. macrophylla* and *T. heterophylla* (Figures 4 to 6). In general, the slope of the regression lines was greater for *S. macrophylla* than for *T. heterophylla*, reflecting differences in species response to environmental conditions. This linearity between plant parameters

TABLE 2.—*Mean and standard deviation of total plant dry mass (g), leaf dry weight (g), stem dry weight (g) and root dry weight (g) measured at the end of the experiment for* Swietenia macrophylla.

RET	Total dry mass (g)	Leaf dry mass (g)	Stem dry mass (g)	Root dry mass (g)
1.0	96.7 ± 19.5 a[1]	29.4 ± 17.2 a	46.7 ± 22.8 a	20.2 ± 21.5 ab
0.75	91.4 ± 14.9 a	27.0 ± 12.02 ab	43.4 ± 17.6 a	21.0 ± 23.0 a
0.5	75.9 ± 17.7 ab	21.7 ± 27.7 a	36.8 ± 23.8 ab	17.4 ± 14.0 abc
0.25	55.5 ± 5.4 bc	14.5 ± 27.2 c	27.2 ± 5.4 bc	13.8 ± 6.3 c
0.125	37.4 ± 19.3 c		23.4 ± 12.8 c	14.0 ± 14.1 bc

[1] Means within a column that do not have a common letter are significantly different ($p<0.05$) according to the Tukey test.

TABLE 3.—*Mean and standard deviation of total plant dry mass (g), leaf dry weight (g), stem dry weight (g) and root dry weight (g) measured at the end of the greenhouse experiment for* Tabebuia heterophylla.

RET	Total dry mass (g)	Leaf dry mass (g)	Stem dry mass (g)	Root dry mass (g)
1.0	16.2 ± 9.0 a[1]	6.6 ± 4.4 a	6.8 ± 4.0 a	2.8 ± 1.7 ab
0.75	14.6 ± 3.0 ab	6.3 ± 1.2 ab	5.2 ± 1.4 ab	3.1 ± 1.3 a
0.5	8.3 ± 2.5 bc	3.4 ± 1.0 ab	2.8 ± 0.9 bc	2.1 ± 1.0 ab
0.25	4.4 ± 2.5 c	0.9 ± 0.6 c	1.8 ± 1.4 c	1.8 ± 0.9 ab
0.125	3.1 ± 0.9 c		1.7 ± 0.7 c	1.4 ± 0.4 b

[1] Means within a column that do not have a common letter are significantly different ($p<0.05$) according to the Tukey test.

and RET is consistent with other observations for a large number of plant species (Doorenbos and Kassam, 1979; Taylor et al., 1983).

However, strong non-linearity was observed between RET and the number of leaves and leaf area (Figure 7). The non-linearity was most evident in the case of *S. macrophylla*, where the number of leaves and leaf area remained virtually constant for RET values between 1 and 0.5, and then dropped sharply with further reduction in RET (Table 4; Figure 7). This was precisely the cutoff point at which plant survivability of *S. macrophylla* began to decrease (Table 1). In the case of *T. heterophylla* the reduction in number of leaves and leaf area began to occur at higher RET values (somewhere in the interval 0.5<RET<0.75) and continued reducing gradually with decreased RET. We suggest that this reflects greater ability of *T. heterophylla* to adjust to even moderate drought stress by shedding leaves and therefore reducing evapotranspiration demand, as opposed to *S. macrophylla* which does not begin shedding leaves and corresponding evapotranspiration demand until high stress levels are encountered.

TABLE 4.—*Mean and standard deviation of basal stem diameter (cm), plant height (cm), number of leaves and leaf area (cm^2) for* Swietenia macrophylla *in a greenhouse experiment.*

RET	Stem diameter (cm)	Plant height (cm)	No. of leaves	Leaf area (m^2)
1.0	1.16 ± 0.22 a[1]	77.5 ± 9.2 a	64 ± 31 a	1.67 ± 0.56 a
0.75	1.08 ± 0.23 ab	69.6 ± 13.8 ab	69 ± 35 a	1.61 ± 0.91 a
0.5	0.88 ± 0.21 b	75.6 ± 12.1 ab	73 ± 24 a	1.70 ± 0.39 a
0.25	0.87 ± 0.10 b	64.7 ± 4.0 b	34 ± 15 b	0.52 ± 0.17 b

[1] Means with different letters in the same column indicate significant differences ($p< 0.05$) according to the Tukey test. For RET = 0.125, all plants died, so no measurements could be made.

