Effects of tree shelters and dew condensers on establishment of young tree seedlings in an arid area in Puerto Rico

By

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Abstract

The first objective of this project was to investigate the growth and survival of seedlings of two tree species at different water levels in a greenhouse environment. The two species were the native *Tabebuia heterophylla Britton* and the exotic species *Swietenia macrophylla King* which requires more humid environments. The different water treatments were based on relative evapotranspiration (RET) demand; i.e. 1.0, 0.75, 0.50, 0.25, 0.125 and zero times the evapotranspiration demand (ET_o) of the trees. Daily evapotranspiration demand ET_o was determined by adding 400 ml of water to one pot in each replication block, measuring the amount percolated, and calculating ET_o as the difference between these two values. For both species, 100 percent survival was possible at RET values as low as 0.50. However only 60 percent of S*. macrophylla* trees survived at RET = 0.25 and no trees survived at RET = 0.125. In contrast, all *T. heterophylla* trees survived even at RET values as low as 0.125.

The second objective was to investigate the effect of tree shelters and dew condensers on the survival and early development of *T. heterophylla* under field conditions in a semiarid climate. *T. heterophylla* growth was evaluated in the field under three irrigation treatments (no irrigation, manual irrigation with 2 L of water per week, and with water supplied by a dew condenser). Each irrigation treatment was further evaluated with and without tree shelters. Treatments were imposed in a randomized complete block with 6 replications.

All seedlings survived under the different experimental treatments, but growth differed among treatments. Statistically significant differences occurred between trees with and without tree shelters, but no significant effects were associated with the irrigation treatments. Trees with tree shelters exhibited greater height than those without tree shelters, but showed reduced plant diameter, biomass and number of leaves. Tree elongation, determined as the ratio of height to basal stem diameter, was significantly greater in the tree shelter treatments, but began decreasing once tree tops emerged from the tops of the tree shelters at approximately 5 to 6 months after planting. At harvest time 18 months after planting, the stems of sheltered trees were still so weak that the trees could not stand without support.

Due to technical difficulties, amounts of dew condensate were not measured at Cabo Rojo. As surrogate estimates, data obtained from a one-year experiment at Rio Piedras were used. Typical volumes of water condensed on a 1 m^2 surface ranged from roughly 75-150 ml/night during the summer months to 150-250 ml/night during the winter months. The major cause for seasonal fluctuations appeared to be changing night length, with longer nights allowing greater amounts of dew condensation. Based on these data and minimum water requirements for tree survival determined in the greenhouse study, the conclusion is that water produced by a 1 m^2 dew condenser should be sufficient to maintain small tree seedlings alive during drought periods. This indicates the potential of dew condensers for avoiding drought failure of reforestation projects. The amount of water provided can be easily increased if necessary, by simply using larger dew condensers.

The research with tree shelters confirmed the need to maintain shelters around the trees for several years, to allow sufficient trunk development for maintaining trees erect.

Resumen

El primer objetivo de este proyecto fue investigar el crecimiento y sobrevivencia de plántulas de dos especies de árbol a diferentes niveles de agua bajo condiciones de invernadero. Las plántulas correspondieron a la especie nativa *Tabebuia heterophylla* Britton, con resistencia a sequía, y la especie exótica *Swietenia macrophylla* King, la cual requiere un ambiente más húmedo. Se aplicaron tratamientos de agua basados en diferentes fracciones de la demanda evapotranspirativa (ET_o); a saber 1.0, 0.75, 0.50, 0.125 y cero veces ET_o . Estos tratamientos se replicaron 5 veces para *Swietenia* y 6 veces para *Tabebuia*, en dos experimentos en bloques aleatorizados al azar. La demanda evapotranspirativa diaria se determinó añadiendo 400 ml de agua cada noche a un árbol en cada bloque, y tomando la diferencia entre dicha cantidad y el volumen de agua percolada la próxima mañana. Ambas especies sobrevivieron en su totalidad a fracciones de ET_o tan bajas como 0.50. Sin embargo, sólo 60 por ciento de las plántulas de *Swietenia* sobrevivieron a una fracción evapotranspirativa de 0.25, y ninguna sobrevivió a una fracción de 0.125. En contraste, todas las plántulas de *Tabebuia* sobrevieron aun a la fracción evapotranspirativa de 0.125.

El segundo objetivo fue investigar el efecto de protectores de árboles y condensadores de rocío sobre la sobrevivencia y desarrollo temprano de *Tabebuia heterophylla* bajo condiciones de campo en un clima semi-árido. Se evaluaron tres tratamientos de riego (ausencia de riego, riego manual con 2 litros de agua por semana, y provisión de agua mediante condensadores de rocio), con y sin protectores de arboles. Los tratamientos se establecieron en un diseño de bloques completamente aleatorizados con 6 repeticiones. Todas las plántulas sobrevivieron, pero el tipo de crecimiento fue diferente según el tratamiento. Se observaron diferencias significativas entre árboles con y sin protectores, pero no hubo efecto significativo atribuible a los tratamientos de riego. Los árboles con protectores mostraron una mayor altura que los árboles sin protectores, pero el diámetro basal del tronco, la biomasa total y el número de hojas fueron menores. El alargamiento de los árboles, definido como la proporción de altura a diámetro basal del tronco, fue significativamente mayor en los árboles con protectores, pero comenzó a disminuir una vez que las copas de los árboles surgieron sobre el tope de los protectores, aproximadamente 5 a 6 meses después de la siembra. Al momento de cosecha, 18 meses después de sembrar, los troncos de los árboles protegidos aun eran tan débiles que los arboles no se podían sostener sin apoyo externo.

A causa de dificultades técnicas, no se midió la condensación de rocío en el experimento de Cabo Rojo. Como aproximación, se utilizaron datos de condensación en una superficie de 1m^2, obtenidos en un estudio de 1 año en Rio Piedras, Puerto Rico. Los volúmenes de agua colectados oscilaron entre aproximadamente 75-150 ml/noche durante los meses de verano, a 150-250 ml/noche durante los meses de invierno. La causa principal de las diferencias entre verano e invierno pareció ser la longitud de noche, observándose mayor cantidad de condensación de rocío durante noches largas. En base a estos datos y al requerimiento mínimo de agua determinado en el experimento de invernadero, se concluye que un condensador de 1 m^2 debe proveer suficiente agua para lograr la sobrevivencia de arbolitos en épocas de sequía. De requerirse una mayor cantidad de agua, se puede aumentar el área de superficie de los condensadores.

Los resultados de la investigación con los protectores de árboles confirmaron la necesidad de mantener los protectores alrededor de los árboles durante varios años, para permitir desarrollo del tronco suficiente para mantener los árboles erguidos.

Dedication

To

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1 Introduction

Studies have shown that more than 1.6 billion people worldwide depend on forests for their livelihood and 60 million indigenous people are almost wholly dependent on forests (Dinh Le et al., 2012). Deforestation represents a serious socio-economic and environmental problem for these peoples in particular and for planet Earth in general (Carpenter et al., 2004). In humid tropical regions, deforestation results in loss of biodiversity and soil degradation due to erosion and loss of fertility (Mainville et al., 2006). It decreases precipitation during dry months and results in longer dry seasons. In semi-arid regions such as the Sahel, the drier climate combined with increased wind erosion associated with deforestation has led to desertification, wherein previously vegetated land becomes covered with windblown sediments. The use of the Earth is intensified by the increase in human population and therefore the negative effect of deforestation tends to get worse over time (Grainger et al., 2003). Over the past century, the area of agricultural land has doubled worldwide (Etter et al., 2006). An estimated 350 million hectares of tropical forests have been deforested and a further 500 million hectares of secondary and primary tropical forest have been degraded.

In Central America and the Caribbean, the loss of forest for crop and livestock production became a major problem after the arrival of Europeans (Griscom et al., 2011). Furthermore, only 0.5% of Central America‘s tropical dry forest are protected by some type of conservation laws, compared to 4.9% globally (Calvo-Alvarado et al., 2009).

Approximately 80% of the native vegetation of Mesoamerica has been converted to agriculture, and deforestation rates have caused the loss of biodiversity (Harvey et al., 2008).

Rapid deforestation still occurs in many tropical countries, including Haiti. In Haiti, the rate of deforestation and the extent of environmental degradation have required new approaches towards protected area management and conservation problems (Dolisca et al., 2007). Only 2% of Haiti's area is covered by permanent vegetation, in contrast to the Dominican Republic, which borders Haiti and has about 28% green cover. The lack of trees in Haiti has been very detrimental to the environment and to the Haitian population that depends on trees for construction and firewood (Mainka and Jeffrey, 2011).

Reforestation is the process by which trees are returned to areas from which they have been previously cleared. Reforestation plays an important role in the world as a means of protection that helps reduce erosion and restore soil fertility (Dou et al., 2013). In the tropics it is a potential strategy to reduce pressure on logging of remaining natural forests (Plath et al., 2010). It contributes to production of timber and other goods and services, and allows the recovery of landscape quality and biodiversity (Van Breugel et al., 2011). A study conducted of eroded land under unfavorable climate conditions by Ruiz-Navarro et al. (2009), showed that the establishment of plantations can promote better soil conditions. Reforestation projects typically progress through two main stages: an initial "establishment" phase and a long-term "building" phase (Latorre Alfonso, 1990).

One of the major challenges in the establishment phase is achieving the survival of young tree seedlings, when they are small in size and have little root development. This makes them vulnerable to damage by animals, water stress and weed competition. Particularly in arid and semi-arid environments, water stress is considered one of the greatest threats to survival and development of newly planted trees (Wang et al., 2007). In many of these regions it is difficult or impractical to apply irrigation water, requiring alternative forms of providing water.

A new technology used to reduce water stress, weed competition and animal damage in new tree plantings, is the use of tree shelters (Del Campo et al., 2006). These are vertical plastic tubes surrounding the tree trunk, which restrict sunlight intensity and air movement inside the tubes and thereby reduce evapotranspiration demand (Navarro Cerrillo et al., 2005). Tree shelters also protect seedlings from damage caused by animals, provide weed control and stimulate rapid growth in tree height (Valkonen, 2007). Tree shelters significantly reduced the effects of drought on seedling mortality during the first 2 years in a plantation forest in California (McCreary et al., 2011).

During the past decade interest has also emerged in use of passive dew condensers (requiring no external power) to satisfy the needs of drinking water in rural areas, particularly arid and semiarid areas (Muselli et al., 2009). The condensers are essentially insulated layers coated with a surface which is an efficient emitter of infrared radiation in the 8-13 μm range (range in which Earth's atmosphere is most transparent to infrared radiation). On clear nights, net infrared emission from the condenser surface to outer space causes cooling of the surface resulting in water vapor condensation (dew). Condensation rates as high as 0.5 L /m^2/night have been reported in semi-arid regions (Berkowicz et al., 2004), with frequent amounts on the order of 0.2 L/m^2/night in more humid regions (Beysens et al., 2005). On clear nights in tropical island environments, Clus et al. (2008) reported dew amounts ranging between 0.1- 0.25 L/m^2/night. The lower condensation amounts may be due to higher absolute atmospheric humidity under tropical conditions, which consequently results in more incoming atmospheric infrared radiation, than in the case of semi-arid conditions.

Dew condensation technology has been used commercially to supplement irrigation water on vegetables in Israel, with claims to reduce the amount of irrigation water by as much as 50 to 90% (Tal-Ya, 2008). This system combines nocturnal dew condensation on the top of the condenser surface with diurnal condensation of soil water vapor on the underside of the surface. Another manufacturer, (AquaPro, 2011), claims that their units have been successfully used for reforestation in desert areas. In addition to providing a surface to collect dew and rain, this unit has a storage chamber for retaining any excess mist or rain, and release water slowly to the ground through a capillary system. Its major limitation is the cost, currently about $27.00 per unit.

Due to the novelty of dew condensation techniques, so far reports have not been found in the scientific (peer reviewed) literature on the use of dew condensers in reforestation projects. Several studies suggest that tree seedlings can survive on water applications as low as 25-50 ml/day, even though biomass production (growth) under these conditions is minimal (Kumsopa et al., 1997). This suggests that the limited water provided by dew condensers may allow seedling survival during drought periods, awaiting rainfall events with sufficient water for growth.

A hypothesis investigated here is that the water supplied by dew condensers during dry season with clear sky, combined with the use of tree shelters to reduce evapotranspiration, is enough to keep tree seedlings alive until the next rainy season. This would obviate the need to transport irrigation water to tree plantations.

1.1. Objectives

1. In a greenhouse experiment, determine effects of different amounts of water relative to evapotranspiration demand on the growth and survival of seedlings of *Tabebuia heterophylla* and *Swietenia macrophylla*.

2. Evaluate the individual and interactive effects of dew condensers and tree shelters on soil moisture and survival and early development of seedlings of *Tabebuia heterophylla* in the semi-arid region of Cabo Rojo, Puerto Rico.

1.2. Hypotheses related to objectives

- If water is applied to tree seedlings in quantities less than the evapotranspiration demand, growth of *Swietenia macrophylla* and *Tabebuia heterophylla* will be reduced in proportion to the reduction in amount of water applied.
- At least 50% of the seedlings can survive on quantities of water equal to or less than 25% of the evapotranspiration demand.
- With adequate weed control, use of tree shelters and condensers under field conditions in a semiarid climate will increase growth and survival of *Tabebuia heterophylla* seedlings.

2. Literature review

2.1. Overview of *Tabebuia* species

In Puerto Rico there are two native species of the genus *Tabebuia* (Little et al., 1977). The Oak Saw (*Tabebuia rigida Urban*) is known only in the east of the island. Another common species, *Tabebuia heterophylla Britton*, known as White Cedar or “Roble Blanco”, is found in the Greater Antilles and along the Lesser Antilles from the Virgin Islands to Grenada and Barbados. It also has been naturalized in Bermuda and is grown in southern Florida. It is a medium sized tree reaching a height of 18 meters and a trunk diameter of 60 cm.

In Puerto Rico, the white cedar occurs commonly in the secondary forests which have covered much of the island since the 1950’s. It occurs in a wide variety of ecosystems ranging from very humid subtropical to dry tropical conditions, where the annual rainfall ranges from about 850 and 2500mm (Francis and Lowe, 2000). The wood, strong and hard, is used for many products. A limitation of the wood is low resistance 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. However, planting has slowed in recent years due to an invasive thrip species (*Protalebra tabebuiae)* which severely attacks young leaves (Weaver, 1990).

2.2. Overview of *Swietenia* species

The genus *Swietenia* belongs to the family Meliaceae, subfamily Swietenioideae (Wightman et al., 2008). Common tropical timber species are (*Swietenia humilis zucc*), big leaf mahogany or "Honduran mahogany" (*Swietenia macrophylla king*), and West Indian or "Dominican" mahogany (*Swietenia mahogany jacquin).* Big leaf mahogany is the most widely studied and exploited of the tropical Meliaceae, The tree can reach heights of up 50 meters, with a straight trunk up to 3 m in diameter with few branches in the first 18 to 20 meters (Brown et al., 2003). It has the advantages of being fast growing and fairly drought tolerant even on poor soils (Grogan et al., 2008). It is a species of major commercial importance in Neotropical forests, and in 2002 it became the first widely traded timber species (Grogana et al., 2005). It 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.

Both *S. macrophylla* and *S. mahogany* have adapted well in Puerto Rico, although neither is endemic on the Island. A hybrid between *S. macrophylla* and *S. mahogany*, known as "hybrid mahogany" or "Santa Cruz mahogany", was brought to Puerto Rico around 1905. Among these three species, *S. macrophylla* requires the most moisture and therefore grows best in northern Puerto Rico (Little et al.,1974). Mahogany is used more for furniture manufacturing in Puerto Rico than any other wood (Longwood, 1989). Due to its large, dense canopy, it makes an excellent shade tree and can be found bordering many streets in urban environments. In southwestern Puerto Rico, mahogany trees are often used for cattle shade on grazing lands.

2.3 Problems in tree seedling establishment

2.3.1 Water stress

A common problem in reforestation is the low percentage of seedling establishment due to insufficient water for growth and survival of plants (Villagra and Cavagnaro, 2006). Generally, tree seedlings are most susceptible to water stress during the first months after planting, when seedlings have not developed good root systems. The planting of seedlings in dry areas and degraded land is often disappointing because of high mortality and poor growth (Chirino et al., 2008). In arid and semi-arid areas during the summer, drought periods exceeding 120 days without rain can result in mortality rates above 80% for seedlings of woody species (Gindaba et al., 2004). However, even small amounts of water applied frequently can prolong survival. For example, in a field experiment in Thailand, Kumsopa et al. (1997) reported the survival of tree seedlings (Acacia) in saline soil in the absence of rain, even though only 35-50 ml of water per day per tree were applied. Water in this case was provided by rudimentary solar stills installed next to the tree seedlings, which condensed water, evaporated from the soil and dripped it near the tree trunk. In Kenya, (Mng'omba et al., 2011) found that species of *Persea americana* and *Infamous vangueria* survived on 50ml/day under hot greenhouse conditions, but suffered over 60% mortality when water application was reduced to 12.5 ml/day. It was not indicated in the publication if water was applied in the form of drip near the trunk, or if applied in a relatively large area around the trunk. In the latter case, one would expect increased evaporative water loss and reduced efficiency of use by the plant.

Pereira et al. (2006) found on the basis of various experiments that the transpiration demand T (L/plant/day) of individual trees is well approximated by the equation $T = E_o A_f / 2.88$, where E_o (with units of mm/day, or equivalently L/m^2/day) is the transpiration rate of a reference crop with leaf area index of 2.88, as estimated by the Penman-Monteith method, and A_f is the total leaf area of the tree in m². According to this equation, for a "typical" value of E_o = 5 mm/day = 5 L/m^2/day, the transpiration demand T would be 1.74 L/day for a tree with a leaf area A_f of one square meter. For a small tree seedling with leaf area of 0.1 m², the transpiration demand would be approximately 0.17 L/day. Assuming that at least 25 percent of this demand must be satisfied in order for the tree to survive, the required application of water for survival would then be 0.043 L/day. This amount of water is similar to the volumes required for seedling survival in the experiments by Kumsopa et al. (1997) and Mng'omba et al. (2011) which were cited earlier.

2.3.2 Weed control

Weeds compete with trees for light, nutrients and available soil water, and therefore represent the major biotic factor affecting the survival and growth of tree seedlings (Garau et al., 2008). Weed competition for water accentuates water stress in the tree seedlings. As an example of the effect of weeds, Kogan et al. (2002) found that lack of weed control in a pine seedling plantation reduced biomass production more than 60 percent in the early years of growth.

