Actual evapotranspiration and crop coefficients for five species of three-year-old bamboo plants under a tropical climate

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A B S T R A C T

Over the last decade, bamboo plantations have started to be used as vegetation filters for wastewater treatment. This treatment system can be useful in reducing wastewater discharge into the environment, thus contributing to the preservation of water resources by using the plantations’ evapotranspiration to reduce the rate of water infiltration. The evapotranspiration rates of the bamboo species used is therefore an important factor. The actual evapotranspiration (ET) and the crop coefficients ($k_c$) for the five tropical and temperate species of three-year-old bamboo plants, i.e. Bambusa oldhamii, Bambusa multiplex, Bambusa vulgaris, Phyllostachys aurea and Pseudosasa japonica, were studied in lysimeters for a period of more than one year under a tropical climate. The average ET rates for the bamboo species studied ranged from 4 to 7 mm day⁻¹ with maximum values of between 10.7 and 17.1 mm day⁻¹ during the wet season, and an average $k_c$ of 1.1 to 1.9. The ET was correlated to weather parameters, especially minimum temperatures. The differences in ET rates between the bamboo species can be explained by morphological parameters, in particular the total aboveground biomass. Among the five bamboo species studied, B. oldhamii had the highest ET rate and produced the most biomass. In comparison with other high-biomass-producing plants, the evaporation rates for young bamboo plants were similar to those for willow and poplar vegetation filters.

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1. Introduction

Water resources conservation is an important issue today. The eutrophication process in water especially is a worldwide concern (Smith, 2009; Smith et al., 1999). Natural wastewater treatment systems using phytoremediation principles have been developed in order to provide a useful alternative to more conventional wastewater treatment systems, particularly in rural or isolated areas. Most of these systems involve constructed wetland using aquatic plants (Vymazal, 2011). Another type of system uses terrestrial plants such as poplar, willow and – more recently – bamboo, where the plants are used as vegetation filters (Arfi et al., 2009; Aronsson and Perttu, 2001; Perttu and Kowalik, 1997; Singh et al., 2008; Yadav et al., 2010).

Although bamboo is still rarely used for phytoremediation purposes (water or soil treatments), it nevertheless shares a number of interesting characteristics with other plants used in phytoremediation. Among these is bamboo’s apparent tolerance to pollutants such as trace metals (Collin et al., 2013; Gui et al., 2011; Shukla et al., 2011), and to the excessive doses of nutrients that can be contained in wastewater (Piouceau et al., 2014). Bamboo also develops a dense root system with a profusion of fine roots and hair roots (Christanty et al., 1996) that favors the hosting of microorganisms and improves the rhizodegradation of organic matter contained in wastewater (Licht and Isébrands, 2005; McCutcheon and Schnoor, 2003). Lastly, giant bamboo species are among the most productive terrestrial plants in the world. The aboveground biomass yield of mature plantations can reach 25 and 47 t ha⁻¹ yr⁻¹ under temperate and tropical climates, respectively (Scurlock et al., 2000). These high-yield plants are interesting for wastewater treatment purposes because they can help preserve the quality of water resources by limiting the eutrophication phenomenon in two complementary ways. First, by storing large amounts of nitrogen and phosphorous (the main elements involved in eutrophication) in their biomass: a
mature bamboo plantation can store 131 to 619 kg ha\(^{-1}\) of nitrogen and 17 to 97 kg ha\(^{-1}\) of phosphorous in its aboveground biomass (Kleinhenz and Midmore, 2001). Second, by slowing the infiltration of water through their high evapotranspiration rates; Kleinhenz and Midmore (2002) estimated that the ET rate of a mature bamboo plantation can range between 9 and 13 mm day\(^{-1}\) under a tropical climate.

The development of vegetation filters using terrestrial plants has been boosted by regulatory pressure to reduce or stop the discharge of any treated water into the environment. Indeed, even if the treated water complies with environmental quality standards, it still contains small amounts of nitrogen and phosphorus that are potentially harmful for the water resources. This is particularly true for sensitive areas such as the lagoons and streams on Reunion Island (Chazottes et al., 2002; Nain, 1993; Semple, 1997; Tedetti et al., 2011), for which a target of zero discharge of any water into the environment needs to be implemented. In vegetation filters, the wastewater is directly spread over the plantation’s soil surface. The treated wastewater is released through percolation, via the root zone to the water table and into the atmosphere through evapotranspiration. This kind of system can be designed and managed to avoid any discharge of any water into the water table. To do this, the evapotranspiration (ET) rates of the plant species used must be accurately known to set the appropriate wastewater volume to be spread on the plantation.