TABLE 5.—*Mean and standard deviation of basal stem diameter (cm), plant height (cm), number of leaves and leaf area (cm²) for* Tabebuia heterophylla *in a greenhouse experiment.*

RET	Stem diameter (cm)	Plant height (cm)	No. of leaves	Leaf area (m^2)
1.0	0.54 ± 0.15 a[1]	32.7 ± 14.6 a	32 ± 27 a	1.28 ± 0.87 a
0.75	0.51 ± 0.12 a	32.4 ± 13.9 a	29 ± 21 a	1.27 ± 0.37 a
0.5	0.48 ± 0.09 ab	25.8 ± 9.2 b	22 ± 12 a	0.81 ± 0.31 ab
0.25	0.43 ± 0.10 b	19.9 ± 5.2 b	10 ± 6 b	0.24 ± 0.07 b

[1] Means with different letters in the same column indicate significant differences ($p<0.05$) according to the Tukey test. For the RET=0.125 treatment, plants remained alive but were completely defoliated, so measurements were not made.

SUMMARY AND CONCLUSIONS

This study evaluated the ability of *T. heterophylla* and *S. macrophylla* to survive and grow for periods of two and three months, respectively, under relative evapotranspiration rates (RET) ranging from 1.0 to 0.125. For both species, most growth parameters increased in approximately linear fashion with RET, as observed in general for many plants. Exceptions were the number of leaves and leaf area, which varied in non-linear fashion with RET. The non-linearity was greatest in the case of *S. macrophylla*, which maintained nearly constant numbers of leaves over the range of RET values from 1.0 to 0.5, with a sharp drop occurring at RET < 0.5. The species *T. heterophylla* exhibited a more gradual loss of leaves, beginning at an RET of approximately 0.75 and decreasing gradually with lower RET values. The two tree species also differed in terms of the threshold RET required for tree survival. Significant mortality began occurring in juvenile trees of species *S. macrophylla* once RET values decreased to the range between 0.5 and 0.25, corresponding to a range in irrigation water volumes of approximately 0.14 to 0.07 L/tree/day. By contrast, all *T. heterophylla* juvenile trees survived at RET values as low as 0.125, corresponding to irrigation volume of only 0.03 L/tree/day. We suggest that the greater drought tolerance of *T. heterophylla* may have been partly associated with ability to begin shedding leaves even at mild water stress levels, thereby reducing leaf surface area and the corresponding evapotranspiration demand.

The minimum water requirement of 0.03 L/tree/day necessary for survival of *T. heterophylla* is well within the typical water production capacity of 0.1 to 0.15 L/night observed for dew condensers with condensation areas of 1 m² (Berkowisz et al., 2004; Beysens et al., 2007; Clus et al., 2008; Snyder et al., 2018). Therefore, it appears that dew condensers could be a viable irrigation technology for reforestation with drought