2.3.3 Herbivore damage

Damage by herbivores represents another biotic factor that can have a negative impact on survival and growth of tree seedlings. Research was conducted in southern Costa Rica with seedlings of four different species, planted in abandoned tropical pastures. Approximately 60% of the seedlings where cut by rabbits and only 40% of seedlings survived two years after planting (Holl and Quiros-Nietzen, 1999). Protection against herbivores on tree seedling plantation should increase plant growth and survival (Simonettia et al., 2007). In Chile, a study of herbivore effects on *Pinus radiata* and *Eucalyptus globulus* showed that *E. globulus* seedlings non-accessible to herbivores had a survival probability of 15%, while only 2.5% of herbivore-accessible seedlings were present at the end of the experiment. In *P. radiata*, survival of non-accessible seedlings was 27.5% compared to zero survival for accessible seedlings (Becerra and Bustamante, 2008). Studies on establishment of blue oak (*Quercus spp*.) in California rangelands have found that cattle damage can be significant (McCreary, 2005). Animals generally produce the most damage when the leaves of the seedlings are young (Gerhardt, 1998).

2.4. Tree shelters

Tree shelters, a newly developed concept and product, have been found to reduce or eliminate some of the above establishment problems. Tree shelters are vertically oriented, perforated translucent plastic tubes approximately 10 cm in diameter which surround the young tree seedling. They help protect recently planted seedlings from animal damage, stimulate rapid growth in height and help to control weeds (Kjelgreen and Rupp, 1997). They also reduce convective air movement in the canopy, reducing evapotranspiration demand. Chaar et al. (2008) found that tree shelters significantly reduced drought mortality of seedlings in a plantation forest during the first two years of planting.

Tree shelters were first developed in Great Britain in 1979, and different combinations of height, diameter, color and design have been tested (Oliet and Jacobs, 2007). Approximately one million shelters were used in the period 1983-1984 (Due, 1991; Dubois et al., 2000). There were 10 million in 1991. Over the past 10 years, British plastic manufacturers have produced in excess of 6 million tree shelters for use in establishing hardwood plantations (Johnson, 1997).

Research in Michigan (Lantagne, 1989) showed that the average height of sheltered northern red oak seedlings was almost twice that of unsheltered seedlings after two growing seasons. Over 64% of sheltered seedlings were 3 ft or taller, whereas only 22 percent of unsheltered seedlings were 3 ft or taller. Studies in California indicated that rapid growth in height was critical to survival of blue oak seedling, which needed to reach 2 meters in order to resist livestock and weed damage (McCreary, 2005)

A limiting effect of tree shelters is etiolation or reduced growth in stem diameter during the time period before the tree canopy emerges from the shelter. This may be due to factors such as reduced light intensity inside the shelter and lack of tree movement by wind, which stimulates stem thickening (Puértolas et al., 2010). Studies have indicated that the shelters should be maintained as tree support for some time after canopy emergence, until stems thicken enough to be self-supporting (McCreary, 2001).

2.5. Dew condensation

Dew is atmospheric humidity that is transformed into liquid water on a surface that is passively cooled by emitting heat in the form of infrared radiation (Muselli et al., 2002). This cooling effect does not usually exceed 10ºC below ambient temperature, and requires a clear sky (for efficient radiative loss) with weak wind (to prevent convective air heating). Some authors state the need for high humidity (Beysens et al., 2006), but high dew condensation rates have also been reported in arid environments (Muselli et al., 2006). This may be caused by lower probability of nocturnal clouds in arid environments, and perhaps greater atmospheric transparency to infrared radiation due to lower humidity.

In nature, dew condensate is widely used by plants and animals in arid and semi-arid environments and can supply enough moisture to microorganisms for survival (Clus et al., 2009). In India studies have reported dew as a source of water for some insects and small animals such as ants and snails (Jacobs et al., 1999). Dew also plays a beneficial role for crops by reducing water vapor pressure deficit and allows stomatal opening and photosynthesis (Wallin, 1967).

The amount of dew condensation can be increased artificially by providing an insulated layer beneath the infrared-emitting surface. Even so, the amounts of dew collected are relatively small (generally on the order of 0.1 – 0.4 L/m^2/night), but in some regions of the world dew water collection appears to be a simple solution to complement sources of potable water, particularly in regions where water accessibility and supply becomes difficult (Agam and Berliner, 2006).

In the Canary Islands, Beysens et al. (2009) showed that a small 18 square meter roof produced a total of 113 liters of dew water during the dry season, equivalent to 6.3 mm of rainfall. In a larger roof of 100 to 300 square meters, dew condensation provided from 600 to 1800 liters of drinking water. This volume is considered a safety margin of water supply for small populations (Beysens et al., 2005). Recently, a study on the Dalmatian Coast reported that the numerous deserted rain collectors (impluviums) existing in the region could potentially be rehabilitated for dew collection, by covering them with standard white TiO_2 - impregnated polyethylene foil with high infrared emissivity (Maestre et al., 2011).

On the Island of Bisevo, in Croatia, Beysens et al. (2007) found that the contribution of dew water collected in the period April 21 to October 21, 2005 was 26% of the total water (dew + rain). For tropical island environments, (Estrela et al., 2009) indicated common quantities from 0.1 to 0.2 L/m^2/night. In semi-arid regions such as Israel, numbers as high as 0.5 L/m^2/night have been reported (Jacobs et al., 2008).

Chemical analyses of dew condensate by Lekouch et al. (2010) indicated that concentrations of Ca^{2+}, K^+, and NH_4^+ in dew water were more than two times higher than in rain water, while Na^+, HCO_3^-, Cl^-, Mg^{2+} and NO_3^- were higher in rain than in dew water. Other studies showed that dew pH is usually less acidic than rain because of the short time that dew is exposed to air, which limits the absorption of gaseous CO_2, SO_x and NO_x (Lekouch et al., 2010).

The aim of the majority of studies on the use of dew condensers has been to provide potable water for human consumption. However, the technology has been used commercially to supplement irrigation water on vegetables in Israel; with claims to reduce the amount of irrigation water required between 50 to 90% range (Tal-Ya, 2008). The Tal-Ya system combines dew condensation on the upper surface of the condenser with condensation of soil water vapor on the underside, and it is uncertain which of these two sources of water is most important. The Company claims that the units can be used as a water source in reforestation projects. Another dew condenser manufacturer, (AquaPro 2011), claims that their units have been successful in the reforestation of desert areas. In addition to providing a surface to collect dew and rain, this unit has a storage chamber for retaining any excess of dew or water and release water slowly to the soil through a capillary system. Its major limitation is the cost, currently about $27.00 per unit. Unfortunately, due to the novelty of dew condensation techniques in agriculture and reforestation, and possibly skepticism by the scientific community, it is difficult to find reports on their use in the scientific (peer reviewed) literature.

3. Materials *and Methods*

3.1. Greenhouse experiment using *S. macrophylla*

3.1.1. Experimental treatments

This experiment was carried out in a greenhouse at the Alzamora experimental farm at the University of Puerto Rico, Mayaguez Campus. Seedlings of mahogany (*S. macrophylla* King) with a height of 50 cm were selected for the study. Seedlings were provided free of cost by the Cambalache nursery facility of the Puerto Rico Department of Natural Resources (DNR). The selected seedlings were planted in 10 L pots (one plant per pot), filled with a mixture of alluvium soil and organic material or compost (Cordeiro et al., 2009). The pots were placed in a plastic-roofed greenhouse open on the sides, which prevented wetting with rain but at the same time allowed air circulation and a high rate of evapotranspiration. The setup is shown in Figure 1. Six treatments were established in a randomized complete block arrangement with 5 replications. The treatments consisted of different amounts of water applied daily in the form of drip beside the trunk. The amount of water in each treatment represented a different fraction of the evapotranspiration demand (ET_o) of the trees. These fractions, termed *relative evapotranspiration rates* (RET) were 1.0, 0.75, 0.50, 0.25, 0.125 and zero.

Daily evapotranspiration demand (ET_o) was determined by adding 400 ml of water to one pot in each replication block (for a total of 5 replicate pots) in the early evening after a full day of evapotranspiration. The water was placed in a plastic cup with a wick (mop string) inserted through a hole in the bottom of the cup. This allowed the water to drip slowly into the soil during the night, much as occurs in the field under dew condensers.

The 400 ml of water added were 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 day before. The procedure was repeated daily for the same set of pots, so that the amount of water depletion in these pots never exceeded one day's worth of ET_o, and therefore the seedlings in this treatment were never under significant water stress, if any. Consequently the measured evapotranspiration could be assumed equal to the demand ET_o under the prevailing greenhouse conditions. The average ET_o for a given day was calculated as the mean of values measured for the 5 replicate pots. The corresponding relative evapotranspiration (RET) value for these 5 pots was taken as 1.0.

The other RET treatments (0.75. 0.5. 0.25, 0.125 and zero) consisted of multiplying the corresponding RET value times the previous day's average ET_o value, and adding that amount of water to each of the corresponding pots. The water was applied with the same cup and wick system as before.

Figure 1. *Swietenia macrophylla King* planted in 10 L pots in an open sided greenhouse. Irrigation treatments were applied by adding water to the plastic cup in each pot.

3.1.2. Plant phenology measurements

Various plant phenology parameters were determined *in-vivo* initially and each month thereafter in the greenhouse experiment. Plant height was measured with a ruler, and stem diameter at 10 cm above the soil was measured with an electronic caliper. At the same time the numbers of leaves on each tree were counted. To estimate leaf area, the area of three representative leaves was measured, placing the leaves “in vivo” against a sheet of paper and tracing the area with a pencil. The area outlined in the paper was then measured by digital image analysis. The tree leaf area was estimated by multiplying the total number of counted leaves by the mean area of the 3 representative leaves (Green et al., 2002).

At the end of the experiment in July 2011, the same measurements as above were made, and the number of dead and surviving trees was recorded. The trees were harvested and separated into stem, leaf and root fractions to determine fresh weights of each fraction and dry weights after drying in the oven for 48 hours at 75ºC.

3.2. Greenhouse experiment using *Tabebuia heterophylla*

A second greenhouse experiment, similar to that described above, was conducted at the same Alzamora facility, using (*Tabebuia heterophylla Britton)* as test species. The seedlings were provided by the DNR nursery facility at Arecibo. Seedlings were planted with heights ranging from 20 to 27 cm, using the same 10 L pots and soil mixture as before.

3.2.1. Treatment establishment

Five water application treatments were imposed in a randomized complete block experiment with 6 replications. The water treatments consisted of relative evapotranspiration (RET) levels of 1.0, 0.75, 0.50, 0.25 and 0.125, applied exactly as described above for the *S. macrophylla* experiment. The only essential difference was that 6 replications instead of 5 were used, and the treatment of zero RET (no water application) was eliminated.

The experiment was begun at Mayaguez in April 1, 2012. On May 2 the seedlings were transported to the Rio Piedras Research Center under the custody of Dr. Victor Snyder, since personnel were not available at Mayaguez after this date to continue the detailed water application treatments. The same treatments were continued at Rio Piedras, except for May 13 when a 400 ml drenching with a systemic pesticide suspension (15 mls of Imidochloraceph diluted in 12 liters of water) was applied to each pot from all treatments to combat a severe thrip attack that had practically defoliated the seedlings. Irrigation treatments were then continued as previously. On June 13, 2012, the seedlings were transported back to Mayaguez in the open back of a pickup truck, because it was only option available to transport the plants. During the trip, all seedlings corresponding to the 0.125 RET treatments lost their few remaining leaves due to wind damage and associated water stress. All other trees retained their leaves during the trip. Plants from the 0.125 RET treatments never recovered their leaves even though the irrigation treatments were continued one month more until July 6. To investigate whether the defoliated 0.125 RET seedlings were actually dead on this date, or were simply in a dormant state awaiting sufficient water to re-foliate, 400 ml of water were applied to each defoliated seedling. An additional one-week period was allowed to see if the plants would begin to re-foliate. All plants were harvested for biomass measurement on July 15.

3.2.2. Plant phenology measurements

Plant parameters were evaluated during this experiment exactly as for the *S. macrophylla* experiment, except that measurements were made every 15 days rather than monthly as in the *S. macrophylla* experiment. The experiment was ended on July15, 2012.

3.3 Cabo Rojo Field Experiment, related to objective 2

3.3.1 Study site

A field study was conducted at the National Wildlife Refuge located near Cabo Rojo on the southwestern side of Puerto Rico. Coordinates of the experimental site were 17º 58' 23''N; 67º 09' 46" W, and the elevation was 33.22 meters. The experiment was carried out during the period of April 2011 to July 2012.The area has a dry tropical climate with an average rainfall of 628 mm, and an average annual air temperature 27°C, with hot and dry summers and cool winters (Wildlife Refuge, 2012).). The predominant soil in the plot is Melones clay (Fine, smectitic, isohyperthermic Chromic Calcitorrerts (National Soil Survey, 2008).

3.3.2 General planting and management procedures

The overall experimental area was 15 m x 15 m, divided into 6 main blocks measuring 5 m x 7.5 m. Each block in turn was divided into 6 experimental treatment plots measuring 2.5m x 2.5 m individually. The location of each treatment within a given block was determined by randomly pulling pieces of paper out of a bag, where each paper contained a number associated with a specific treatment. The specific treatments are described below.

In each of the 36 experimental plots, a soil sample was taken with a shovel from the top 0 - 20 cm depth layer. The samples were sent for analyses to the Central Analytical Laboratory of the University of Puerto Rico Agricultural Experiment Station at Rio Piedras, Puerto Rico. Analyses performed were organic matter by the Walkley-Black wet combustion method, pH and electrical conductivity in 2:1 water: soil suspensions, Olsen-extractable P, KCl–extractable NO_3^- and NH_4^+, and exchangeable K^+, Ca^{+2} and Mg^{+2}.

In April of 2011, one *Tabebuia heterophylla* seedling measuring 50 cm in height was planted at the center of each treatment plot, for a total of 36 seedlings. The seeds had been collected in the Guanica Dry Forest reserve, near Guanica, Puerto Rico, and grown to planting age at a nearby nursery. Holes 25 cm wide and 30 cm deep were dug at the required spacing with a tractor-mounted auger, taking care to separate soil from the A horizon. Seedlings were removed from their plastic pots, placed in the holes and packed in with soil from the A horizon. No fertilizer was used. The plots were then well irrigated to provide favorable moisture conditions at the start of the experiment. Experimental treatments were established one month after planting, as described below. The study was terminated in July of 2012.

3.3.3 Experimental treatments

Three irrigation treatments were imposed (no irrigation, manual irrigation with 2 L of water per week, and irrigation water supplied only by a dew condenser). Each of these irrigation treatments was investigated with and without tree shelters, for a total of 6 treatments. The treatments were imposed in a randomized complete block arrangement with 6 replications. The treatments are identified below with the letter ***T*** followed by subscripts ***s***, ***d*** and/or ***w*** which indicate whether the corresponding treatment had a tree shelter (***s***), dew condenser (***d***) or received manual irrigation water (***w***). Lack of a given subscript indicates that the corresponding management practice was not applied.

T: Control treatment. Tree seedling with no manual irrigation, and no dew condenser or tree shelter.

T_d: Tree seedling with a dew condenser placed alongside the tree, but no tree shelter or manual irrigation.

T_{sd}: Tree seedling enclosed in tree shelter, with a dew condenser placed alongside and no manual irrigation.

T_s: Tree seedling enclosed by a tree shelter, with no dew condenser or manual irrigation.

T_w: Tree seedling irrigated manually with 1 L of water twice weekly, with no dew condenser or tree shelter.

T_{sw}: Tree seedling enclosed by a tree shelter with no dew condenser, irrigated manually with 1 L of water twice weekly.

3.3.4. Construction and installation of dew condensers

Dew condensers were constructed using the following commercially available materials.

- Polyurethane foam insulation, 2.5 cm thick, obtained from American Plastics, Inc., San Juan, PR
- Foam spray adhesive, obtained from American Plastics, Inc., San Juan, PR
- Thermoplastic polyolephine (TPO) roof surfacing material manufactured by Mulehide Corp. and represented by Danosa, Inc., Catano, Puerto Rico. Rated thermal emissivity of 0.91.
- Bubble plastic insulation, with one side covered with infrarerd-reflecting aluminum foil.

- White insulating polyurethane roofing paint with ceramic microspheres, with a rated dry thermal emissivity of 0.89, manufactured locally by Lanco Paint Co., Inc.

The dew condensers were basically multi-layer composite sheets of the different materials glued together, with planar dimensions of 3 x 4 feet creating a surface of approximately 1.1 m^2 (Figure 2). The bottom layer was the bubble plastic insulation, with the aluminum surface facing downwards to reflect infrared radiation emitted from the soil surface. The next layer was the 2.5 cm thick polyurethane foam insulation, glued onto the bubble plastic with spray adhesive. The TPO roofing material was glued on top of the foam with the white infrared emitting surface facing upwards. Finally, the TPO surface was painted with a thin layer of Urethanizer insulating paint (Lanco, Inc.) with a rated infrared emissivity of 0.87. The purpose of the paint was to transform the slightly hydrophobic TPO surface into a more hydrophilic surface, thereby facilitating water runoff, without significantly reducing the high infrared emissivity characteristic of TPO.

In order to ensure that all dew runoff from a condenser was concentrated onto a small area of ground surface, a V-shaped border was created at the lower end of each condenser, formed by heat-welding strips of TPO onto the main TPO surface. This border acted as a funnel, diverting all runoff water to the bottom of the V-notch and allowing it to pass through a small opening onto the ground beside the tree trunk. Each dew condenser was placed alongside the tree, with the V-notch close to the stem, and was held inclined at a 30° angle to maximize runoff. The inclination angle was achieved by anchoring the sides of the condenser to PVC stakes with plastic lock ties. The back of the condensers was faced against the prevailing nocturnal winds to minimize convective heat transport to the condenser surface (Sharan et al., 2007).

In addition to providing water in the form of dew, during rainfall events the condensers served the purpose of concentrating rainfall near the tree trunk. Calculation shows that for a 1 m^2 condenser surface, even a small rainfall event of 0.1 mm results in 100 ml of runoff water. Under normal rainfall conditions (with no dew condenser), such small amounts of rain water would rapidly evaporate from the soil surface and be lost to the plant. However, because of the funneling effect of the dew condenser, rainfall runoff water was concentrated over a small soil surface area which promoted deep infiltration, protecting the water from evaporation and conserving it for plant use.