Some studies were carried out on the transpiration of various bamboo species using the sap-flow method (Dierick et al., 2010; Komatsu et al., 2010, 2012; Kume et al., 2010), but most of these did not take into account the evaporation via the soil. Furthermore, they were conducted in non-irrigated conditions so the experimental method did not allow the plants’ full transpiration potential to be quantified. Another experimental method uses lysimeters (Aboukhalel et al., 1982). The lysimeter method is well-adapted to measuring the ET, that is to say both the plant transpiration and the soil evaporation are measured in field conditions. This method also allows the crop coefficient\( (k_c)\) to be calculated. The \(k_c\) of a plant species is the ratio between the ET rate of the plant studied and the reference evapotranspiration\( (ETo)\) (Allen et al., 1998). The lysimeter method has been successfully used to study the ET and \(k_c\) of some high-biomass-producing plants such as poplar and willow (Guidi et al., 2008; Pauliukonis and Schneider, 2001; Pistocchi et al., 2009). To our knowledge, there is currently a lack of data on the evapotranspiration rates of bamboo and other giant grasses\( (e.g.\) switchgrass, Miscanthus sp. or Arundo donax). Consequently, the aim of our study was to determine the ET rates and \(k_c\) of several bamboo species and to compare them in order to select the most appropriate species for vegetation filters\( (i.e.\) the species with the highest ET rate). To this end, we put in place percolation-type lysimeters (Allen et al., 2011) to measure ET rates over a period of more than one year. Morphological parameters, such as leaf area and total aboveground biomass, were also measured to account for differences in ET rates between species.

2. Materials and methods

2.1. Experimental conditions

The experiment was conducted over one year, from August 20th, 2008 to October 30th, 2009 (436 days), on Reunion Island, an overseas French department in the south-west Indian Ocean. The experimental site was located at Le Guillaume, Saint Paul (21°03’ 48”S; 55°19’ 24”E) at an elevation of 1043 m.

Fifteen percolation-type lysimeters were set up at the experimental site (Fig. 1). The lysimeters consisted of 1.2 m\(^{3}\) plastic tanks\( (1.00\ \text{m deep, } 1.00 \times 1.20\ \text{m in area})\). The lysimeters were placed 70 cm apart to protect their sides from direct sunlight. The sides of the lysimeters were also insulated with a polypropylene membrane to prevent heating.

The lysimeters were filled with 20 cm of gravel at the bottom as a drainage layer. A geotextile (bidim green\(^{6}\), Ten Cate Geosynthetics, France) was laid on top of the gravel before the tanks were filled with a 3:1:1 (v:v:v) mixture of soil, scoria and sugar cane fibers, the characteristics of which are listed in Table 1.

The lysimeters were planted with five different species of three-year-old bamboo plants: three tropical species\( (\text{pachymorph rhizome: Stapleton (1998): Bambusa oldhamii Munro (BO), Bambusa multiplex (Lour.) Raeusch (BGG) and Bambusa vulgaris Schrad. (BVV)) and two temperate species (leptomorph rhizome: Stapleton (1998): Phyllostachys aurea Rivière & C. Rivière (PA) and Pseudosasa japonica (Steud.) Makino (PJ))\). The lysimeters were arranged in a completely randomized design based on the factor species (five levels) with three replicates per species. The bamboo species were planted in the lysimeters’ reconstituted soil in May 2008, four months before the start of the experiment, to allow for the bamboo’s proper rooting and a natural compaction of the soil.

![Drip irrigation system](Image)

**Fig. 1.** Lysimeter set up at the experiment site.

<table>
<thead>
<tr>
<th>Table 1: Average lysimeter soil properties after bamboo plantation.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Particle density (g cm(^{-3}))</strong></td>
</tr>
<tr>
<td><strong>Bulk density (g cm(^{-3}))</strong></td>
</tr>
<tr>
<td><strong>Soil water holding capacity (mm)</strong></td>
</tr>
<tr>
<td><strong>pH(_{\text{H2O}})</strong></td>
</tr>
<tr>
<td><strong>EC (mS cm(^{-1}))</strong></td>
</tr>
<tr>
<td><strong>Total nitrogen (g kg(^{-1}))</strong></td>
</tr>
<tr>
<td><strong>Total organic carbon (g 100 g dry soil)</strong></td>
</tr>
<tr>
<td><strong>Phosphorus Olsen-Dablain (g kg(^{-1}))</strong></td>
</tr>
<tr>
<td><strong>CEC (meq 100 g)</strong></td>
</tr>
</tbody>
</table>