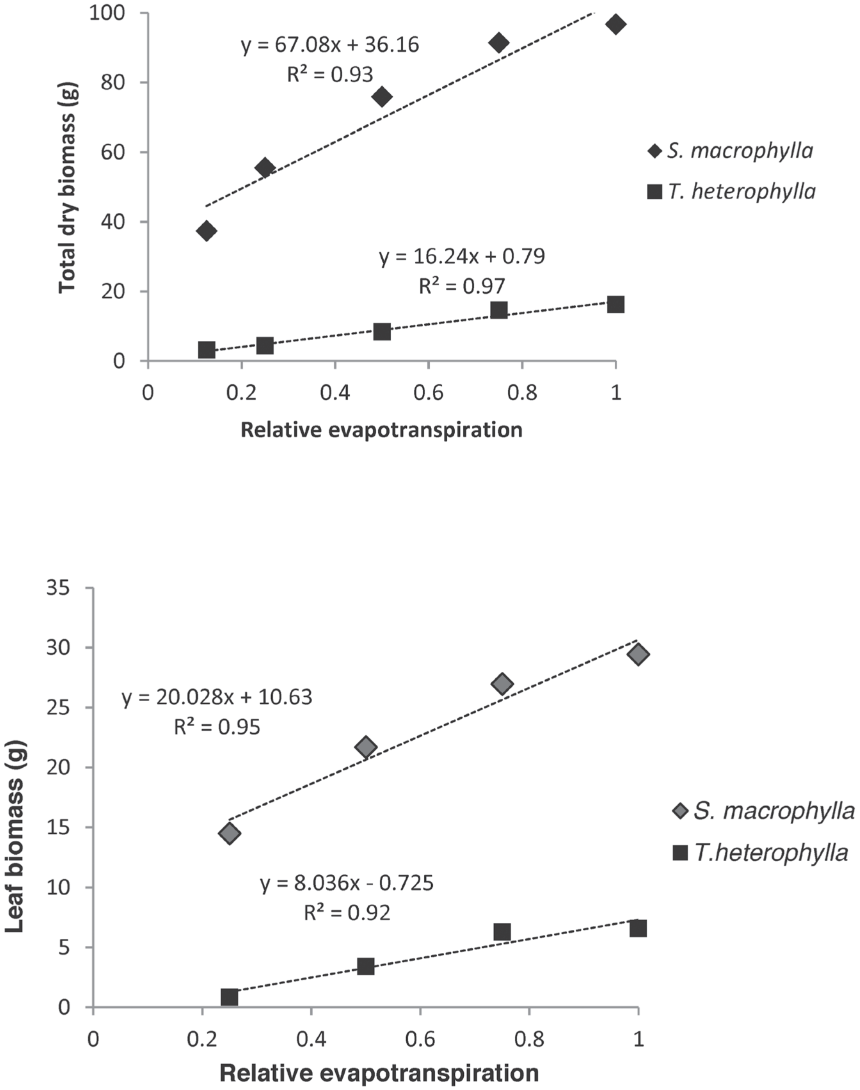


FIGURE 4. Mean values of total seedling oven-dry biomass at harvest and total oven-dry leaf biomass at harvest, as a function of relative evapotranspiration. Error bars are not shown but may be inferred from standard deviations in Tables 2 and 3. Dashed lines represent best-fitting linear regression lines.