3.3.5. Installation of tree shelters in the field

The tree shelters (Tree Pro ® Company, Lafayette, IN) were 8.9 cm in diameter and 120 cm tall, with pre-drilled holes in the lower half to allow ventilation of tree shelters (Figure. 3). They were constructed of polyethylene material that was selectively transparent to photosythetically active radiation (PAR), reducing the amount of total radiation reaching the interior and therefore ameliorating heating effects. The shelters were maintained upright by fastening them to vertical PVC stakes with plastic lock ties.

3.3.6. Manual irrigation procedure

For treatments T_w and T_{sw}, requiring manual irrigation, approximately 2L of water was applied to each seedling twice weekly (Rolando and Little, 2008). The water was poured onto the soil surface alongside the tree trunk, usually forming a wetted surface area of approximately 20 cm in diameter. This amount of water was applied regardless of rainfall during a given week.

Figure 2. Dew condenser for providing water to a young *Tabebuia heterophylla* seedling, Cabo Rojo, Puerto Rico.

3.3.7. Plant measurements

Seedling growth was evaluated every five (5) months. The parameters measured were total tree height, basal trunk diameter, leaf number and leaf area. Total height was measured to the tip of the dominant lateral shoot by tape measure. Trunk diameter was measured at 10 cm above the soil with an electronic caliper. An average diameter was estimated by measuring the diameter twice (in mutually perpendicular orientations) and taking the mean. Leaf area was measured by counting leaves and multiplying by the average area of a leaf sample. To estimate leaf area, the area of six representative leaflets was measured, placing the leaflets against a sheet of paper and tracing the area with a pencil. The area outlined in the paper was then measured by digital image analysis. At the end of the experiment in July 2012, plants were harvested and all leaves and stems from each plot were bagged and transported to a laboratory of Piñero building at Mayagüez. Stem and leaf fractions were measured at field moisture and after oven drying for 48 hours at 75ºC.

Figure 3.Tree shelter placed around a tree, approximately 8 months after planting, at Cabo Rojo, P.R.

3.3.8. Distributions of internode elongation of plants

Several days before harvest, trees were selected corresponding to treatments T_{sd} and T_d (trees with dew condensers with and without tree shelters, respectively) from five of the six main blocks. The length and diameter of every individual internode on each tree was determined using a caliper and measuring tape. These data were used to establish statistical distributions of elongation ratio (length/diameter) of internodes for each tree. The analysis was restricted to treatments T_{sd} and T_d due to the large number of measurements involved (10 trees were characterized, in some cases requiring more than 500 internode measurements per tree).

3.3.9. Weed control

During the duration of the field experiment in Cabo Rojo, manual weeding was conducted monthly by hoeing (Figure 4). This was done to eliminate weed competition as a variable in the experiment.

3.3.10. Soil moisture measurements

For all treatments except the control treatment, dielectric matric potential sensors (Model MPS-1, Campbell Scientific, Inc.) were installed at 15 cm depth near the tree stem and connected to Campbell Em-50 data loggers. The sensors measured dielectric constant of porous ceramic discs, the moisture content of which varied with soil water matric potential. Sensor calibrations by the manufacturer indicated that matric potentials between -5 and -500 kPa could be measured with reasonable accuracy.

Figure 4. Manual weed control in experimental plots using a hoe during the experiment in Cabo Rojo, P.R

Additionally, in all treatments involving either manual irrigation or dew condensers (treatments T_d, T_{sd}, T_w and T_{sw}), tensiometers with septum stoppers were installed at a 15 cm depth. In the dew condenser treatments, the tensiometers were installed directly under the funnel mouth of the dew condensers where they would be most sensitive to water dripped from the condensers. Tensiometer readings were made twice weekly with a Tensimeter pressure transducer instrument (Soil Measurement Systems, Inc.).

In the control plots (treatment T), gypsum blocks were installed at 15 cm depth and readings were made twice weekly with an AC resistance meter (Soil Moisture Equipment Co., Inc.). Soil water matric potential was estimated using the manufacturer’s calibration curve. Gypsum blocks, rather than tensiometers or MPS-1 matric sensors, were used in the control plots because it was estimated that the control plots would frequently dry out beyond the tensiometer or MPS-1 measurement range. Another reason was simply lack of enough MPS-1 sensors and data loggers to instrument all plots.

3.3.11. Meteorological measurements

Meteorological data were taken through the internet (www.raws.dri.edu), from a weather station of the U.S. Fish and Wildlife Service installed about 500 meters away from the experimental site. These data included precipitation, temperature, relative humidity, solar radiation and wind speed and direction.

Initially the attempt was made to measure dew condensation at the site by placing a recording tipping bucket rain gauge under a dew condenser identical to those on the experimental plots. However, recurrent technical difficulties with the rain gauge, and confounding effects of rainfall events (which were unusually abundant during the experimental period) led to the decision to discard the results. This was unfortunate since dew condensation constituted a major focus of the study. To obtain at least some idea of the amount of dew which could have been obtained at Cabo Rojo, the decision was made to use dew condenser data that had been obtained by V. Snyder during one year at the Botanical Gardens in Rio Piedras, Puerto Rico. The Rio Piedras dew condensers were made with the same materials as at Cabo Rojo, and had a similar condensing area (1 m^2). Conditions at Rio Piedras were probably more cloudy at night (a dew reducing factor) than Cabo Rojo, but on the other hand were probably less windy (a dew enhancing factor) since the condensers at Rio Piedras were further inland and were surrounded on all sides by forest areas. The qualifier “probably” is used because night cloud cover was not measured at either site, and wind speed was not measured at Rio Piedras. Night length (a major factor determining dew yield) was the same at both sites, since the respective latitudes differ by less than 1 degree.

3.3.12. Statistical analysis

Both the greenhouse and field experiments had a randomized complete block design, as described above. Statistical analyses, including ANOVA, regression and graphical representations, were generally performed with the program INFOSTAT v. 2012. Also used were graphics capabilities and statistical packages available in the Microsoft Excel™ Spreadsheet program. The specific type of statistical analysis used will be indicated when the topics are considered in the Results and Discussion section.

4. Results and Discussion

4.1. Results of greenhouse experiments

4.1.1. Environmental conditions inside greenhouses

Daily values of evapotranspiration demand (ET_o) for *S. macrophylla* and *T. heterophylla* in the greenhouse experiments are shown in Figures 5 and 6, respectively.

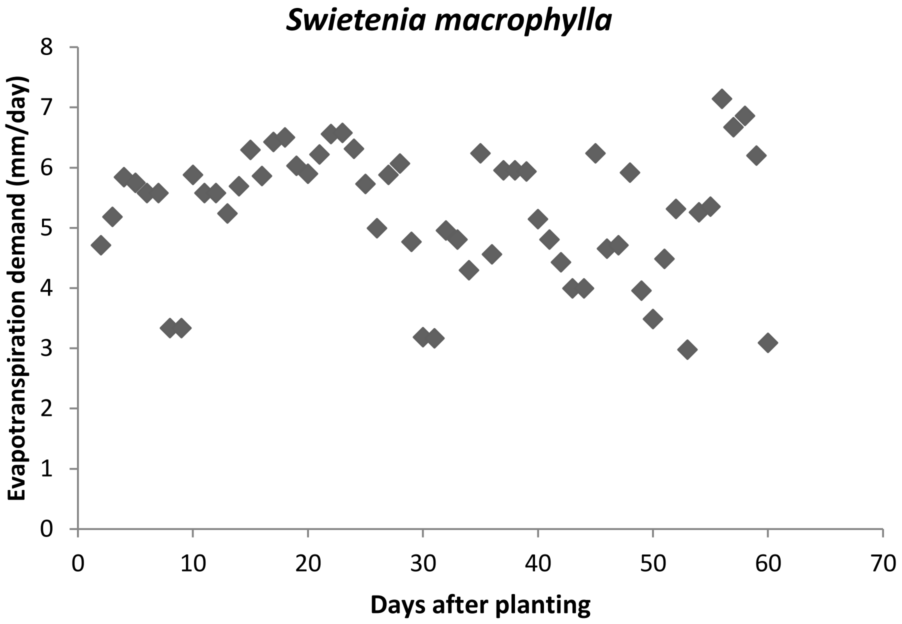

Figure 5. Daily evapotranspiration demand for *S. macrophylla* under greenhouse conditions.

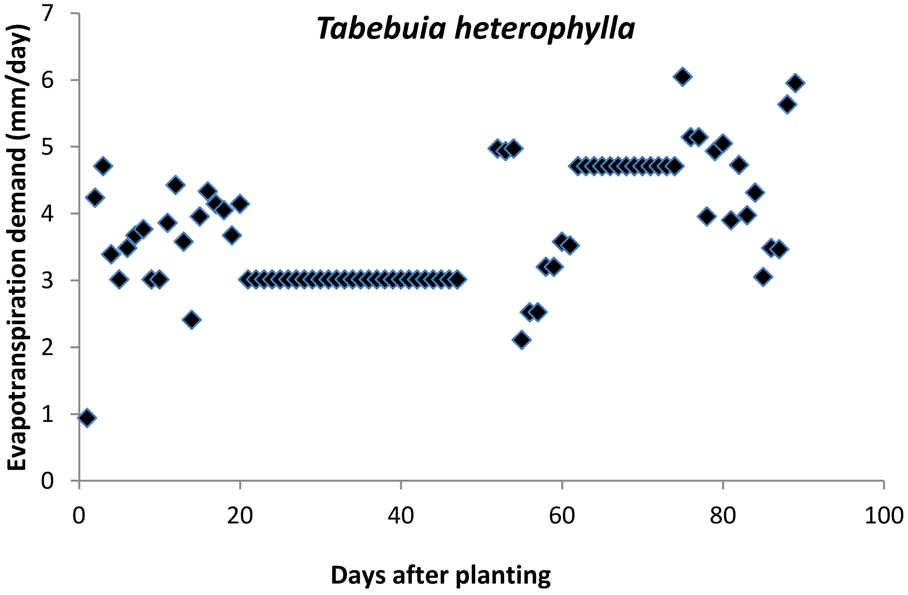

Figure 6. Daily evapotranspiration demand for *T. heterophylla*. The straight line segments correspond to periods when ET_o was not actually measured daily but was estimated equal to previous average values. The ET_o values shown for these periods correspond to the actual amount of water added daily to each pot in treatment T.

Evapotranspiration demand was higher in the *S. macrophylla* experiment than for *T. heterophylla*. Part of the reason is that much of the *T. heterophylla* experiment was conducted in a greenhouse at Rio Piedras, where temperature and light intensity were lower than at Mayaguez. After day 60, when the *T. heterophylla* seedlings were transported back to Mayaguez, evapotranspiration demand increased to values more similar to those for *S. macrophylla*.

Evapotranspiration values in both Figures 5 and 6 generally ranged between 3 and 7 mm/day, which are similar to reference evapotranspiration (ET_o) patterns reported under field conditions in Puerto Rico (Harmsen et al., 2004).Therefore, evapotranspiration conditions in the greenhouse experiments were fairly representative of conditions expected in the field. Even though light intensity and wind speed inside the greenhouses were lower than in the field, which would cause a reduction in ET_o, this was compensated by higher greenhouse temperatures that increased $ET_{o.}$

In terms of volume of water per tree, the evapotranspiration demand for the RET = 1 treatment in the *S. macrophylla* experiment averaged 278 ml/day, with a standard deviation of 7 ml/day. The average daily volumes corresponding to RET values of 0.75, 0.5, 0.25 and 0.125 were 209, 139, 70 and 35 ml/day per tree, respectively. It should be noted that these amounts of water are generally within the range of 100 – 250 ml/day typically collected by a dew condenser with a surface area of 1 m^2.

4.1.2 Survival of *Swietenia macrophylla king* and *Tabebuia heterophylla* under different relative evapotranspiration (RET) treatments.

Table 1 shows the percentage of *S. macrophylla* and *T. heterophylla* seedlings which survived at each level of imposed RET.

Table 1. Percentage survival of *T. heterophylla and S. macrophylla* under different water management treatments in greenhouse experiments. (n= 30 plants at the beginning of the experiment).

Relative ET	**Surviving plants (%)**	
RET	***S. macrophylla***	***T. heterophylla***
1.0	100 %	100 %
0.75	100 %	100 %
0.50	100 %	100 %
0.25	60 %	100 %
0.125	0 %	100 %
0	0%	

For *S. macrophylla,* all seedlings survived at RET values of 0.5 and higher, and 60% of the plants survived at RET = 0.25. Complete mortality of occurred at the RET value of 0.125.

In contrast, the *T. heterophylla* seedlings showed a 100% survival rate at all RET levels. Even the plants of the RET = 0.125 treatment, which had become defoliated during transport from Rio Piedras to Mayagüez in an open pickup truck, remained alive at the end of the experiment. This was evidenced by the fact when 400 ml of water were applied to the defoliated trees at the end of the experiment, 2 days later the trees began growing leaves (Figure 7) and were vigorously growing by 6 days (Figure 8).

Summarizing, the above results show that both *S. macrophylla* and *T. heterophylla* were able to survive at RET values as low as 0.5. However, whereas S*. macrophylla* trees survived only by 60% at the RET = 0.25 level and all trees died at RET = 0.125, *T. heterophylla* demonstrated 100 survival even at the lowest RET value of 0.125. This indicates considerable difference between ability of the two species to survive drought periods.

The sample sizes in Table 1 were insufficient to perform a Χ-square analysis for statistical significance, but results are consistent with the hypothesis that at least 50 percent of tree seedlings should survive at RET values of 0.25 or higher.

Figure 7. Sprouting leaves of *T. heterophylla* from the RET = 0.125 treatment, 2 days after receiving 400 ml of irrigation water.

Figure 8. Sprouting leaves of *T. heterophylla* from the RET = 0.125 treatment, 6 days after receiving 400 ml of irrigation water.

4.1.3. Effect of relative evapotranspiration on accumulation and partitioning of dry matter by *S. macrophylla* and *T. heterophylla.*

Tables 2 and 3 give the means and standard deviations of total dry matter and its partitioning between shoot, leaves and roots for *S. macrophylla* and *T. heterophylla* in the different RET treatments. Statistically significant differences between means, determined by ANOVA and a Tukey test are indicated by different letters following the values in the tables. In general, results do not show significant differences between means of consecutive RETD classes (for example the RETD classes 1.0 and 0.75). Rather, they reflect a gradual change in the means, with significant differences occurring only between RETD classes that are far apart (for example the RETD classes 1.0 and 0.25). The changes are monotonic, showing consistently decreasing means with decreasing RETD values.

Table 2. Means and standard deviations of total dry mass (g), leaves dry weight (g), stem dry weight (g) and root dry weight (g) measured at the end of the greenhouse experiment for *Swietenia macrophylla*.

Species	Relative ET	Total dry weight (g)	Leaves dry weight (g)	Stem dry weight (g)	Root dry weight (g)
Swietenia macrophylla	1.0	96.73±19.53 a	29.43±17.23 a	46.72± 22.76 a	20.15±21.48 ab
	0.75	91.36 ±14.86 a	26.97±12.02 ab	43.35±17.60 a	21.04± 22.99 a
	0.50	75.92±17.67 ab	21.69±27.72 a	36.84±23.83 ab	17.39±13.98 abc
	0.25	55.48±5.44 bc	14.50±27.15 c	27.21±5.44 bc	13.77±6.26 c
	0.125	37.37±19.34 cd	-	23.38±12.75 c	13.99±14.11 bc
	0	31.57±10.58 d	-	19.76±11.09 c	11.81±15.57 c

Means within a column that do not have a common letter are significantly different ($p<0.05$) according to the Tukey test. Number following ± is the standard deviation.

Table 3. Means and standard deviations of total dry mass (g), leaves dry weight (g), stem dry weight (g) and root dry weight (g) measured at the end of the greenhouse experiment for *Tabebuia heterophylla.*

Species	Relative ET	Total dry mass (g)	Leaves dry weight (g)	Stem dry weight (g)	Root dry weight (g)
Tabebuia heterophylla	1.0	16.20±8.98 a	6.60±4.36 a	6.80±4.04 a	2.80±1.70 ab
	0.75	14.60±2.99 ab	6.30±1.15 ab	5.18±1.36 ab	3.12±1.26 a
	0.50	8.28±2.46 bc	3.43±1.00 ab	2.80±0.88 bc	2.05±0.98 ab
	0.25	4.38±2.54 c	0.85±0.55 b	2.15±1.20 bc	1.38±0.99 ab
	0.125	3.10±0.85 c	-	1.70±0.59 c	1.40±0.38 b

Means within a column that do not have a common letter are significantly different ($p<0.05$) according to the Tukey test. Number following ± is the standard deviation.

Since RETD as well as the plant biomass parameters are quantitative variables, the trends indicated in Tables 2 and 3 can be further investigated by regression analysis. Linear regressions were performed relating the means of plant biomass parameters to RETD. Results are shown in Figures 9 -12 together with the corresponding scatter plots. Error bars associated with the means are not presented in these Figures, since standard deviations are already provided in Tables 2 and 3.

In all cases the relationship between plant biomass components and RET was almost linear, with r^2 values > 0.8. Such linearity between plant biomass production and RETD has been observed previously for many crops (Taylor et al., 1983).

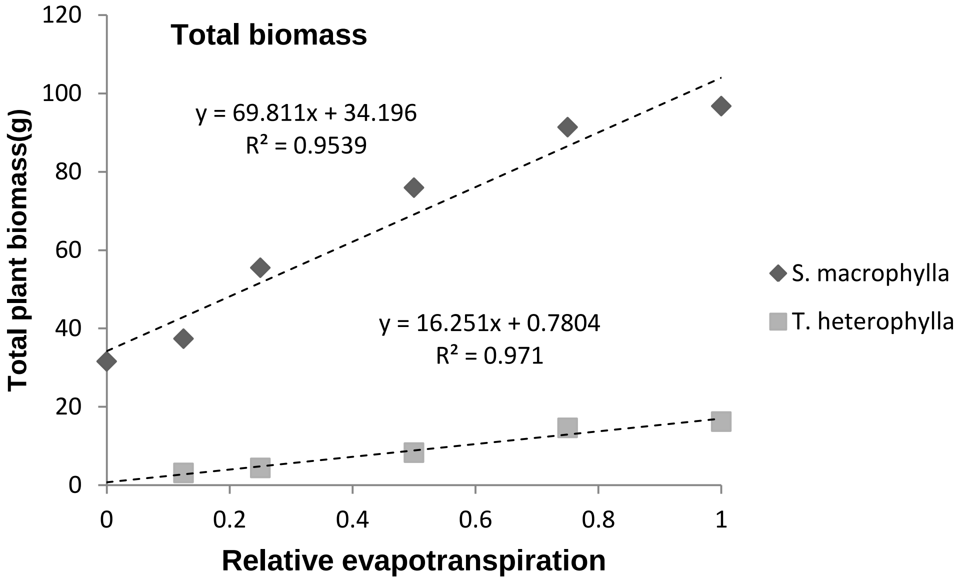

Figure 9.Mean values of total seedling oven-dry biomass at harvest, as a function of relative evapotranspiration. Error bars are not shown, but may be inferred from standard deviations in Tables 2 and 3. Dashed lines represent best – fit linear regression lines.