Electrical conductivity (EC); Cation exchange capacity (CEC).
Each lysimeter was irrigated with an automatic drip system (Netafim®M, Israel) using four drippers. Two spikes delivering 4 × 1 h⁻¹ per spike were inserted into the soil for each dripper, giving a total flow of 32 × 1 h⁻¹ for each lysimeter. The lysimeters were irrigated once a week with tap water, with a twice-weekly addition of a fertilizer solution comprising a commercial fertilizer (20:20:20 NPK soluplant dulcose®. Duclos International, France) and a trace element solution (Oligo Drip 25 Fe, Duclos international, France) diluted with tap water. The fertilizer solution was diluted in-line using a metering pump (DI 16, Dosatron International, France) with the resulting nutrient solution going to the drip irrigation system. The dilution was 1% in the dry season (May to October) and 1.6% in the wet season (November to April). The solution concentration was 300 mg l⁻¹ of nitrogen (N), 300 mg l⁻¹ of phosphorus (P) and 300 mg l⁻¹ of potassium (K) (electric conductivity 1.3 mS cm⁻¹) during the dry season and 480 mg l⁻¹ of N, P and K (1.8 mS cm⁻¹) in the wet season. The application of nutrients was designed to make fertilization a non-limiting factor in the bamboo’s growth; during the experiment, a total of 672.1 g of N, P and K were applied to each lysimeter, representing a total of 5.6 t ha⁻¹ yr⁻¹ of nitrogen, phosphorus and potassium. The average daily height of water (tap water or fertilizer solution) added to the lysimeters was 8.9 mm day⁻¹ in the dry season, and 22.2 mm day⁻¹ in the wet season. The volume of irrigation water supplied to the lysimeter was adjusted according to the soil’s water-holding capacity, 210 mm. This supply of water allowed the soil’s moisture content to be maintained close to field capacity throughout the experiment.

A faucet at the base of each lysimeter was connected to 20-l plastic can to collect the drainage water.

2.2. Climatic parameters measurements

The air temperature and relative humidity were measured on the experimental site every hour using data loggers (EL-USB-2, Lascar electronics, UK) (Fig. 2a and b). Three data loggers were set up on three lysimeters chosen at random.

The rainfall height was measured by the site’s meteorological station and reference evapotranspiration (ET₀) was obtained from the Météo-France (French meteorological agency) meteorological station at Bois de Nèfles on Reunion Island, at 7.656 km from our experimental site. The ET₀ was determined by Météo-France (French meteorological agency) using the FAO-56 Penman-Monteith equation (Allen et al., 1998), with daily meteorological data (including air temperature, relative humidity, wind speed and solar radiation) obtained using an automatic weather station.

2.3. Determination of actual evapotranspiration and crop coefficients

Ten-day mean ET for each bamboo species was calculated using the simplified water balance equation (Rana and Katerji, 2000) (Eq. (1) below), assuming that the soil’s water content was kept at field capacity throughout the experiment (Guidi et al., 2008; Pisticci et al., 2009):

\[ ET = I + R - D \]  (1)

where \( I \) is the amount of water provided by irrigation (mm), \( R \) the rainfall height (mm) and \( D \) the drainage height (mm). The drainage volumes of each lysimeter were measured every two days by weighing the 20-l plastic cans with a 20 g-precision spring scale (HS-50, Voltcraft®, Germany). The drainage height was obtained by dividing the drainage volumes by the surface area of the lysimeters (i.e. 1.2 m²).

The mean 10-day crop coefficients (\( k_c \)) were calculated using the following Eq. (2) (Allen et al., 1998):

\[ k_c = \frac{ET}{ET_0} \]  (2)

where \( ET \) is the actual evapotranspiration (mm), and \( ET_0 \) the reference evapotranspiration (mm).

2.4. Growth measurements and plant sampling

At the beginning and end of the experiment, the number of culms was counted in each lysimeter, their height measured with a tape measure and their basal diameters measured with a digital caliper at the middle of the first internode. The initial aboveground fresh biomass for each bamboo species was calculated from the basal diameters of culms using allometric equations established by Piouceau et al. (2014). At the end of the experiment, all the culms in each lysimeter were cut. The total aboveground fresh biomass, total fresh leaf mass and fresh culm mass was weighed with a 0.1 g-precision scale (Kern & Sohn GmbH, Germany).