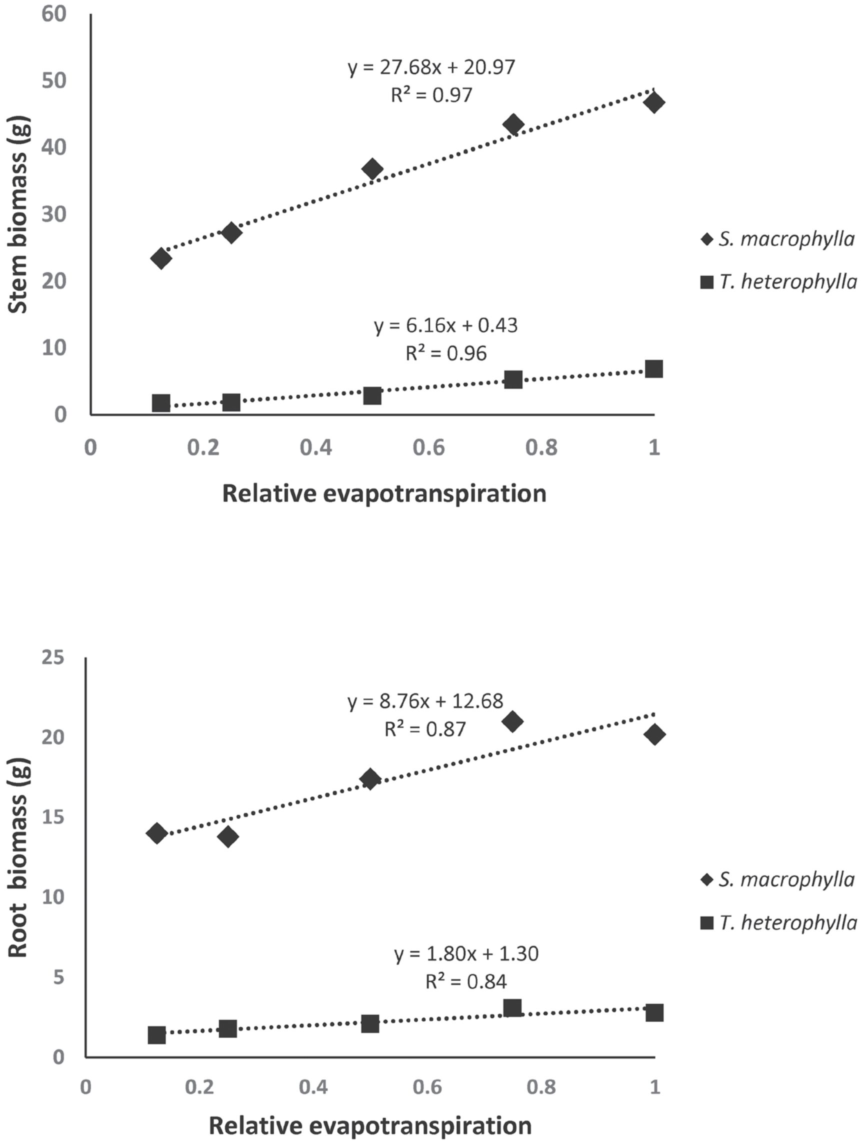
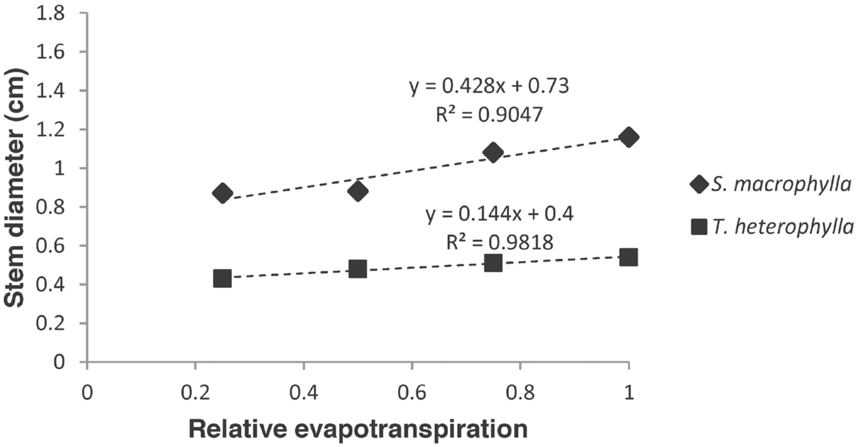


FIGURE 5. Mean values of oven-dry stem biomass at harvest and oven-dry root biomass at harvest, as a function of relative evapotranspiration. Error bars are not shown but may be inferred from standard deviations in Tables 2 and 3. Dashed lines represent best-fitting linear regression lines.



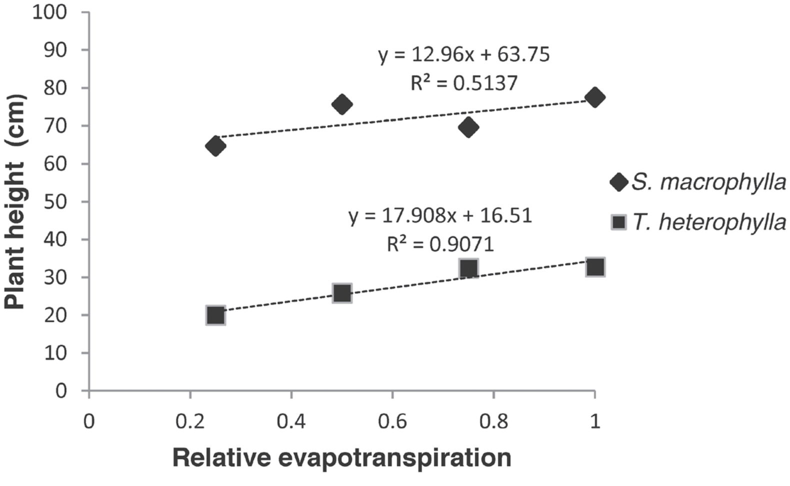


FIGURE 6. Mean values of stem diameter and plant height of *S. macrophylla* and *T. heterophylla* as a function of relative evapotranspiration. Error bars are not shown but may be inferred from standard deviations in Tables 4 and 5. Dashed lines represent best-fitting linear regression lines.