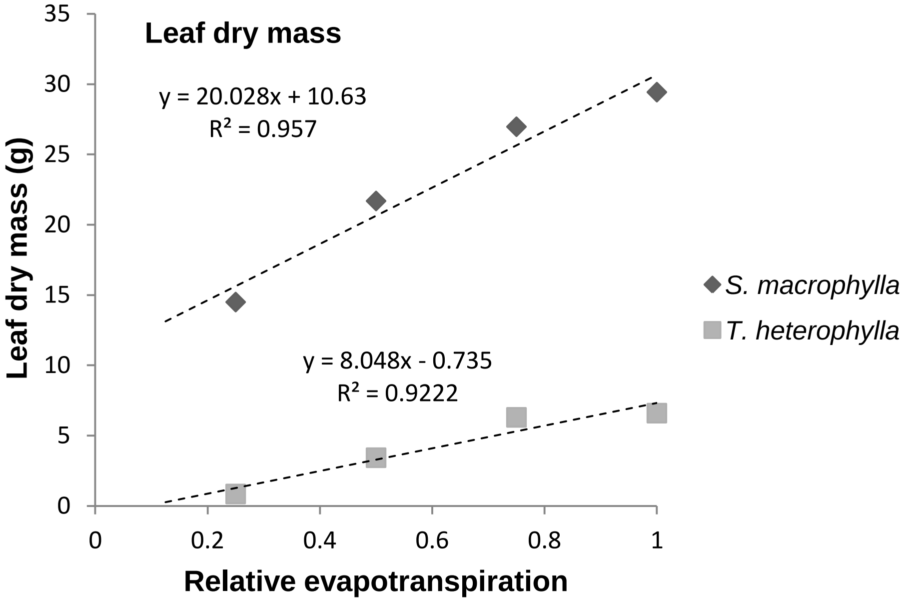

Figure 10.Mean values of total leaf oven-dry biomass at harvest, as a function of relative evapotranspiration. Error bars are not shown, but may be inferred from standard deviations in Tables 2 and 3. Dashed lines represent best – fit linear regression lines.

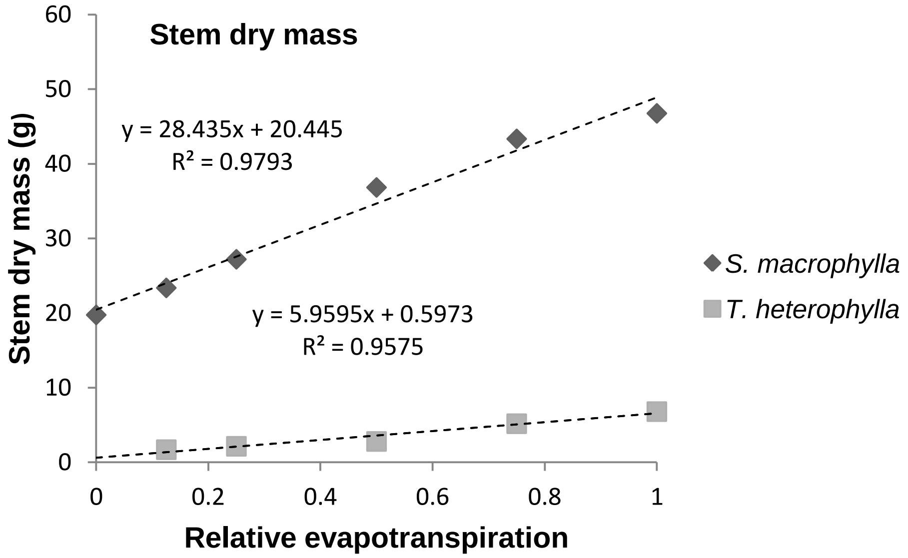

Figure 11.Mean values of stem oven-dry biomass at harvest, as a function of relative evapotranspiration. Error bars are not shown, but may be inferred from standard deviations in Tables 2 and 3. Dashed lines represent best – fit linear regression lines.

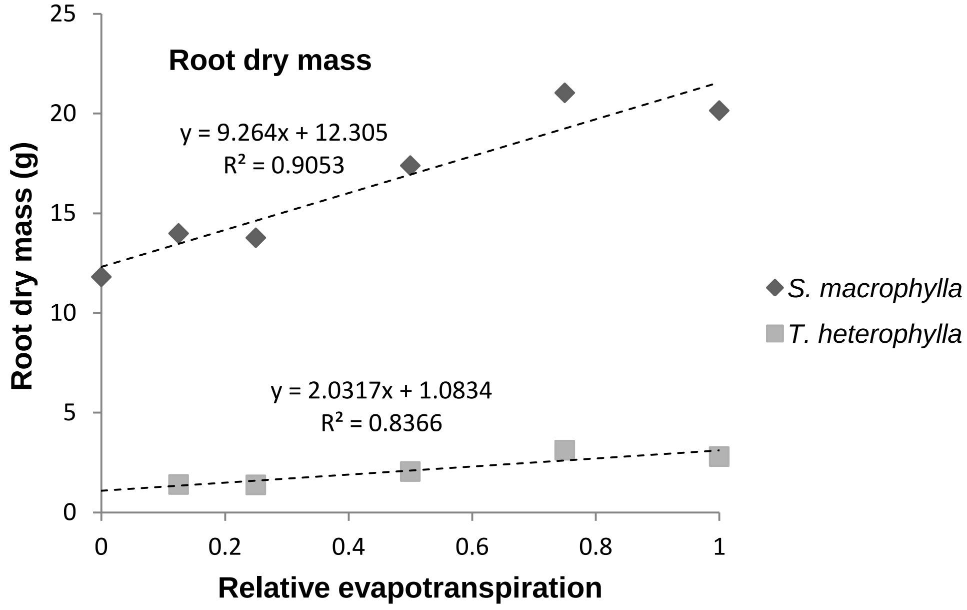

Figure 12. Mean values of root oven - dry biomass at harvest, as a function of relative evapotranspiration. Error bars are not shown, but may be inferred from standard deviations in Tables 2 and 3. Dashed lines represent best – fit linear regression lines.

4.1.4 Effect of relative evapotranspiration on dry matter partitioning by *Swietenia macrophylla and Tabebuia heterophylla*

The partitioning of dry matter between different plant components, expressed as percentage of total dry matter, is shown for the different RET treatments in Figures 13 and 14.The most notable difference between *S. macrophylla* (Figure 13) and *T. heterophylla* (Figure 14) is that *T. heterophylla* accumulated a greater fraction of its biomass in the roots at low RET values. This is one mechanism for the greater ability of *T. heterophylla* to survive drought than *S. macrophylla* (see results on drought survival discussed earlier).

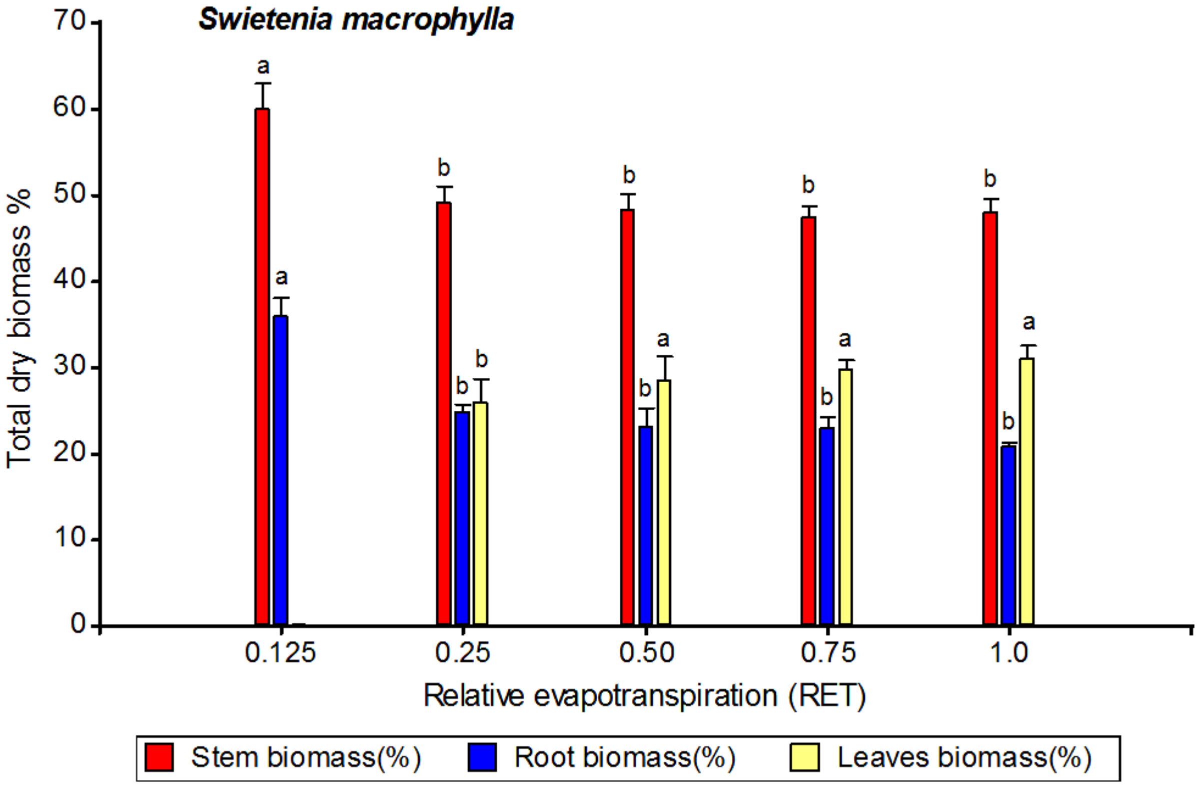

Figure 13.The percentage of stem, root and leaf biomass of *Swietenia macrophylla* after three months in the greenhouse. Plant parts were oven-dried for 48 hours at 75ºC. For RET= 0.125, no leaves were counted; all plants died. Letters indicate differences within a plant part across RET values, not among plant parts within a single RET value.

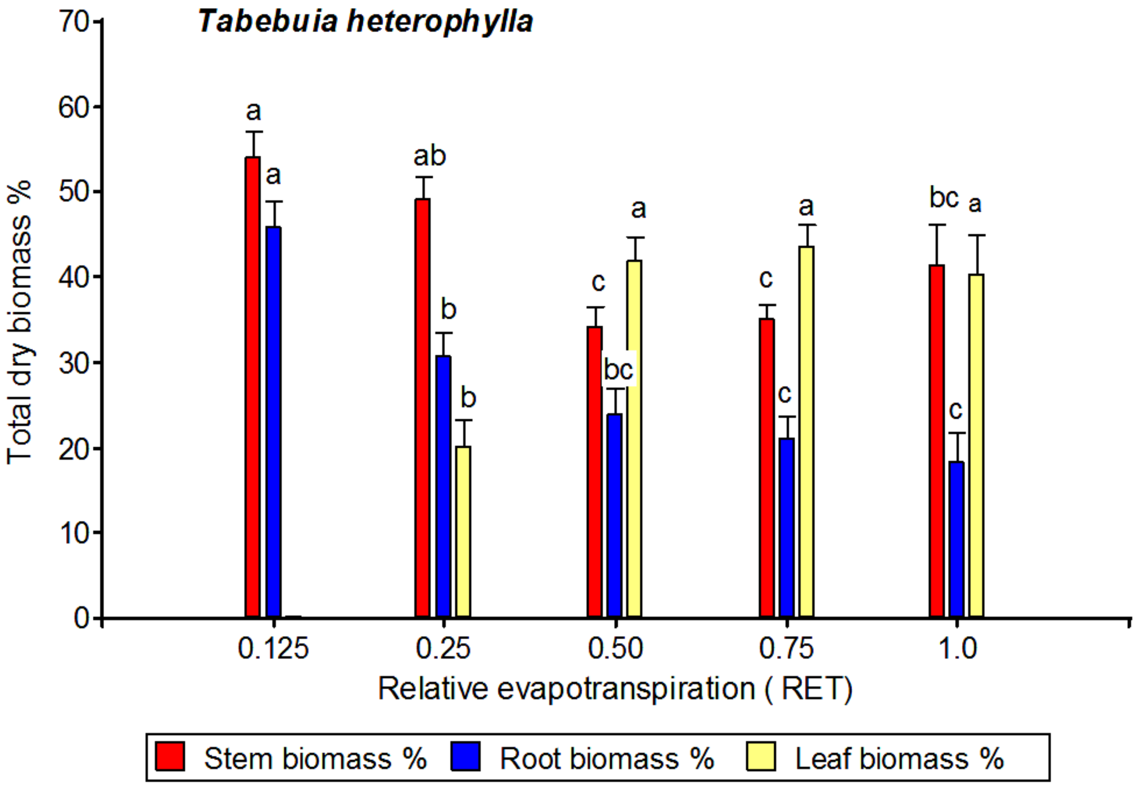

Figure 14. Percentage of stem, root and leaf biomass for *T.heterophylla* after three months in the greenhouse. Plant parts were oven-dried for 48 hours at 75ºC. For the RET=0.125 treatment, plants remained alive but were completely defoliated, so leaf measurements were not made. Letters indicate differences within a plant part across RET values, not among plant parts within a single RET value.

4.1.5 Effect of relative evapotranspiration on plant phenology of *Swietenia macrophylla and Tabebuia heterophylla*

Tables 4 and 5 give plant phenology properties at harvest for *S. macrophylla* and *T. heterophylla,* respectively, for each of the relative evapotranspiration (RET) treatments. The measured properties were basal stem diameter, seedling height, number of leaves and total leaf area. Significant differences between treatment means were determined by ANOVA and the Tukey test, and are indicated in Tables 4 and 5 by different letters alongside the treatment means. Scatter plots and linear regressions relating trends between RET and the means of the different parameters are given in Figures. 15–18.

Table 4. Means and standard deviations of basal stem diameter (cm), plant height (cm), number of leaves and leaf area (cm²) for *Swietenia macrophylla* in a greenhouse experiment.

Species	Relative ET	Diameter (cm)	Height (cm)	No. of leaves	Leaf area (cm²)
Swietenia	1.0	1.16±0.22 a	77.50±9.22 a	64.20±30.38 a	16655.69±5577 a
macrophylla	0.75	1.08±0.23 ab	69.60±13.83 ab	69.00±35.06 a	16089.32±9020 a
	0.50	0.88±0.21 b	75.60±12.11 ab	72.50±23.64 a	16968.65±3940 a
	0.25	0.87±0.10 b	64.70±4.00 b	34.00±14.75 b	5187.96±1691 b
	0.125	-	-	-	-

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. Number following ± is the standard deviation.

Table 5. Means and standard deviations of basal stem diameter (cm), plant height (cm), number of leaves and leaf area (cm²) for *Tabebuia heterophylla* in a greenhouse experiment***.***

Species	Relative ET	Diameter (cm)	Height (cm)	No. of leaves	Leaf area (cm²)
	1.0	0.54±0.15 a	32.67±14.59 a	31.64±27.10 a	12759.29±8668 a
Tabebuia	0.75	0.51±0.12 a	32.39±13.92 a	28.50± 20.53 a	12703.45±3700 a
heterophylla	0.50	0.48±0.09 ab	25.81±9.18 b	21.78±11.52 a	8118.35±3130 ab
	0.25	0.43±0.10 b	19.94±5.15 b	10.25±5.95 b	2417.67±725 b
	0.125	-	-	-	-

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. Number following ± is the standard deviation.

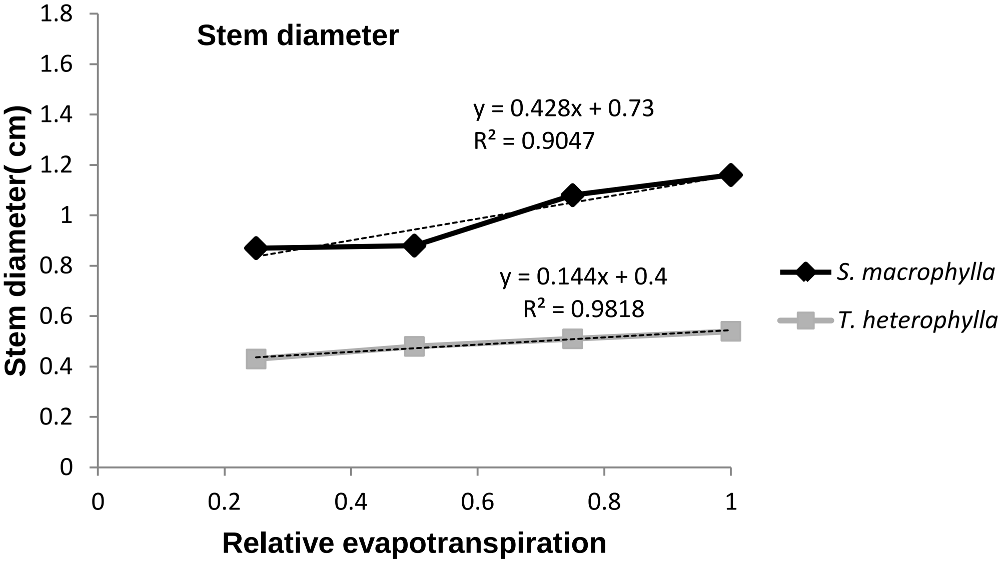

Figure 15. Mean values of S.*macrophylla* and *T.heterophylla* as a function of relative evapotranspiration. Error bars are not shown, but may be inferred from standard deviations in Tables 4 and 5. Dashed lines represent best – fit linear regression lines.