2.5. Leaf area measurements

Three culms were randomly sampled per lysimeter to take sub-samples of leaves. These samples were immediately scanned (Mustek Scanexpress, Mustek Systems Inc., Taiwan) and weighed. The leaf area was calculated using scan images processed using
Adobe Illustrator CS4 software (Adobe Systems Inc., USA). The specific leaf area (SLA), i.e. leaf area per mass unit, was calculated and the total leaf area per clump was deduced by multiplying the average specific leaf area of the sub-sample by the total fresh mass of leaf per clump.

2.6. Statistics

We used an univariate repeated ANOVA (SPSS inc., IBM, USA) to study the difference in 10-day ET or \( k_6 \) among species. Sphericity was checked with Mauchley’s test; when this assumption was rejected the Greenhouse-Geisser corrections were used for the F-statistics. The LSD test was used for post-hoc analyses; \( p < 0.05 \) was chosen to identify significant differences between species.

A one-way ANOVA (SPSS inc., IBM, USA) was performed to test the effect of the species factor on the number of culms, culm diameter and height, total aboveground fresh biomass, average fresh culm mass, total fresh leaf mass, total leaf area, and total annual ET. We performed square root or logarithmic transformations of data to satisfy the ANOVA assumptions. The LSD test was used for post-hoc analyses; \( p < 0.05 \) was chosen to identify significant differences between species.

We conducted a two-tailed Pearson correlation analysis (SPSS inc., IBM, USA) to determine the relationships between ET rates of each species, ET\textsubscript{c} and the weather variables: maximum temperature, average temperature, minimum temperature, maximum relative humidity, average relative humidity, minimum relative humidity and ET\textsubscript{c}. Another two-tailed Pearson correlation analysis (SPSS Inc., IBM, USA) was performed to determine the relationships between the total annual ET and morphological parameters: total aboveground fresh biomass, total fresh leaf mass and total leaf area.

3. Results

3.1. Meteorological conditions

The temperature, relative humidity and 10-day rainfall are shown in Fig. 2a and b. The climate is tropical with a wet season between November and April, and a dry season between May and October. During the experiment, the temperatures on site ranged from 6 to 38.8 °C with an average of 18.6 °C, and a relative humidity from 33.7% to 99.3%, with an average of 81%. The total rainfall during the experiment was 1373.9 mm.

Our experiment took place over three seasons: two dry (DS1 and DS2) from August to October 2008 and from May to October 2009, and one wet (WS), from November 2008 to April 2009, the latter corresponding to the main growth period for bamboo. The two dry seasons were characterized by average temperatures that ranged from 13.5 to 21.5 °C, a relative humidity of 61.9% to 90.4%, and low rainfall (only 63 mm in DS2, the wetter of the two dry seasons). The average temperature during DS2 was lower than in DS1 by 2.8 °C in September and 1.6 °C in October. The wet season was characterized by average temperatures that ranged from 19.2 to 22.3 °C, a relative humidity of 75.8% to 90.4% and abundant rainfall (up to 426.8 mm in one 10-day period).

The abundant rainfall recorded in the first 10-day period of February 2009 were due to Hurricane Gaël that caused the three temperature data loggers to break down. The data loggers were replaced on March 10th 2009. Consequently, temperatures were not recorded during this period.

3.2. Actual evapotranspiration and crop coefficients

The evapotranspiration patterns are shown in Fig. 3. During DS1, the different bamboo species showed similar ET rates until the end of October 2008. During this period the ET ranged from 0.98 to 1.97 mm day\(^{-1}\) for BGG, 1.72 to 2.39 mm day\(^{-1}\) for PA, 1.52 to 3.09 mm day\(^{-1}\) for PJ, 1.33 to 3.18 mm day\(^{-1}\) for BVV, and 1.42 to 3.65 mm day\(^{-1}\) for the BO species.

At the beginning of the WS, i.e. in November 2008, the BGG and BO species started to show significantly different patterns of ET rates compared to the other species. The BGG species showed the lowest ET rate and BO the highest. In December 2008, the ET rates increased rapidly and reached their maximum values in January 2009. During the WS, the ET rates showed four peaks for all species. The same differences between species were observed as in DS1: the BGG species showed the lowest ET rate and BO the highest. The BVV and PA species showed similar ET rates, and the PJ species showed a lower ET rate than the BVV and PA species. Between November 2008 and March 2009, the ET rates ranged from 2.20 to 12.34 mm day\(^{-1}\) for BGG, 2.62 to 12.18 mm day\(^{-1}\) for BVV, 2.69 to 12.93 mm day\(^{-1}\) for PA, 2.92 to 13.24 mm day\(^{-1}\) for PJ and 3.83 to 17.17 mm day\(^{-1}\) for the BO species. At the end of March 2009, the irrigation system broke down and consequently the ET rates were not recorded until May.