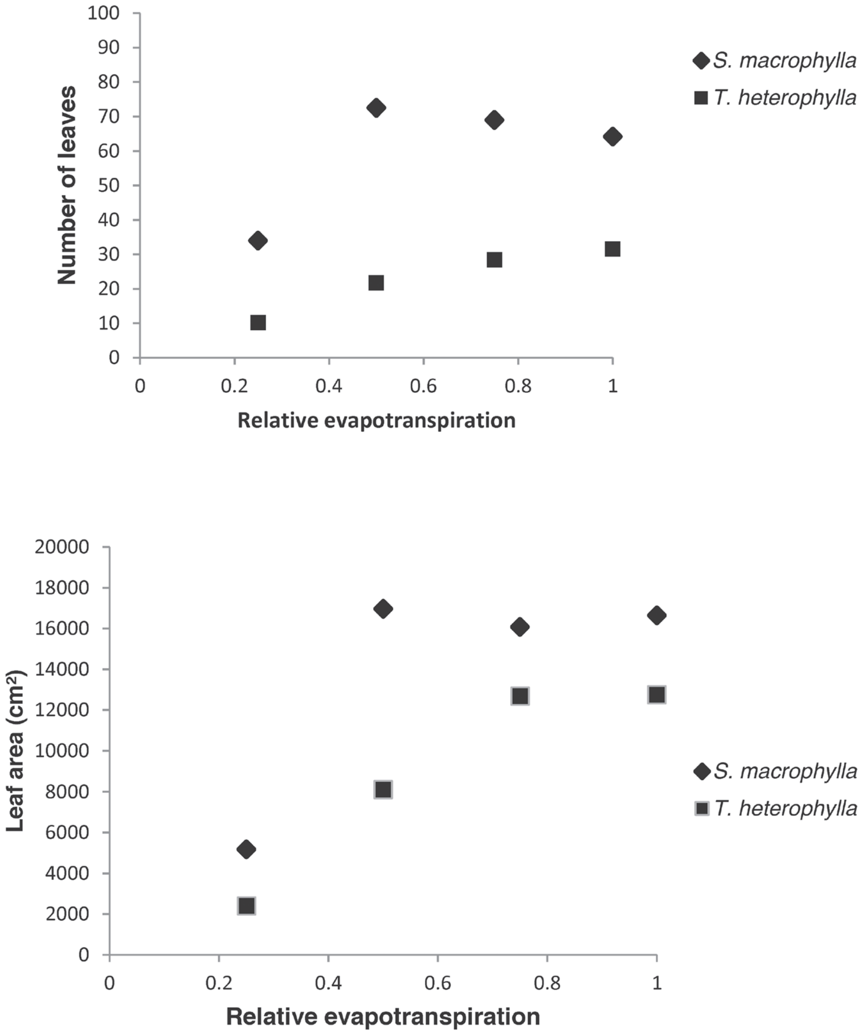


FIGURE 7. Mean values of number of leaves and leaf area of *S. macrophylla* and *T. heterophylla* as a function of relative evapotranspiration. Error bars are not shown but may be inferred from standard deviations in Tables 4 and 5.

tolerant species having water requirements similar to those of *T. heterophylla*. However, the above amounts of dew condensate may not provide sufficient safety against drought mortality of species such as *S. macrophylla* requiring on the order of 0.14 L/day for survival. For such species, it may be necessary to plan additional water supply through supplemental irrigation, increasing the condensation area of dew condensers or planting in regions and/or seasons with high rainfall probabilities.

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