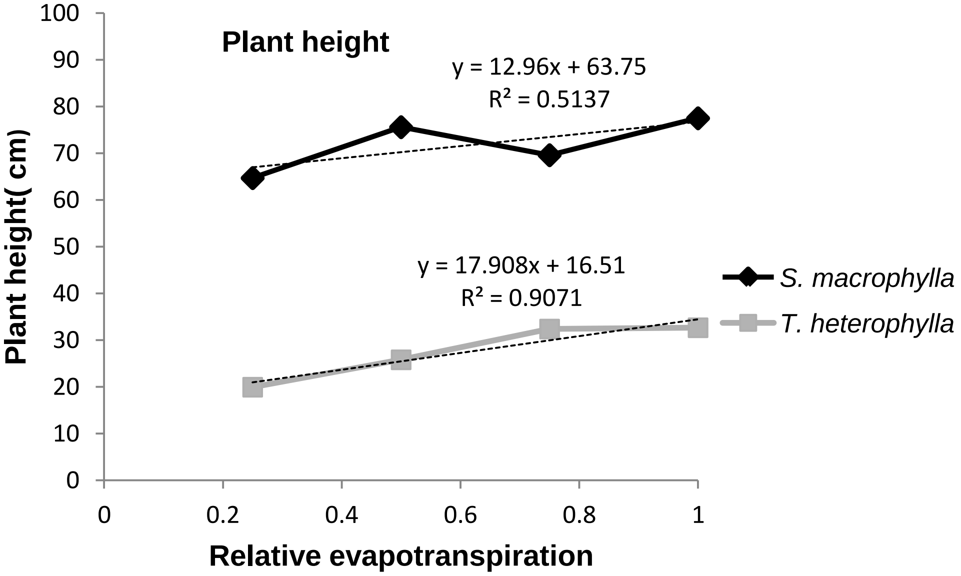

Figure 16. Mean values of *S. macrophylla* and *T. heterophylla* as a function of relative evapotranspiration. Error bars are not shown, but may be inferred from standard deviations in Tables 4 and 5. Dashed lines represent best – fit linear regression lines.

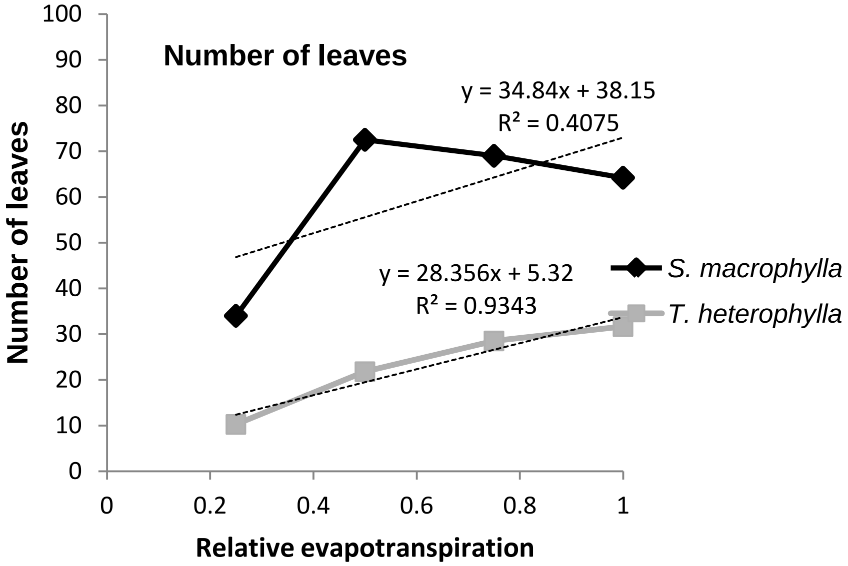

Figure 17. Mean values of *S. macrophylla* and *T. heterophylla* as a function of relative evapotranspiration. Error bars are not shown, but may be inferred from standard deviations in Tables 4 and 5. Dashed lines represent best – fit linear regression lines.

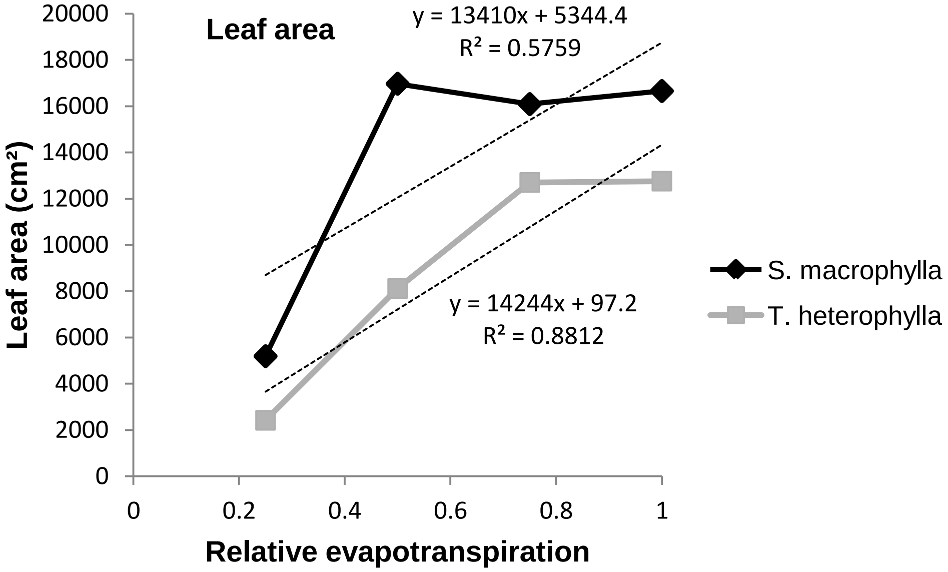

Figure 18. Mean values of *S. macrophylla* and *T. heterophylla* as a function of relative evapotranspiration. Error bars are not shown, but may be inferred from standard deviations in Tables 4 and 5. Dashed lines represent best – fit linear regression lines.

In general, ANOVA indicated that plant phenological parameters in Tables 4 and 5 were less sensitive to RET than the biomass components listed in Tables 2 and 3. Practically no statistical differences existed between phenology parameters for RET values of 1.0, 0.75 and 0.5. Only at RET=0.25 did most parameters become significantly smaller than at higher values of RET.

The means of stem diameter and plant height are regressed against RET values in Figures.15 and 16. Values of R^2 are fairly high, but in all cases the fitted slopes are quite low. The low slopes, combined with fairly high sample standard deviations shown in Tables 4 and 5, provide some explanation as to why ANOVA generally did not indicate significant differences between adjacent RET treatments.

In contrast to the approximately linear response of stem diameter and plant height to RET, the response of leaf number and leaf area was more non-linear (Figures 17 and 18). The greatest non-linearity occurred in the case of *S. macrophylla*, where leaf area remained practically constant for RET values between 1.0 and 0.5, then dropped sharply at RET = 0.25. On the other hand, the tendency for *T. heterophylla* was to begin shedding leaves at higher RET values and continue to shed them more or less proportionally with further reduction in RET. This ability to shed leaves at relatively low water stress levels may be another reason for the observed drought tolerance of *T. heterophylla*.

4.2 Results of the Cabo Rojo field experiment

4.2.1. Field environmental conditions

Figure 19 shows the monthly precipitation and reference crop evapotranspiration at Cabo Rojo during the experimental period. Rainfall was determined directly from weather station data. Reference evapotranspiration was estimated by the modified Penman–Monteith method (Kaya et al., 2011), using temperature, wind run, relative humidity and solar radiation records obtained by the weather station.

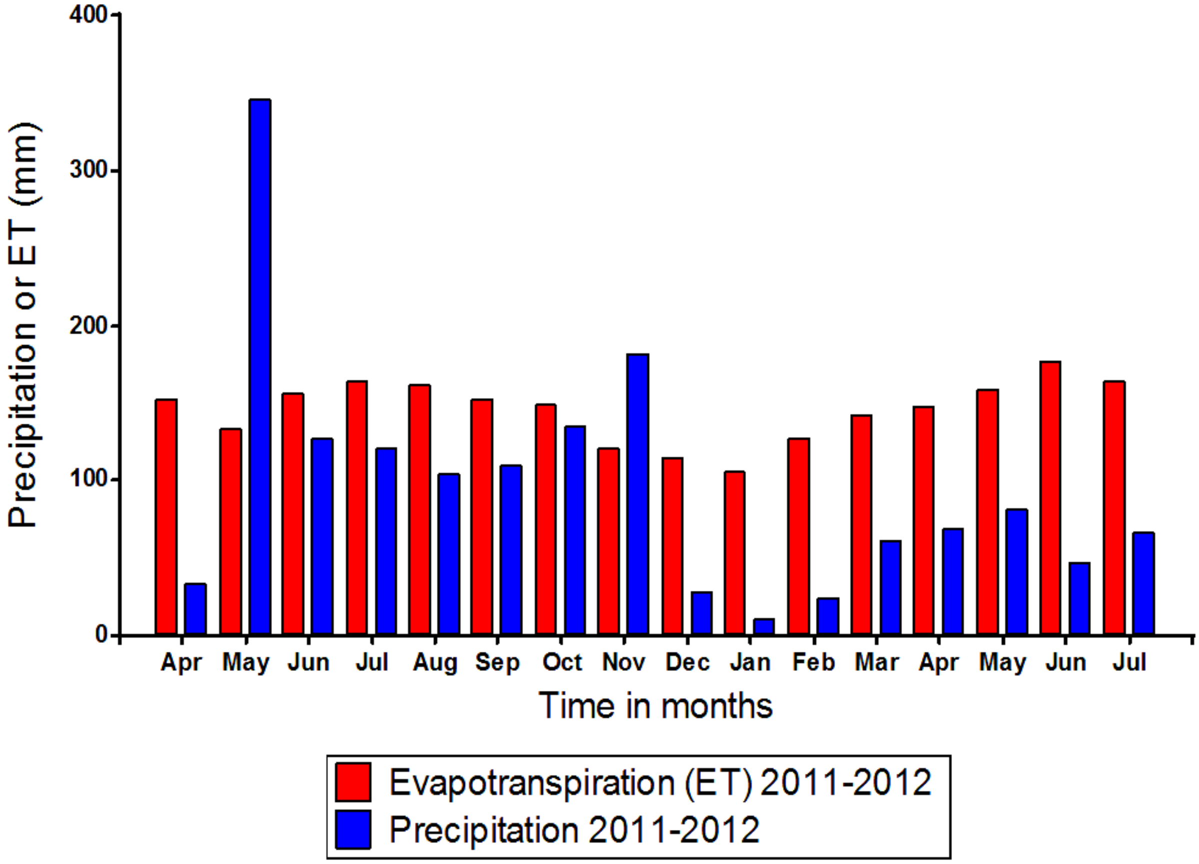

Figure19. Monthly precipitation (P) and evapotranspiration (ET) estimated by the Penman–Monteith method at Cabo Rojo, P.R.

Although conditions at planting (April 2011) were quite dry, unusually high amounts of rainfall fell during the following 7 months (May through November of 2011). Drier conditions, which had been expected, based on previous weather records, and which were necessary to test dew condensers in arid environments, did not begin until January of 2012, nine months after planting.

4.2.2. Results of soil chemical analyses

Soil chemical analyses for each main block of the experimental area are shown in Table 6. Although ANOVA indicated statistically significant differences ($p<0.05$) between blocks for some chemical parameters, in general the differences were small. The only possibly limiting chemical property in Table 6 appeared to be the low level of Olsen-extractable phosphorus, on the order of 2 ppm. The other parameters were within generally acceptable limits.

Table 6. Soil chemical data for each main block of the Cabo Rojo field experiment. The analyses were performed by the Central Analytical Laboratory of the University of Puerto Rico Agricultural Experiment Station.

		Extractable (ppm)			Exchangeable (ppm)			
Block	OM (%)	NH_3	NO_3	P	K	Ca	Mg	CE (ms/m)
1	1.83 a	4.17 ab	16.83 a	1.83 a	107.83 ab	7363.33 a	108.67 ab	244.67 a
2	1.33 a	6.33 ab	18.33 a	2.00 a	98.00 ab	7421.67 a	98.17 b	254.50 a
3	1.67 a	7.33 a	19.83 a	2.00 a	118.50 a	7314.67 a	114.50 a	267.33 a
4	1.83 a	5.67 ab	19.33 a	2.33 a	107.17 ab	7903.67 a	118.00 a	229.17 a
5	1.33 a	6.33 ab	16.00 a	2.00 a	88.67 b	6996.00 a	127.17 a	260.00 a
6	1.50 a	2.33 b	13.33 a	2.67 a	96.83 ab	7304.50 a	128.00 a	249.50 a

Means within a column that do not have a common letter are significantly different ($p<0.05$) according to the Tukey test. Legend: OM = organic matter by Walkley-Black wet combustion; NH_3 = KCl extractable ammonia; NO_3 = KCl extractable nitrate; P= Olsen-extractable phosphorus; K= exchangeable potassium; Ca= exchangeable calcium; Mg= exchangeable magnesium, EC = electrical conductivity of 2:1 water: soil extract.

4.2.3 Effect of experimental treatments on tree seedling mortality

The high rainfall during the first months after planting allowed all tree seedlings to become established with zero mortality, even in the control treatment which depended only on rainfall for its water supply. Therefore the field experiment did not provide any information on tree seedling mortality under the different experimental treatments. Measurements focused instead on tree growth parameters and soil moisture conditions during the experimental period.

4.2.4. Effect of experimental treatments on tree growth parameters

4.2.4.1. Basal stem diameter and plant height

For each of the four sampling dates, conducted at planting and at 5-month intervals thereafter, ANOVA was used to establish differences between mean values of tree stem diameter for the different experimental treatments (Table 7).

Table 7. Mean and standard deviation of stem diameter (cm) measured for each of the four sampling dates.

Treatment	sampling date and mean plant stem diameter (cm)			
	April 2011	August 2011	February 2012	July 2012
T	0.81±0.15 a	1.37±0.27 ab	2.35±0.32 ab	2.62±0.59 abc
Td	0.87±18.04 a	1.61±0.25 a	2.58±0.60 a	3.33±0.69 a
Tsd	0.93±0.10 a	1.35±1.16 ab	1.75±0.39 bc	2.21±0.65 bc
Ts	0.81±0.18 a	1.03±0.12 b	1.60±0.34 c	1.95±0.75 c
Tw	1.05±0.17 a	1.36±0.29 ab	2.53±0.64 a	3.00±0.75 ab
Tsw	0.91±0.10 a	1.21±0.20 b	1.68±0.56 c	1.84±0.67 c

Means within a column that do not have a common letter are significantly different ($p<0.05$) according to the Tukey test. Number following ± is the standard deviation.

As expected, no significant difference ($p<0.05$) was observed between treatment means on the first sampling date, which occurred the month following planting. Significant differences between means were observed on all subsequent sampling dates (August 2011, February 2012 and July 2012). However, the differences were always associated with presence or absence of tree shelters, with sheltered trees showing smaller stem diameters than those without, as found in previous studies (Arnold and Alston, 2012). No significant differences occurred between treatments with tree shelters (T_s, T_{sd} and T_{sw}) or between treatments without shelters (T, T_d and T_w). Implicit in this finding is that dew condensers and/or irrigation had no effect on basal stem diameter, relative to the control treatment. This is not unexpected given the unusually high rainfall during much of the experimental period. The above ANOVA results may be observed graphically in Figure 20, where stem diameter for the different experimental treatments is plotted as a function of sampling date. It is evident that treatments with and without tree shelters are separated into two distinct groups, with only small differences within any given group.

A very similar trend, except in the opposite direction, occurred in the case of plant height (Table 8 and Figure. 21). As before, the only statistically significant differences were associated with presence or absence of tree shelters, with no effect of dew condensers or irrigation. However, in this case the test parameter (tree height) was observed to be *greater* in the tree shelter treatments, as opposed to stem diameter which decreased in the sheltered treatments.

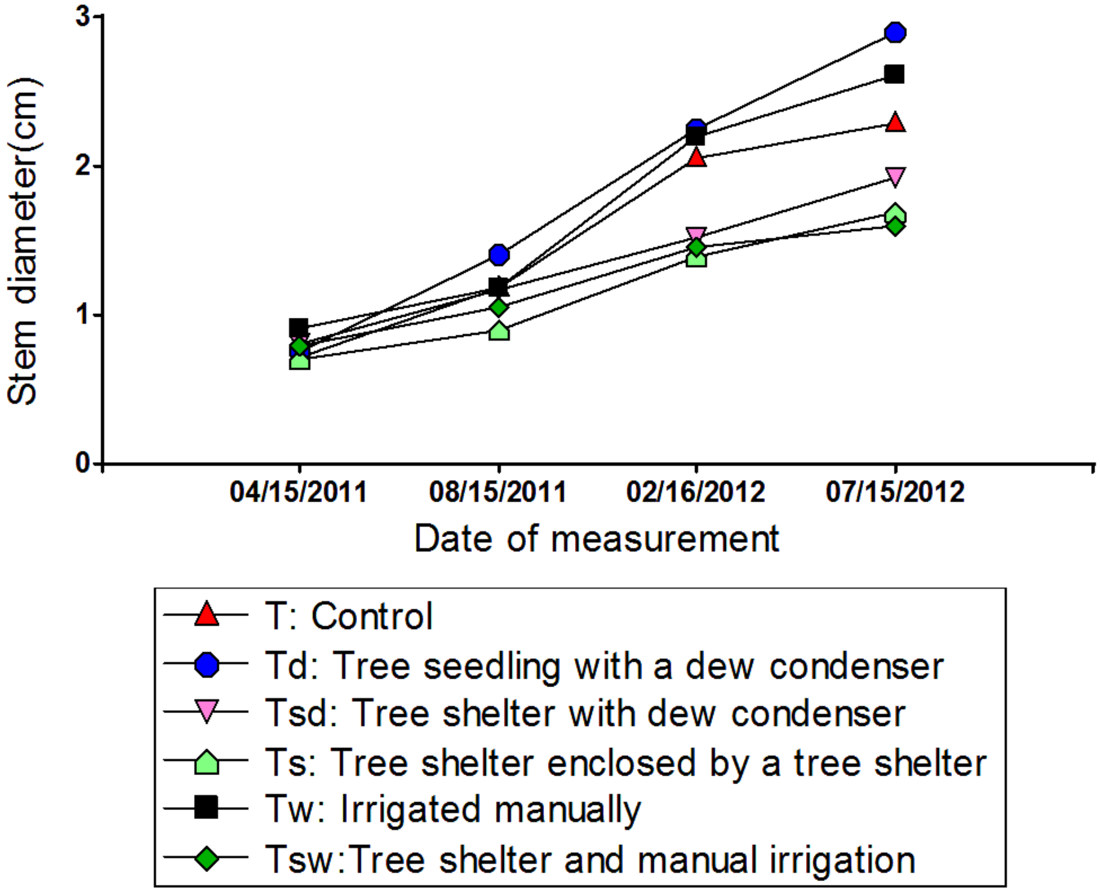

Figure 20. Basal stem diameter measured every five months, in the experimental trial in Cabo Rojo, P.R.

Table 8. Mean and standard deviation of plant height (cm) measured for each of the four sampling dates.