During DS2, from May 2009 to October 2009, the ET rates of the species decreased from 29% to 56% compared to the WS. However, two peaks of ET were recorded in the third 10-day period of June and the second 10-day period of August. Once again, the ET rates of the BGG and BO species were lower and higher, respectively, than the other species. During DS2, the ET rates were higher than during DS1, ranging from 1.19 to 6.12 mm day\(^{-1}\) for BGG, 1.67 to 8.46 mm day\(^{-1}\) for PJ, 2.46 to 9.87 mm day\(^{-1}\) for PA, 2.73 to 10.00 mm day\(^{-1}\) for BVV, and 3.23 to 10.60 mm day\(^{-1}\) for BO.

The crop coefficients closely followed the same trend as the 10-day ET (Fig. 4). During DS1, the different bamboo species showed similar \( k_c \) values: from 0.5 to 1.2 and 0.7 to 1.8 for the BGG and BO species, respectively. During the WS the \( k_c \) ranged from 0.5 to 3.8 and 1.0 to 5.7 for the BGG and BO species, respectively, and, during DS2, from 0.5 to 3.0 and 1.3 to 5.2 for the BGG and BO species, respectively.

The average \( k_c \) was significantly different for the BGG and BO species (\( p < 0.05 \)) with values of 1.1 and 1.9, respectively (Table 4). The other species showed average \( k_c \) of 1.4, 1.5 and 1.6 for the PJ, BVV and PA species, respectively.

The ET\textsubscript{c} rates correlated significantly with weather parameters (Table 2). Average 10-day ET for the species were positively correlated with minimum temperature. The ET rates of tropical species, i.e. BGG and BVV species seem to be more strongly correlated with
minimum temperature ($r = 0.72$ and $r = 0.74$, respectively) than the temperate species, i.e., PA and PJ species ($r = 0.63$ and $r = 0.66$, respectively). As expected, the ET rates of all the species were correlated with average temperature and average relative humidity.

### 3.3. Bamboo morphology and influence on the actual evapotranspiration

Between the beginning and end of the experiment, the number of culms, culm diameter and height, and the aboveground fresh biomass yield increased significantly ($p < 0.001$). The number of culms increased by a factor of between 2.1 and 9.4 for the BO and PA species, respectively, the culm diameter by a factor of between 1.3 and 2.0 for the PA and BGG species, respectively, the culm height by a factor of between 1.1 and 1.7 for the PA and BGG species, respectively, and the biomass yield by a factor of between 5.4 and 18.1 for the BO and BGG species, respectively.

Table 3 shows that the species can be grouped by their morphological parameters. The BO and BVV species showed fewer, taller culms with larger diameters compared to the other species. In contrast, the PJ and BGG species showed a greater number of shorter culms with smaller diameters than the BO and BVV species.

The annual total ET (mm year$^{-1}$) correlates with the total fresh biomass ($r = 0.72$, $p < 0.01$), total fresh leaf mass ($r = 0.62$, $p < 0.01$) and total leaf area ($r = 0.61$, $p < 0.05$). The BO species, which showed the highest total ET rate, also produced the highest total aboveground fresh mass (with an average of 39 kg per clump), fresh leaf mass (8.6 kg) and total leaf area (117.6 m$^2$). Likewise, the BGG species, which showed the lowest ET rate, also produced the lowest biomass, fresh leaf mass and total leaf area (14.5 kg per clump, 3 kg and 30 m$^2$, respectively).

### 4. Discussion

The ET rates varied significantly throughout the year with a high seasonal factor ($p < 0.001$). All the species showed the same temporal pattern, with the highest ET rates recorded during the WS (October 2008 to April 2009), when the temperatures and rainfall reached their highest levels of the year (Fig. 2a). As mentioned previously, the WS is the main growth period for bamboo during which new shoots emerge from the soil (Kleinhinz and Midmore, 2001). The high ET rates measured during this season can be ascribed therefore to the increase in total number of shoots (Table 3), which leads to an increase in the total leaf area of the bamboo clumps and therefore to an increase in ET. Moreover, before this WS, the ET rates were lower and closely followed the reference evapotranspiration's values (Fig. 3). We also noticed that ET rates increased between DS1 and DS2 despite lower temperatures in DS2, which indicates that the increase in biomass during the WS had a significant effect on the increase in ET in DS2.