Treatment	sampling date and mean plant height (cm)			
	April 2011	August 2011	February 2012	July 2012
T	38.17±11.17 a	84.33±8.58 b	132.00±11.33 c	154.33±12.28 b
Td	38.50±11.59 a	88.67±21.10 b	139.00±21.73 bc	157.50±19.06 b
Tsd	38.33±26.84 a	143.50±7.09 a	172.17±8.26 ab	178.70±8.87 ab
Ts	35.00±21.53 a	135.83±15.23 a	165.50±14.03 abc	165.17±19.49 ab
Tw	41.17±20.35 a	94.17±9.12 b	141.67±16.22 bc	154.83±15.97 b
Tsw	39.50±10.83 a	147.00±16.62 a	181.17±11.50 a	195.67±11.64 a

Means within a column that do not have a common letter are significantly different (p<0.05) according to the Tukey test. Number following ± is the standard deviation.

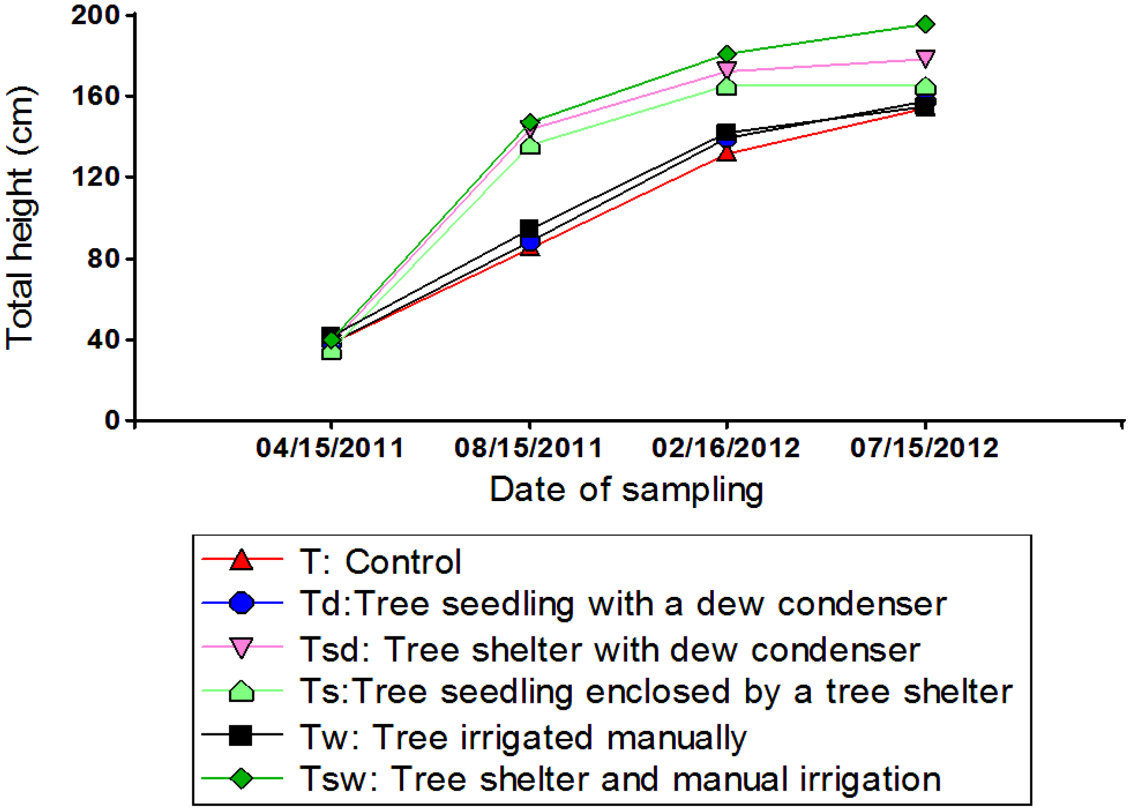

Figure 21. Total plant height measured every five months, at the experiment in Cabo Rojo, P.R.

Photographs of trees with and without tree shelters are compared in Figure 22. Particularly at the earlier dates, trees with tree shelters were so elongated and thin that they exhibited an almost vine-like appearance, and were so weak that they could not stand upright without support of the tree shelter. But even at harvest 18 months after planting the trees were very elongated and many still could not stay upright without support.

Significant elongation of trees grown in tree shelters has been observed in other experiments (Dunn et al., 1994; Costello et al.,1996; Randall, 2012), often requiring that tree shelters be left in place for several years before trees can continue growing without support.

Figure 22. (A) Saplings after growing inside tree shelter; (B) tree saplings without tree shelter, shown with dew condenser.

A parameter which better indicates the tree elongation effect is the ratio of plant height to basal tree diameter (H/D). Values of H/D are listed in Table 9 and shown graphically in Figure 23. It can be seen in Figure. 23 that the greatest elongation occurred at about 5 months after planting, just before the canopy emerged from the tree shelter. After canopy emergence, elongation decreased, manifested by gradual decrease of H/D values after 5 months.

Table 9. Mean and standard deviation of the ratio of plant height (cm) divided by stem diameter (cm)

Treatments	**Sampling date and ratio of plant height / stem diameter**			
	April 2011	**August 2011**	**February 2012**	**July 2012**
T	47.71±14.32 a	65.55±31.77 b	56.90±16.96 b	61.14±23.49 bcd
Td	46.22±28.74 a	55.74±22.64 b	54.13±8.73 b	48.04±20.18 d
Tsd	40.91±17.82 a	107.96±13.59 b	101.51±16.15 a	85.36±24.07 abc
Ts	44.99±28.82 a	132.77±17.14 a	105.19±12.81 a	93.89±33.04 ab
Tw	40.05±22.59 a	70.87±14.57 b	57.65±14.99 b	52.83±12.51 cd
Tsw	44.03±17.29 a	124.48±21.90 a	114.93±23.75 a	114.72±25.31 a

Means within a column that do not have a common letter are significantly different ($p<0.05$) according to the Tukey test. Number following ± is the standard deviation.

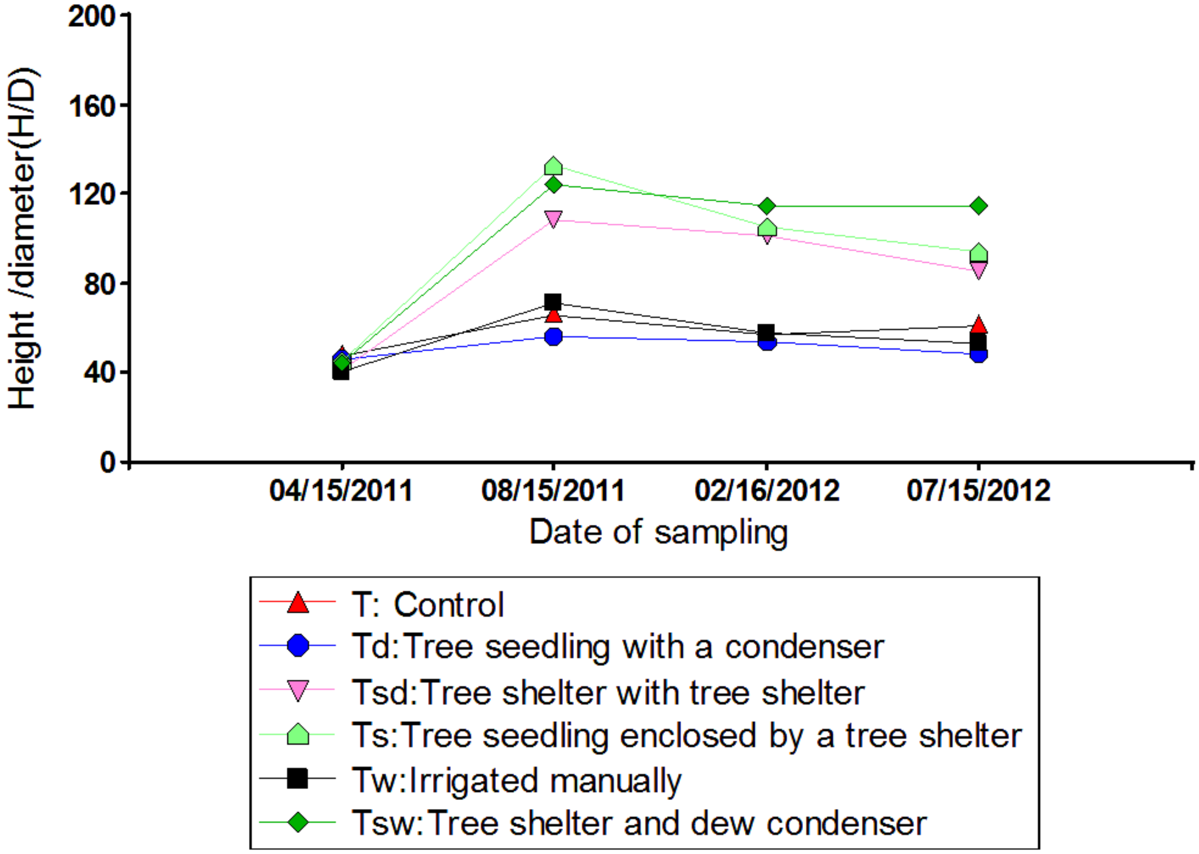

Figure 23. The ratio of plant height to basal stem diameter (H/D) measured every five months, in the experiment in Cabo Rojo, PR.

4.2.4.2. Distributions of the elongation ratios (L/D) of internodes

In general, the internode length divided by branch diameter (L/D) distribution for trees without tree shelters were symmetrical around the mean, as illustrated in Figure 24A, whereas distributions for tree shelters were more asymmetrical with significant “tailing” toward larger L/D values (Figure 24B). In both cases the data could be fitted well to Weibull distributions, indicated by the curved lines in Figures 4 A and B.

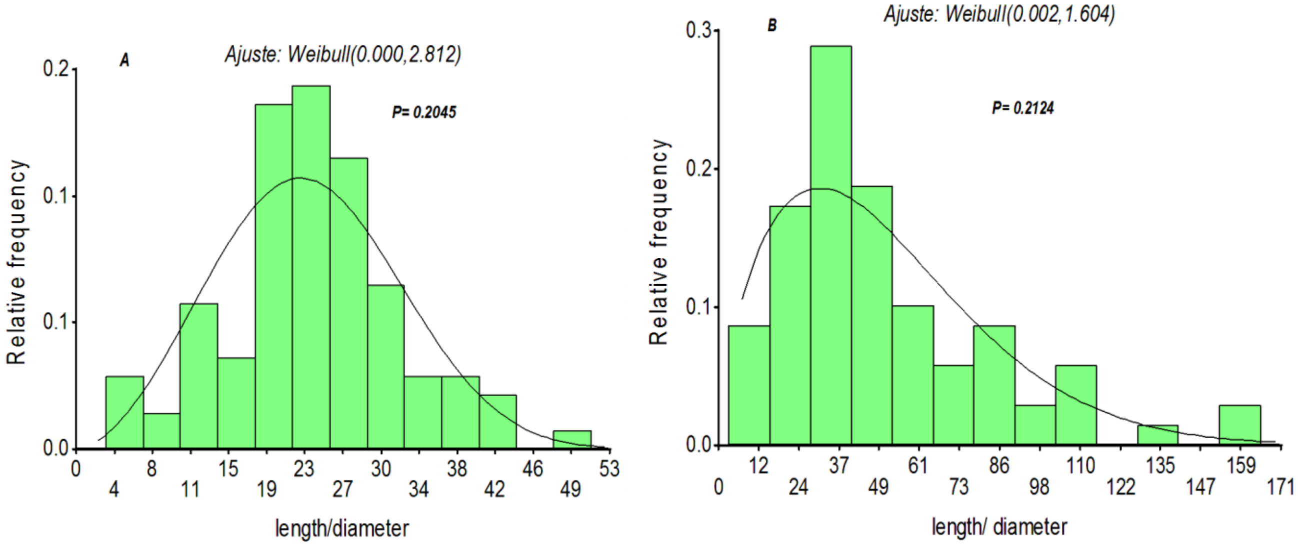

Figure 24. (A) Symmetrical distributions of L/D values for trees without shelters; and B) Asymmetrical distributions with trees shelters. The curved lines represent fitted Weibull distributions. The P-values > 0.05 indicate non rejection of the null hypothesis that the distribution is Weibull, according to the Kolmogorov criterion.

Table10 lists the mean and median values for the L/D distributions with and without tree shelters in each of the five replication blocks, along with coefficients of variation (CV) and the difference between mean and median (mean – median) values. Average values for each parameter are listed in boldface at the bottom of the table. An asterisk (*) alongside a given average value for the tree shelter treatment indicates that it was statistically different (P<0.05) than the corresponding value for the no-shelter treatment.

Table 10. Parameters for the L/D distributions of trees with and without tree shelters, listed for each replication block.

Replication	Trees with tree shelters				Trees without tree shelters			
	Mean	median	mean-median	CV	mean	median	mean-median	CV
1	50.2	41.9	8.3	0.67	23.6	23.5	0.1	0.18
2	43.7	36.7	7.0	0.55	30.1	30.0	0.1	0.38
3	39.5	32.6	6.9	0.61	31.0	31.1	0.1	0.37
4	41.6	36.4	5.2	0.4	27.3	26.9	0.4	0.36
5	29.4	25.7	3.7	0.52	37.3	36.0	1.3	0.38
Average	**40.9***	**34.7***	**6.2***	**0.57***	**29.9**	**29.5**	**0.4**	**0.33**

*. The presence of an asterisk (*) alongside a given average value for the tree shelter treatments indicates that it was statistically different ($p< 0.05$) than the corresponding value for the no- shelter treatments. Significant differences were established using a two sample t-test for samples with unequal variance, available in the Excel^{TM} data analysis module.

The L/D distribution means in Table 10 were significantly greater for the tree shelter treatments than for the no-shelter treatments, consistent with the greater ratio of tree height to basal trunk diameter mentioned earlier. The greater distribution asymmetry for the tree shelter treatment, observed in Figure 24B, is reflected in Table 10 by a significantly greater difference between the mean and median (*mean – median*) for the sheltered T_{sd} treatment than for non-sheltered T_d treatment. In the sheltered treatments the mean always exceeded the median, since the mean was influenced by the long tail of the distribution at high L/D values. In contrast, for non-sheltered trees the *mean – median* parameter was nearly zero, reflecting the symmetry of the L/D distributions. The greater distribution asymmetry for the tree shelter treatments was also reflected by a significantly greater coefficient of variation in L/D values than for the non-sheltered treatments.

4.2.3.3. Number of leaflets per tree

The mean number of leaflets per tree (proportional to leaf area) for each treatment and sampling date is summarized in Table 11 and Figure 25.

Table 11. Mean and standard deviations for number of leaflets on *Tabebuia heterophylla* on four sampling dates.

Treatments	sampling date and mean number of plant leaflets			
	April 2011	August 2011	February 2012	July 2012
T	62.33±13.71 a	841.50±32.93 ab	2202.50±29.54 ab	1619.83±34.12 a
Td	70.17±30.27 a	1104.50±51.34 a	2859.50±83.47 a	1495.00±66.07 a
Tsd	72.17±33.52 a	527.17±19.51 b	651.83±55.10 b	787.10±67.48 a
Ts	47.83±12.30 a	383.83±15.23 b	620.33±43.76 b	782.50±43.63 a
Tw	56.17±20.21 a	1060.50±24.46 a	2134.00±68.60 ab	1171.33±52.72 a
Tsw	62.83±25.59 a	514.33±45.03 b	1053.00±54.67 ab	1222.50±56.56 a

Means within a column that do not have a common letter are significantly different ($p<0.05$) according to the Tukey test. Number following ± is the standard deviation.

As in the case of basal trunk diameter and plant height, the greatest effects on number of leaflets were associated with tree shelters. When no tree shelters were used, the number of leaflets initially increased rapidly over time up to the third sampling date. During this period the sheltered trees also showed a steady increase in leaflet number, but at a much lower rate than the unsheltered trees.On the last sampling date the unsheltered trees showed a sharp drop in the number of leaflets, whereas the shelteres.

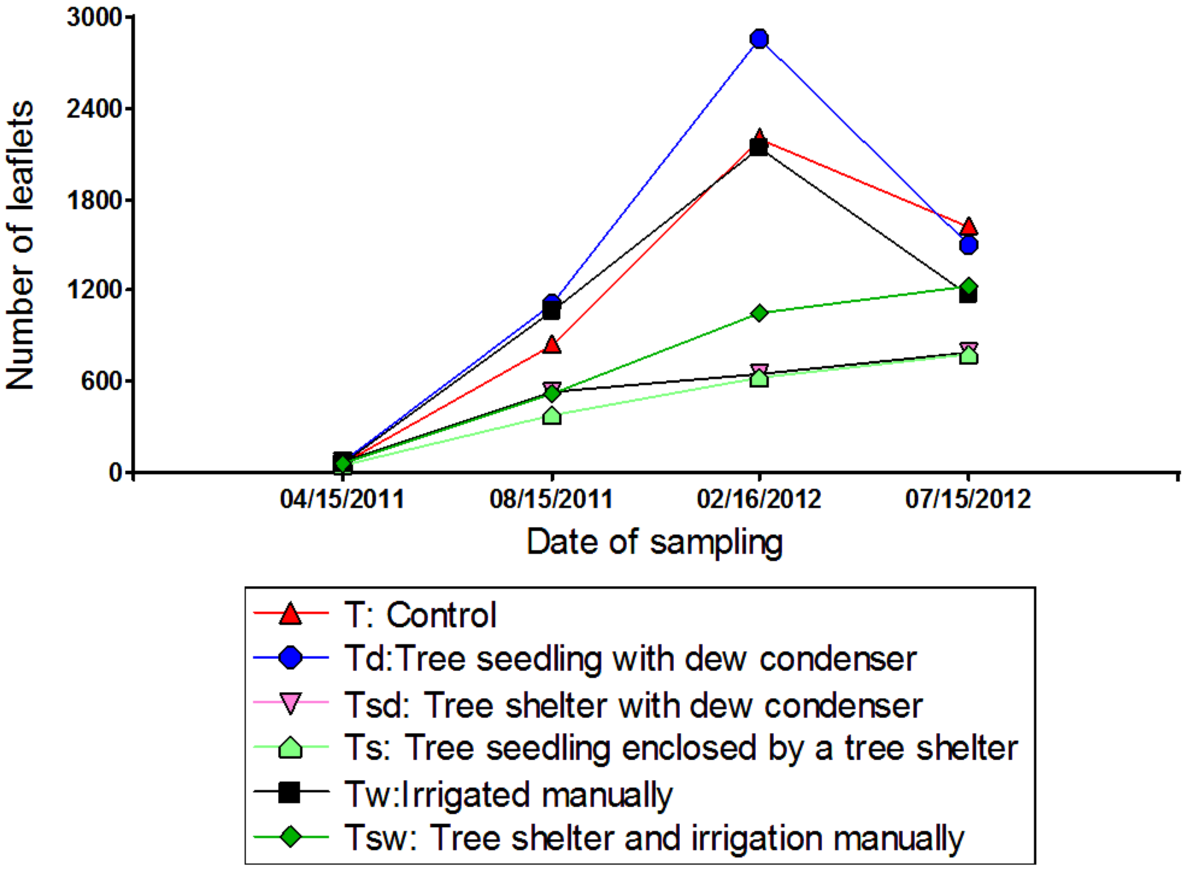

Figure 25. Total number of leaflets counted manually each five months, at the experimental trial in Cabo Rojo, P.R.

trees maintained the same small rate of increase as before. The sharp loss of leaflets for the non-sheltered trees during the last sampling interval (Figure 25) was very likely a water stress protection mechanism responding to drier weather during that period. The sheltered trees, on the other hand, had fewer leaflets to start with at the beginning of the dry period, so they did not have to shed as many leaflets to adjust to drought.

4.2.4.4. Effect of experimental treatments on dry matter accumulation and partitioning

The dry mass of stems and leaves at harvest, together with total dry mass, are shown in Table 12. The root fraction was not harvested, to allow re-growth of the trees as requested by administrators of the Cabo Rojo Fish and Wildlife Reserve. As of this writing, 25 of the 36 trees planted originally have sprouted new growth from the stumps left after harvest.

For total biomass and stem biomass, the only treatment having any enhancing effect was the dew condenser treatment (T_d). This difference occurred with respect to the 3 tree shelter treatments T_s, T_{sd} and T_{sw}. All other comparisons among treatments yielded no significant differences. For leaf biomass, the dew condenser treatment T_d yielded significantly higher yields than all other treatments except the control (T). It is difficult to draw strong conclusions from these data. But results do indicate that whenever significant differences in biomass components occurred between treatments, they were usually in favor of the dew condenser treatment T_d.

When stem and leaf biomasses were expressed as fractions of total biomass (Table 13), no significant difference occurred between treatments. Thus, increases in stem and leaf biomass were a function of total biomass increase instead of differences in allocation.

Table 12. Means and standard deviations of total dry mass, shoot dry weight and dry weight of leaves of Tabebuia heterophylla measured at harvest in the experiment at Cabo Rojo, P.R.

Treatment	Total dry mass (g)	Stem dry weight (g)	leaves dry weight (g)
T	655.73±33.73 ab	550.88±37.33 ab	104.85±30.93 ab
Td	890.75±73.24 a	754.00±80.94 a	136.75±36.20 a
Tsd	334.65±59.77 b	278.58±65.12 b	54.21±55.16 c
Ts	323.62±52.26 b	267.03±54.87 b	56.58±41.49 bc
Tw	719.88±50.41 ab	632.00±55.41 ab	87.88±22.20 bc
Tsw	383.72±64.71 b	325.18±69.16 b	58.53±53.24 bc

Means within a column that do not have a common letter are significantly different ($p<0.05$) according to the Tukey test. Number following ± is the standard deviation.

Table 13. Mean and standard deviation of total harvested tree biomass (%) contributed by stems and leaves for the different experimental treatments at Cabo Rojo, Puerto Rico.

Treatment	Leaf biomass (%)	Stem biomass (%)
T	16.75±5.39 a	83.25±6.47 a
Td	18.56±6.14 a	81.44±7.54 a
Tsd	17.25±8.48 a	82.75±10.25 a
Ts	18.58±3.90 a	81.42±4.79 a
Tw	14.50±5.81 a	85.50±6.79 a
Tsd	16.07±7.68 a	83.93±9.15 a

Means with the same letter are not significantly different ($p<0.05$) according to the Tukey test.Number following ± is the standard deviation.

4.2.4.5. Relation between basal stem diameter and total above-ground biomass for seedlings with and without tree shelters

Basal stem diameter is often used as an indicator of total above-ground biomass. Regression between these two parameters is shown in Figure 26. Separate regressions were conducted for trees with and without tree shelters. The coefficient of determination (R^2) was virtually the same for both regressions. But the slope of the regression line for trees without shelters was almost twice the slope for sheltered trees. This result can be attributed to greater stem elongation observed above for the sheltered trees.

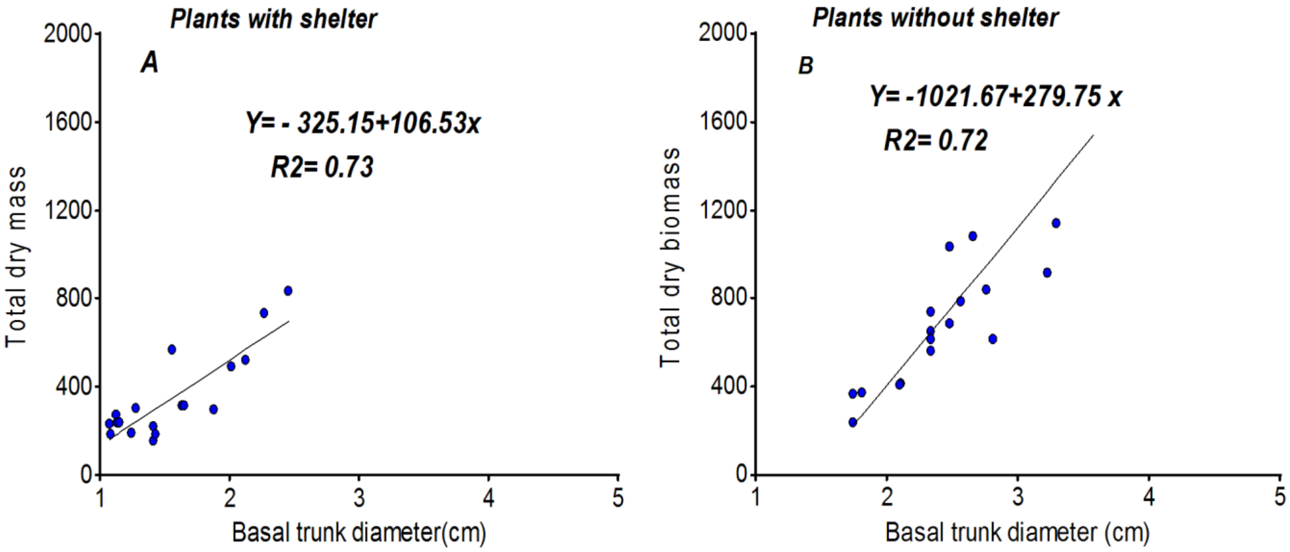

Figure 26. (A) Linear relation between basal stem diameter and total dry mass for tree seedlings growing inside tree shelters; (B) Linear relation between trunk diameter and total dry mass for tree seedlings without tree shelters.

4.2.5. Soil moisture measurements

Figure. 27 shows a time-series of soil water matric potential measured at 15 cm depth with the MPS-1 dielectric sensors. As noted earlier, the factory calibration was used to infer matric potential from the MPS-1 readings.

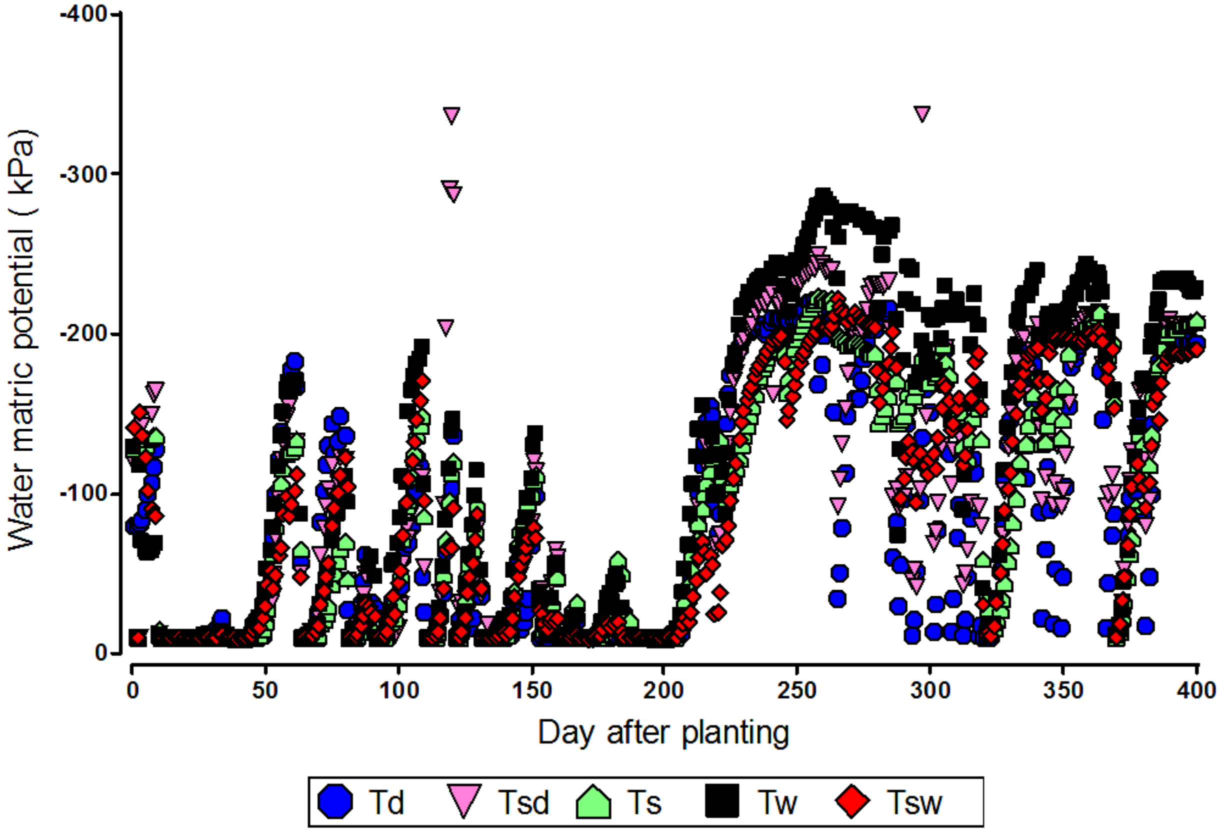

Figure 27. Soil water matric potential measurements with MPS-1 sensors, for different experimental treatments during the experiment in Cabo Rojo, P.R. Td: tree seedling with a dew condenser. Tsd: tree shelter with dew condenser. Ts: seedling enclosed by tree shelter. Tw: seedling irrigated manually. Tsw: tree shelter and manual irrigation.

It may be observed in Figure. 27 that matric potentials were generally more negative during the second half of the experiment than at the beginning. This reflects the lower rainfall patterns during the second period (after December 2011) which were seen in

Figure 19. During this drier second period, it may also be seen that blue and purple data points in Figure 27, corresponding to the two dew condenser treatments T_d and T_{sd}, respectively, tended to predominate during the second half of the experiment near the bottom of the graph indicating higher (less negative) matric potentials. The most negative matric potentials tended to be associated with black data points, corresponding to the manually irrigated treatment T_w, indicating the driest soil conditions for this treatment.

In order to provide some statistical analysis of the above data, matric potential measurements were averaged by month for each experimental plot, and treatment-related differences between the means for each month were examined using ANOVA. Results are summarized in Table 14, and they generally confirm the qualitative interpretation of Figure 27 described earlier. Soil water matric potential tended to be highest (less negative) in treatments with dew condensers, particularly in treatment T_d, and lowest (more negative) for the manually irrigated trees with no dew condenser or tree shelter.

Table 14. Mean matric potential values for different treatments during each month of the trial.

Month	Matric potential (kPa) for each treatment Td		Tsd		Ts		Tw		Tsw	
Apr	-34.83	ab	-47.60	b	-45.45	ab	-32.18	a	-41.29	ab
May	-52.65	bc	-45.18	abc	-41.31	ab	-54.17	c	-33.31	a
Jun	-67.01	d	-58.09	cd	-32.75	a	-48.03	bc	-54.05	b
Jul	-39.64	a	-43.21	a	-47.91	a	- 69.18	b	-51.99	a
Aug	-31.30	a	-57.15	b	-41.94	ab	-46.16	ab	-33.58	a
Sep	-23.18	a	-31.99	b	-31.87	b	-34.53	b	-23.47	a
Oct	-11.17	a	-12.70	a	-20.36	b	-20.84	b	-12.34	a
Nov	-155.63	c	-150.68	c	-25.71	b	-169.82	d	-106.56	a
Dec	- 84.02	a	-212.62	c	-202.27	bc	-256.90	d	-195.21	ab
Jan	-143.43	a	-167.92	b	-170.87	b	-225.30	c	-158.06	ab
Feb	- 68.84	a	-93.61	b	-111.06	c	-146.02	d	-113.82	c
Mar	-136.21	a	-165.30	ab	-162.12	ab	- 217.55	b	-186.06	c
Apr	-114.69	a	-138.19	b	-141.30	b	-167.08	c	-135.44	b
May	-197.46	a	-207.47	b	-207.47	b	-230.87	c	-192.45	a

Means within a row that do not have a common letter are significantly different ($p<0.05$) according to the Tukey test. T_d: Tree seedling with a dew condenser. T_{sd}: Tree shelter with dew condenser. T_s: Seedling enclosed by tree shelter. T_w: Seedling irrigated manually. T_{sw}: Tree shelter and manual irrigation.

The above comparisons do not include the control treatment, where MPS-1 matric potential sensors were not installed due to lack of sufficient sensors and data loggers. In these plots matric potential was monitored by making weekly measurements with gypsum blocks. Results for the control treatment are shown in Figure 28. These measurements show similar tendencies as the MPS-1 readings for the other treatments (Figure 27), in the sense that low matric potential readings were more abundant during the drier second half of the experiment than earlier. Gypsum block readings for the control plots during this period often indicated soil water matric potentials < - 1500 kPa, considerably lower than MPS-1 matric potential measurements for the other treatments, which never dropped below - 500 kPa.

Some uncertainty exists in comparing the gypsum block measurements in the control treatment (Figure 28) to MPS-1 measurements for the other treatments in Figure 27. This is because two different techniques were used and furthermore only factory calibrations were used in each case. Nevertheless, the factory calibrations should not be considered too inaccurate, because they depend mostly on moisture release characteristics and electromagnetic properties ***of the sensors themselves*** and not of the surrounding soil. The difference between estimated matric potential in the control

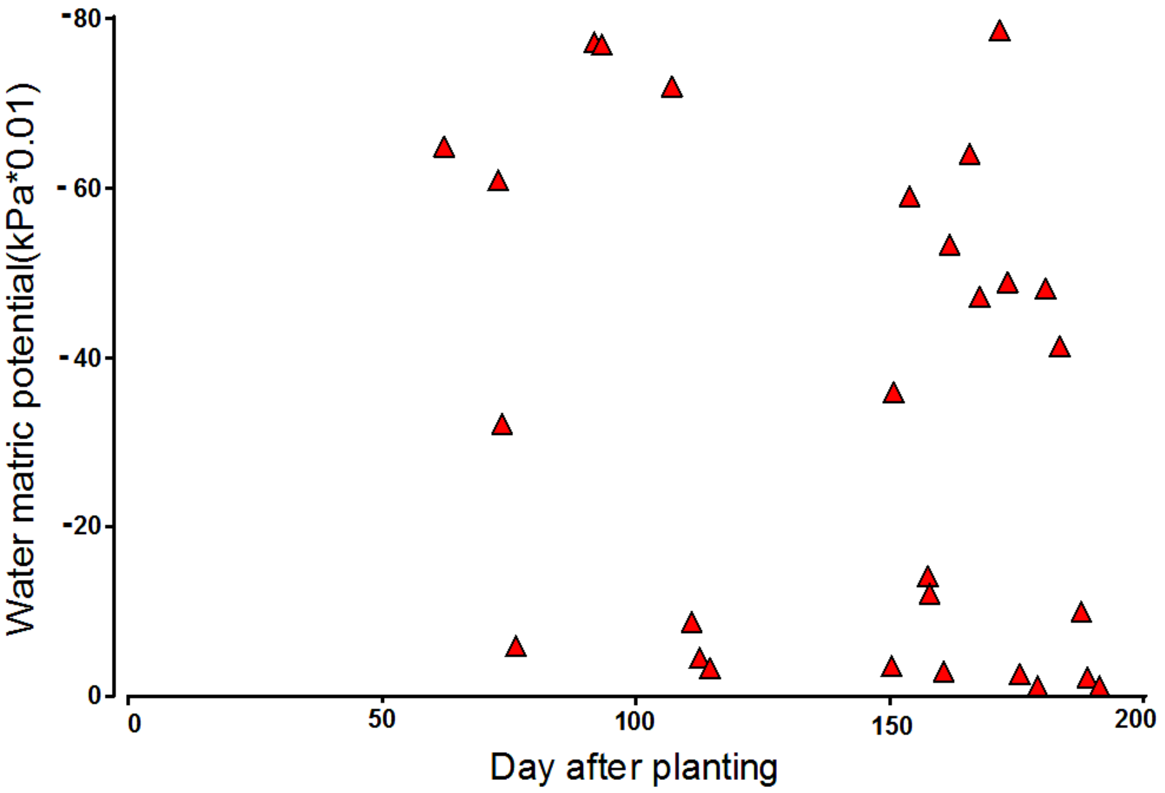

Figure 28. Matric potential for control plots (treatment T), estimated from gypsum block readings.

and all other treatments was very large during the second half of the experiment. It seems unlikely that these differences were only due to calibration errors in the two different sets of sensors.

Monthly average values of tensiometer readings for treatments T_d, T_{sd}, T_w and T_{sw} are compared in Table 15. Results are represented graphically in Figure 29. ANOVA in general did not indicate significant differences between treatments. The most noticeable trend was for matric potential to be more negative for all treatments in the second half of the growing period, consistent with the drier weather which was mentioned earlier. Relatively few data points were available for analysis, because soil water matric potential was often more negative than the tensiometer limit of – 80 kPa, as indicated by the MPS-1 measurements in Figure 28. This may be one reason for lack of significant differences between tensiometer readings for the different treatments.

Table15. Monthly means and standard deviations of matric potential (kPa) measured with tensiometers in different treatments.