During the WS, the ET rates showed four peaks in December, January and March. These peaks may be explained by the increase in average minimum temperatures at the corresponding periods. Indeed, Table 2 shows that ET rates correlate more closely with minimum temperature than any other climate parameter. Many studies have demonstrated that an increase in ET is closely correlated with an increase in minimum air temperatures. Conversely, when the temperature drops below a certain value – depending on the species –, the stomatal conductance of leaves and the roots' hydraulic conductivity decrease (Jarvis, 1976; Mu et al., 2007), with a consequent decrease in evapotranspiration. Air temperature also strongly correlates with photosynthesis (Gratani et al., 2008; Van Goethem et al., 2013), which also impacts transpiration in bamboo (Agata et al., 1985). There are important differences in optimum temperature ranges for photosynthesis activity depending on the bamboo species' ecological distribution. Gratani et al. (2008) showed that bamboo of the genus *Phyllostachys* from temperate climates have a higher sensitivity to high temperature and that, conversely, bamboo of the genus *Bambusa* from tropical and subtropical climates have a higher sensitivity to low temperatures. For example, in the case of the genus *Bambusa* (i.e. tropical species), the net photosynthesis decreased more than 50% when temperatures dropped below 16.2 °C (Gratani et al., 2008). This physiological behavior and its consequences on the plant's transpiration are consistent with our study, in as much as we have noticed a better correlation between the ET rates and minimum temperatures in the tropical species (BO and BGG) than in the temperate species (PA and PJ) (Table 2).

The average and total ET, and $k_c$ varied significantly depending on the species ($p < 0.001$). Among the five species studied, the average and total ET, and $k_c$ of the BO and BGG species were significantly different to the other three (BVV, PA and PJ; $p < 0.05$) (Table 4).
In addition to the species’ original ecological habit, the main explanation for the difference in their ET rates is their different biomass yields, as shown in Tables 3 and 4. As observed for the BO and BVV species, a high biomass is related to a large total leaf area, which implies high ET (Table 4). Indeed, these two species produced taller and larger culms compared with the three others (Table 3).

For all the species, the average ET ranged between 4 and 7 mm day$^{-1}$, with maximum values during the WS of 12.3 and 17.18 mm day$^{-1}$, for the BGG and BO species, respectively. As stressed in the introduction, few studies have dealt with the evapotranspiration of bamboo species. By using the sap-flow measurement method, Dierick et al. (2010) and Komatsu et al. (2010) reported transpiration rates of 1.4 mm day$^{-1}$ and of between 3 and 4 mm day$^{-1}$ for Bambusa blumeana refurb Schult.f. and Phyllostachys pubescens J. Houz., respectively. However, unlike in our experiment, the soil evaporation in these studies was not included. Only Kleinheinz and Midmore (2002) have estimated the evapotranspiration of B. oldhamii (BO) with ET rates ranging between 9 and 13 mm day$^{-1}$. These values are consistent with those reported in our experiment. However, the latter study was carried out using small lysimeters (pots) which can generate experimental artifacts (Rana and Katerji, 2000). Since there is little data available on the evapotranspiration of bamboo and other giant grasses in literature, our results can be compared only with other plant species. For sugar cane grown on Reunion Island (the site of our own study), Chopart et al. (2007) reported an average annual ET of between 2.90 and 2.93 mm day$^{-1}$, with maximum values of 3.50 mm day$^{-1}$. These values are lower than those found in our study of the BGG and BO species; however, they correspond to a biomass yield for sugar cane of 101 t ha$^{-1}$ of fresh mass (Chopart et al., 2007), whereas the biomass yields in our study ranged between 120 and 325 t ha$^{-1}$ for the BGG and BO species, respectively, based on the surface area of the lysimeter. Although willow and poplar are trees and temperate plant species, they, like bamboo, are used for wastewater treatment (Dimitriou and Rosenqivist, 2011). Indeed, they have a high growth rate, biomass yields close to those of temperate bamboo species (10 to 15 t ha$^{-1}$ yr$^{-1}$ of dry mass) and high water uptakes (Aronsson and Bergstrom, 2001; Aronsson and Pertz, 2011; Dimitriou and Aronsson, 2011; Pertz and Kowalik, 1997). The ET values for the young bamboo plants in our study are similar to those reported for willow and poplar using the same lysimeter method as in our study. Under a Mediterranean climate, Guidi et al. (2008) reported an average of between 3.33 and 4.02 mm day$^{-1}$ (with a maximum of 15.46 mm day$^{-1}$) for poplar and between 3.47 and 6.65 mm day$^{-1}$ (with a maximum of 21.7 mm day$^{-1}$) for willow. Other authors such as Pistocchi et al. (2009) reported similar ET values for poplar and willow.

The $k_c$ values follow the same pattern as ET and ranged from 1.1 to 1.9 for the BGG and BO species, respectively. The values recorded in DS1, are consistent with the values reported by Payet et al. (2009), who reported a $k_c$ of between 0.48 and 1.2 for maize crops on Reunion Island. After the dry season, the $k_c$ values recorded for bamboo were higher than the maximum average $k_c$ found in literature for crops which is 1.25 in sugar cane (Allen et al., 1998). As expected, the average $k_c$ values for the bamboo in our study are closer to those for willow and poplar in short rotation coppices. Guidi et al. (2008) reported a $k_c$ of between 0.33 and 5.30 for willow and between 0.36 and 4.28 for poplar. Pistocchi et al. (2009) reported a $k_c$ of between 2.54 and 4.03 for both willow and poplar combined.

The evapotranspiration rates for the young bamboo in our study appear high, raising the question of possible experimental artifacts. The main potential source of error with the lysimeter method can be drastic differences in atmospheric conditions between the lysimeter and its immediate surroundings; this artifact is known as the “oasis effect” (Rana and Katerji, 2000). If the surrounding area consists of bare or poorly vegetated earth, net radiation in excess of latent heat is converted into sensible heat that is advected toward the lysimeter. Such a net input of energy into the lysimeter canopy results in an overestimation of ET (Rana and Katerji, 2000). As shown by Wegehenkel and Gerke (2013), the oasis effect in lysimeters similar to those used in our study (i.e. 1 m$^3$) can periodically occur during the summer when solar radiation reaches its maximum intensity. The oasis effect could not be totally excluded.

### Table 3

<table>
<thead>
<tr>
<th>Parameters</th>
<th>BGG</th>
<th>PA</th>
<th>PJ</th>
<th>BVV</th>
<th>BO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of culms Initial</td>
<td>72 ± 12.8d</td>
<td>5.7 ± 2.3a</td>
<td>36.7 ± 2.8c</td>
<td>11.7 ± 3ab</td>
<td>15.7 ± 1.2b</td>
</tr>
<tr>
<td>Final</td>
<td>325.3 ± 78.8c</td>
<td>54 ± 8b</td>
<td>195 ± 23c</td>
<td>25.7 ± 3.5a</td>
<td>34.3 ± 3.2ab</td>
</tr>
<tr>
<td>Culm diameter (mm) Initial</td>
<td>3.3 ± 0.1a</td>
<td>8.4 ± 0.7bc</td>
<td>7.3 ± 0.3b</td>
<td>11.1 ± 1c</td>
<td>11.2 ± 1c</td>
</tr>
<tr>
<td>Final</td>
<td>6.6 ± 0.5a</td>
<td>11.3 ± 0.8b</td>
<td>9.5 ± 0.4b</td>
<td>22.0 ± 2.8c</td>
<td>20.5 ± 1.0c</td>
</tr>
<tr>
<td>Height (cm) Initial</td>
<td>115.1 ± 5.4a</td>
<td>205.6 ± 7.4b</td>
<td>170 ± 13.3b</td>
<td>170.9 ± 22.8b</td>
<td>170 ± 13.3b</td>
</tr>
<tr>
<td>Final</td>
<td>201.4 ± 13.9a</td>
<td>239.4 ± 9.3ab</td>
<td>208.1 ± 6.8a</td>
<td>259.3 ± 26.9b</td>
<td>274.4 ± 10.0b</td>
</tr>
<tr>
<td>Aboveground fresh biomass (kg) Initial</td>
<td>0.8 ± 0.1a</td>
<td>1.4 ± 0.3a</td>
<td>3.4 ± 0.5b</td>
<td>2.9 ± 1.1b</td>
<td>7.2 ± 0.7c</td>
</tr>
<tr>
<td>Final</td>
<td>14.5 ± 0.3a</td>
<td>18.5 ± 4.3ab</td>
<td>27.0 ± 3.4b</td>
<td>24.6 ± 2.0ab</td>
<td>39 ± 0.1c</td>
</tr>
</tbody>
</table>

Values are means ±SE. The values with different letters indicate significant differences between the species (LSD, p < 0.05). Actual evapotranspiration (ET); reference evapotranspiration (ET0); crop coefficient ($k_c$); Bambusa multiplex (BGG); Phyllostachys aurea (PA); Pseudosasa japonica (PJ); Bambusa vulgaris (BVV) and Bambusa oldhamii (BO).