	Treatments, Matric potential (kPa)			
Months	**Td**	**Tsd**	**Tw**	**Tsw**
Oct	-7.41±10.97 a	-7.15±11.11 a	-10.43±12.16 a	-7.71±10.77 a
Nov	-4.93±8.27 a	-5.54±11.61 ab	-20.30±23.86 c	-11.92±10.99 b
Dec	-51.97±24.16 ab	-46.33±25.41 a	-61.61±18.38 b	-54.64±23.07 ab
Feb	-26.96±23.63 a	-24.25±23.44 a	-31.92±24.25 a	-27.96±18.09 a
Mar	-35.52±23.13 a	-31.91±20.66 a	-37.63±25.49 a	-30.63±20.29 a
Apr	-51.63±24.02 a	-59.50±17.94 b	- 47.77±14.81 ab	-33.78±13.64 a
May	-66.25±25.06 a	- 78.50±1.41 a	-67.17±12.74 a	-49.50±11.27 a

Means within a row that do not have a common letter are significantly different ($p<0.05$) according to the Tukey test. No matric potential measured with tensiometer for T and Ts, only treatments with irrigation and dew condenser. Number following ± is the standard deviation.

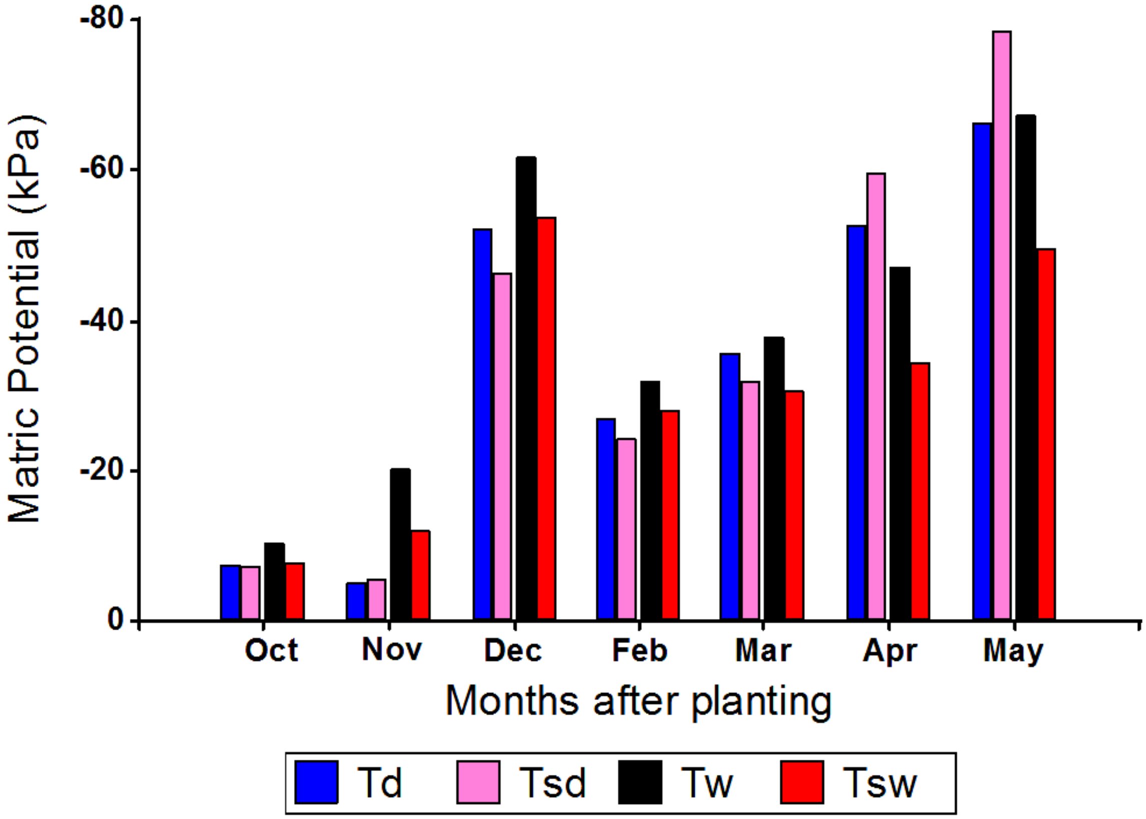

Figure 29. Monthly means of matric potential measurements with tensiometers, for various experimental treatments in the Cabo Rojo field study. Data collected from Oct. 2011 to May 2012.

4.3 Dew condenser measurements at Rio Piedras, Puerto Rico

Figure 30 shows results of dew condenser measurements during 1 year at Rio Piedras, Puerto Rico. Measurements began on October 1, 2010 and ended September 30, 2011. (Unpublished data provided by Dr. Victor Snyder of the University of Puerto Rico Agricultural Experimental Station).The data are shown according to the calendar day of the year (number of days after January 1) on which they were measured. This was done in order to begin and end the data series near the times of year with longest nights, with the midpoint of the series corresponding to summer months with the shortest nights.

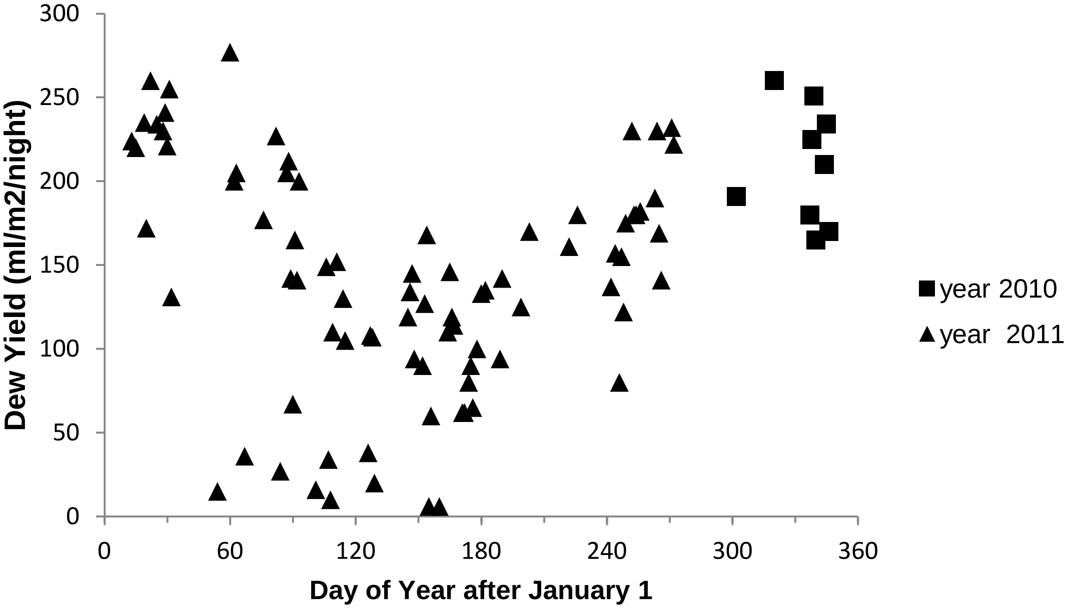

Figure 30. Dew yields (ml/m^2/night) obtained at Rio Piedras during the period October 1, 2010 through September 30, 2011. (Unpublished data provided by Dr. Victor Snyder of the University of Puerto Rico Agricultural Experimental Station).

A sinusoidal pattern of dew condensation is evident in Figure 30, corresponding closely with the sinusoidal pattern of night hours. The amount of dew collected during summer nights (roughly 75-150 ml/m^2/night or 0.075-0.150 L/m^2/night) was approximately half the amount collected in the winter (150-250 ml/m^2/night or 0.150-0.250L/m^2/night). For evapotranspiration conditions similar to those in the greenhouse experiments reported here, even the low range of dew condensation of 75-150 ml/m^2/night should be sufficient to sustain tree seedlings. However, for larger tree seedlings more water may be necessary, requiring dew condensers with greater condensation area than those used here. The same is true for higher latitudes with long hot summer days and short nights.

The above dew condensation results obtained at Rio Piedras obviously cannot be directly extrapolated to Cabo Rojo conditions without experimental verification. However, the day-night duration patterns at Rio Piedras are the same as Cabo Rojo, and furthermore results are similar to those reported in other parts of the World (Beysens et al., 2005; Clus et al., 2008). Therefore, it does not seem unreasonable to use these data at least as an approximation of dew conditions at Cabo Rojo.

5. Conclusions

This present study it may be concluded that:

- In greenhouse experiments both species S*. macrophylla* and *T. heterophylla* were able to survive at RET values as low as 0.5, and at least 50% of seedlings survived at RET = 0.25. This was consistent with the original hypothesis on tree survival rate.
- The two species S*. macrophylla* and *T. heterophylla* behaved differently at low RET values. Whereas only 60% of the S*. macrophylla* seedlings survived at the RET = 0.25 level and all seedlings died at RET = 0.125, *T. heterophylla* demonstrated 100% survival even at the lowest RET value of 0.125. This indicates a considerable difference between ability of the two species to survive drought. The greater drought tolerance of *T. heterophylla* appeared related to its ability to reduce transpiration demand by shedding leaves, and to store a greater percentage of biomass in the roots during periods of water stress. Allocating

more biomass to roots may allow drought- stressed trees to better access limiting water resources.

- The amount of water per seedling required to provide an RET value of 0.25 was within a conservative estimate of water condensation capacity (75–150 ml//night) of dew condensers with a surface area of 1 m^2, verified under Puerto Rico conditions and elsewhere. This again confirmed one of the working hypotheses, namely that dew condensers could provide sufficient water to prevent drought mortality of small tree seedlings.
- The field experiment did not provide any information on tree seedling mortality under the different experimental treatments, due to unusually high rainfall during the seedling establishment period. However, trees with dew condensers grew at least as much as trees receiving 2 L of irrigation water per week, and were the only trees to yield statistically more total biomass than trees with shelters. The enhancing effect can be attributed not only to dew condensation but also concentration of rainfall near the tree trunk thereby increasing water use efficiency.
- Results indicated that trees with tree shelters exhibited greater height than trees without tree shelters. But tree shelters also reduced plant diameter, biomass and number of leaves. Even after 18 months the stems of sheltered trees were so weak that the trees could not stand without support.

VI. Implications for further research

1. The greenhouse study at Mayaguez and Rio Piedras evaluated response of only two tree species, *S. macrophylla* and *T. heterophylla*, to different RET values. It is important to determinate response of many other tree species to RET. Similar studies should also be conducted under field conditions.

2. In order to further document the effectiveness of dew condensers for preventing drought mortality of tree seedlings, field experiments need to be performed under drier conditions than at Cabo Rojo.

3. To better understand the influence of tree shelters on seedling survival and growth, it is necessary to further evaluate parameters such as light intensity and temperature inside the tree shelters. In the case of species such as *Tabebuia*, it is necessary to evaluate their response to tree shelters over longer growing periods than in the Cabo Rojo experiment.

4. In countries such as Haiti where livestock is often allowed to roam freely, tree shelters may help to protect tree seedlings against livestock in reforestation projects. Adaptive research is needed in Haiti to validate this possibility and promote its acceptance by the local population.

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Appendix A. Construction and installation of dew condensers

Dew condensers were constructed using the following commercially available materials.

- Polyurethane foam insulation, 2.5 cm thick, obtained from American Plastics, Inc., San Juan, PR
- Foam spray adhesive, obtained from American Plastics, Inc., San Juan, PR
- Thermoplastic polyolephine (TPO) roof surfacing material manufactured by Mulehide Corp. and represented by Danosa, Inc., Catano, Puerto Rico. Rated thermal emissivity of 0.91.
- Bubble plastic insulation, with one side covered with infrarerd-reflecting aluminum foil.
- White insulating polyurethane roofing paint with ceramic microspheres, with a rated dry thermal emissivity of 0.89, manufactured locally by Lanco Paint Co., Inc.

Appendix B. Variance's analysis of growth parameters of *S. macrophylla* in the greenhouse experiment.

```
    Variable        N       R²    R² Aj   CV
Total height(cm)   40     0.41     0.28 13.37

Cuadro de Análisis de la Varianza (SC tipo III)
 F.V.          SC        gl      CM          F     p-valor
Modelo.      2017.30      7     288.19      3.12    0.0125
Block         995.60      4     248.90      2.70    0.0482
Treat        1021.70      3     340.57      3.69    0.0218
Error        2953.80     32      92.31
Total        4971.10     39

Test:Tukey Alfa=0.05 DMS=11.64119
Error: 92.3063 gl: 32
Treat Medias        n     E.E.
1.00   77.50       10     3.04  A
3.00   75.60       10     3.04  A     B
2.00   69.60       10     3.04  A     B
4.00   64.70       10     3.04        B
Medias con una letra común no son significativamente diferentes(p<= 0.05)
```

```
     Variable            N      R²    R² Aj   CV
Trunk diameter (cm)     40     0.33    0.18 20.74

Cuadro de Análisis de la Varianza (SC tipo III)
 F.V.         SC    gl      CM     F     p-valor
Modelo.      0.66    7     0.09   2.21    0.0594
Block        0.04    4     0.01   0.21    0.9298
Treat        0.63    3     0.21   4.88    0.0066
Error        1.37   32     0.04
Total        2.03   39

Test:Tukey Alfa=0.05 DMS=0.25038
Error: 0.0427 gl: 32
Treat Medias        n     E.E.
1.00    1.16       10     0.07  A
2.00    1.08       10     0.07  A     B
3.00    0.88       10     0.07        B
4.00    0.87       10     0.07        B
Medias con una letra común no son significativamente diferentes(p<= 0.05)
```

```
 Variable    N      R²   R² Aj  CV
leave number      40    0.44   0.32 41.53

Cuadro de Análisis de la Varianza (SC tipo III)
 F.V.          SC        gl      CM         F    p-valor
Modelo.     15849.83      7    2264.26     3.66    0.0052
Block        6541.15      4    1635.29     2.64    0.0518
Treat        9308.68      3    3102.89     5.01    0.0058
Error       19818.95     32     619.34
Total       35668.78     39

Test:Tukey Alfa=0.05 DMS=30.15417
Error: 619.3422 gl: 32
Treat Medias      n     E.E.
3.00   72.50      10    7.87  A
2.00   69.00      10    7.87  A
1.00   64.20      10    7.87  A
4.00   34.00      10    7.87        B
Medias con una letra común no son significativamente diferentes(p<= 0.05)
```

```
Variable    N      R²   R² Aj  CV
Leaf area   20    0.68   0.50 37.63

Cuadro de Análisis de la Varianza (SC tipo III)
 F.V.            SC             gl        CM               F    p-valor
Modelo.      691346778.07        7     98763825.44        3.70    0.0228
Block        203439971.52        4     50859992.88        1.91    0.1740
Treat        487906806.54        3    162635602.18        6.10    0.0092
Error        320033680.16       12     26669473.35
Total       1011380458.23       19

Test:Tukey Alfa=0.05 DMS=9696.90072
Error: 26669473.3470 gl: 12
Treat  Medias     n      E.E.
3.00  16968.65     5    2309.52     A
1.00  16655.69     5    2309.52     A
2.00  16089.32     5    2309.52     A
4.00   5187.96     5    2309.52           B
Medias con una letra común no son significativamente diferentes(p<= 0.05)
```

Appendix C. Variance’s analysis of growth parameters of *T. Heterophylla* in the greenhouse experiment.

```
    Variable        N      R²   R² Aj  CV
total height (cm) 144    0.30    0.25 38.65

Cuadro de Análisis de la Varianza (SC tipo III)
 F.V.           SC        gl      CM          F    p-valor
Modelo.       6544.28      8     818.03       7.12 <0.0001
Block         2589.14      5     517.83       4.51  0.0008
Trat          3955.14      3    1318.38      11.47 <0.0001
Error        15515.69    135     114.93
Total        22059.97    143

Test:Tukey Alfa=0.05 DMS=6.50253
Error: 114.9311 gl: 135
Trat  Medias       n     E.E.
1.00   32.64      36     1.79  A
2.00   32.42      36     1.79  A     B
3.00   25.94      36     1.79        B     C
4.00   19.94      36     1.79              C
Medias con una letra común no son significativamente diferentes(p<= 0.05)

     Variable            N      R²   R² Aj  CV
trunk diameter(cm)      144    0.20    0.15 23.30

Cuadro de Análisis de la Varianza (SC tipo III)
 F.V.          SC   gl     CM     F    p-valor
Modelo.       0.43    8    0.05  4.16   0.0002
Block         0.18    5    0.04  2.83   0.0184
Trat          0.25    3    0.08  6.38   0.0004
Error         1.76  135    0.01
Total         2.20  143

Test:Tukey Alfa=0.05 DMS=0.06930
Error: 0.0131 gl: 135
Trat  Medias       n     E.E.
1.00    0.54      36     0.02  A
2.00    0.51      36     0.02  A
3.00    0.48      36     0.02  A     B
4.00    0.43      36     0.02        B
Medias con una letra común no son significativamente diferentes(p<= 0.05)

 Variable    N      R²    R² Aj  CV
Leaf number 144    0.25    0.21 76.50

Cuadro de Análisis de la Varianza (SC tipo III)
 F.V.           SC        gl      CM          F    p-valor
Modelo.      14070.81      8    1758.85       5.66 <0.0001
Block         4389.33      5     877.87       2.83  0.0185
Trat          9681.47      3    3227.16      10.39 <0.0001
Error        41942.94    135     310.69
Total        56013.75    143

Test:Tukey Alfa=0.05 DMS=10.69119
```

```
Error: 310.6885 gl: 135
Trat  Medias      n     E.E.
1.00   31.64      36    2.94  A
2.00   28.50      36    2.94  A
3.00   21.78      36    2.94  A
4.00   10.25      36    2.94        B
Medias con una letra común no son significativamente diferentes(p<= 0.05)
```

Análisis de la varianza

```
Variable     N      R²    R² Aj  CV
Leaf area    24     0.66   0.48 50.72
```

Cuadro de Análisis de la Varianza (SC tipo III)

```
 F.V.             SC           gl        CM              F    p-valor
Modelo.     614952380.43        8     76869047.55      3.69   0.0141
Trat        431713037.31        3    143904345.77      6.91   0.0038
Block       183239343.12        5     36647868.62      1.76   0.1821
Error       312533848.44       15     20835589.90
Total       927486228.87       23
```

Test:Tukey Alfa=0.05 DMS=7595.53992

```
Error: 20835589.8961 gl: 15
Trat   Medias     n      E.E.
1.00  12759.29     6    1863.49     A
2.00  12703.45     6    1863.49     A
3.00   8118.35     6    1863.49     A     B
4.00   2417.67     6    1863.49           B
Medias con una letra común no son significativamente diferentes(p<= 0.05)
```