### Table 4

<table>
<thead>
<tr>
<th>Parameters</th>
<th>BGG</th>
<th>PA</th>
<th>PJ</th>
<th>BVV</th>
<th>BO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total aboveground fresh biomass (kg)</td>
<td>14.5 ± 0.3a</td>
<td>18.5 ± 4.3ab</td>
<td>27.0 ± 3.4b</td>
<td>24.6 ± 2.0ab</td>
<td>39 ± 0.1c</td>
</tr>
<tr>
<td>Average fresh culm mass (g)</td>
<td>45.5 ± 5.6a</td>
<td>184.6 ± 25.4c</td>
<td>95.9 ± 8.3b</td>
<td>514.7 ± 196.7cd</td>
<td>1149.7 ± 102.2d</td>
</tr>
<tr>
<td>Total fresh leaf mass (kg)</td>
<td>3.0 ± 0.8a</td>
<td>3.5 ± 0.4a</td>
<td>5.0 ± 0.5b</td>
<td>7.5 ± 0.6c</td>
<td>8.6 ± 0c</td>
</tr>
<tr>
<td>Total leaf area (m$^2$)</td>
<td>30.0 ± 6.2a</td>
<td>35.6 ± 3.7a</td>
<td>32.4 ± 4.7a</td>
<td>81.3 ± 4.6b</td>
<td>117.6 ± 2.6c</td>
</tr>
<tr>
<td>Average ET (mm day$^{-1}$)</td>
<td>4.0 ± 0.3a</td>
<td>5.5 ± 0.3b</td>
<td>5.1 ± 0.3b</td>
<td>5.4 ± 0.3b</td>
<td>7 ± 0.4c</td>
</tr>
<tr>
<td>Average ET0 (mm day$^{-1}$)</td>
<td>3.0 ± 0.1a</td>
<td>3.1 ± 0.1b</td>
<td>3 ± 0.1</td>
<td>3 ± 0.1</td>
<td>3 ± 0.1</td>
</tr>
<tr>
<td>$k_c$ (mm day$^{-1}$)</td>
<td>1.1 ± 0.1a</td>
<td>1.6 ± 0.2b</td>
<td>1.4 ± 0.1b</td>
<td>1.5 ± 0.2b</td>
<td>1.9 ± 0.2c</td>
</tr>
<tr>
<td>Annual total ET (mm yr$^{-1}$)</td>
<td>1270.1 ± 67.1a</td>
<td>1605.5 ± 42.7b</td>
<td>1605.8 ± 98.5b</td>
<td>1704.1 ± 27.9b</td>
<td>22187.7 ± 30.8c</td>
</tr>
</tbody>
</table>

Values are means ±SE. The values with different letters indicate significant differences between the species (LSD, p < 0.05). Actual evapotranspiration (ET); reference evapotranspiration (ET0); crop coefficient ($k_c$); Bambusa multiplex (BGG); Phyllostachys aurea (PA); Pseudosasa japonica (PJ); Bambusa vulgaris (BVV) and Bambusa oldhamii (BO).
in our case, especially during the wet season, which corresponds to the period of the year when solar radiation is the highest (Allen et al., 1998). However, comparing our results with other studies dealing with evapotranspiration in crops such as maize and sugar cane, and in poplar and willow, suggests that the data reported in our study is reliable. Furthermore, in addition to providing new data on bamboo species, our study could provide useful information for optimizing the design for future experiments on ET in bamboo and other giant grasses.

Lastly, the ET values measured were those for three-year-old bamboo that is to say for non-mature bamboo. Indeed, a bamboo plantation reaches maturity in five to eight years, depending on the growth conditions. This suggests that for a mature bamboo plantation of giant bamboo such as the BO species, in which culms can reach 18 m in height at maturity (Castaneda-Mendoza et al., 2005), the ET rates would be even higher.

5. Conclusions

The experiment reported here is – to our knowledge – the first lysimeter experiment to investigate the evapotranspiration rates of different species of bamboo. The results show that seasons and minimum temperatures are the main climatic factors affecting ET. As expected, the differences in ET observed between species can be explained by the aboveground biomass yield and the total leaf surface area, the two morphological parameters showing a high correlation with ET rates. Among the five bamboo species used, B. oldhamii had the highest ET rate and produced the highest amount of biomass during the experiment. In comparison with evaporation rates for other high-biomass-producing plants, those for young bamboo plants are similar to those for willow and poplar used in short rotation coppices. In conclusion, our study provides useful data for the design and management of vegetation filters using bamboo plantations. The data could also be useful for the water management of commercial bamboo plantations.

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