Measurements of transpiration in four tropical rainforest types of north Queensland, Australia

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Abstract:

Transpiration of four different rainforest types in north Queensland, Australia, was determined using the heat pulse technique for periods ranging between 391 and 657 days. Despite the complexity of the natural rainforest systems being studied, the relationship between sample tree size and daily water use was found to be strong, thus providing a robust means by which to scale transpiration from individual trees to the entire forest stand. Transpiration was shown to be dependent on solar radiation and atmospheric demand for moisture with little evidence of limitation by soil moisture supply. Total stand transpiration was controlled by forest characteristics such as stem density, size distribution and sapwood area. Annual transpiration for each of the four sites ranged between 353 mm for cloud forest and 591 mm for montane rainforest. In comparison with the international literature, transpiration from Australian rainforests is low; the reasons for this could be related to a combination of differences in forest structure, climatic conditions, canopy wetness duration and tree physiology. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS tropical rainforest; transpiration; sapwood area; vapour pressure deficit; solar radiation; potential evapotranspiration

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INTRODUCTION

The Wet Tropics of north Queensland, Australia, cover an area of almost 9000 km² on the coastal strip adjacent to the Great Barrier Reef. This area contains Australia’s most extensive remaining area of tropical rainforest. Much of this area is World Heritage listed because of high conservation and ecological values, however, hydrological understanding of these systems remains poor. Consequently, the effects of changes in vegetation type and cover on water yield and water quality in these humid tropical catchments are poorly understood. Such knowledge is vital in developing a modelling framework for predicting the effects of possible land use and climate changes on water resources in the region.

In order to address some of these knowledge gaps we have been undertaking extensive long-term water balance studies throughout the Wet Tropics region over several years. For example, McJannet et al. (2007a,b) have reported on the wet canopy water balance of six different rainforest types from the coast to the mountains, including measurements of throughfall, stemflow, cloud interception and interception by the canopy. In this paper we report the results of our transpiration measurements that were undertaken in four of the six canopy water balance sites described in McJannet et al. (2007b).

Despite a growing body of international literature on the hydrology of tropical forests, studies reporting measurements (rather than modelling) of stand-level transpiration remain limited. A selection of literature reporting measured rainforest stand transpiration rates (expressed as daily averages in mm day⁻¹), including location, methodology, study duration and source is given in Table I. From this table it can be seen that transpiration rates in different tropical forest types exhibit much variation; ranging from a daily average transpiration of 0.4 mm in montane rainforest to 4.6 mm for a lowland rainforest. Average rates depend on the duration of the study and the season/conditions during which the study was undertaken, hence, short-term measurements or measurements restricted to certain conditions (i.e. periods without rain) must be treated with some caution. Long-term transpiration measurements are essential for the construction of long-term water balance estimates or development of predictive hydrological modelling techniques.

Table I also shows that a range of techniques have been used to estimate rainforest transpiration. In the present study we used the well established heat pulse technique, as with sufficient care and maintenance it was possible to obtain reliable estimates of long-term rainforest stand transpiration. The majority of research using the heat pulse technique has focused on the determination of transpiration by trees in plantations (e.g. Morris et al., 1998; McJannet and Vertessy, 2001) or forest stands dominated by a single species of a similar age (e.g. Hatton et al., 1995; Vertessy et al., 1995). Use of the
heat pulse technique in mixed-species forests, particularly tropical rainforest, has been very limited (e.g. Hutley et al., 1997), although heat balance probes, which also measure sapflow in individual trees, have been used in a number of studies (e.g. Granier et al., 1996; Oren et al., 1996; Phillips et al., 1999; Giambelluca et al., 2003). Some of the reasons that the sapflow techniques have not been more widely used could relate to the sampling and scaling issues that are perceived to occur in tropical rainforest. The sampling issues relate to the high species diversity and variations in tree size; whereas the scaling issues relate to the complex canopy architecture and interspecies transpiration differences. In this paper we describe the ways in which we have dealt with these factors and present long-term transpiration rates for four different forest types. In addition, we will demonstrate how environmental factors control tropical rainforest transpiration rates at the sites investigated.

METHODS

Field site characteristics

The locations of the field sites used in this study are shown in Figure 1. The four sites represent different forest types, geologies and altitudes found in this region. Full characteristics of each site are given in Table II and detailed site descriptions are given in McJannet et al. (2007b); brief descriptions are given below. Leaf area index (LAI) and canopy gap fraction were determined using hemispherical photographs (McJannet et al., 2007a) and the resulting images were processed using the Gap Light Analyzer software package (Frazer et al., 2007a). Stem density and basal area were calculated from surveys across a 1600 m² plot at each site. Basal area of each of the sites was determined by measuring the diameter at breast height (1.3 m) of trees larger than 10 cm. The four distinct forest types studied were classified using the Australian tropical rainforest classification technique of Tracey (1982).

The Oliver Creek (OC) site is a pristine lowland rainforest which is located in the Daintree National Park at an altitude of 30 m. The Upper Barron (UB) site is a lower montane rainforest located on the Atherton Tablelands in Longlands Gap State Forest at an altitude of 1050 m. The Mount Lewis (ML1) site is a pristine lower montane rainforest located on the Carbine Tablelands in the World Heritage listed Mt Lewis State Forest at an altitude of 1100 m. The highest altitude site (1560 m) is located in upper montane cloud forest near the summit of Bellenden Ker (BK), which is the second highest mountain in Queensland. All sites are subject to a distinct wet and dry season. The dry season covers the months from June to November, whereas the wet season generally occurs from December to May. The predominant wind direction in this region is from the south-east, i.e. across the Coral Sea.

Transpiration

Transpiration was estimated by measuring sapflow velocity and sapwood area of sample trees. Two different systems, both based on the heat pulse technique, were

<table>
<thead>
<tr>
<th>Location</th>
<th>Forest type</th>
<th>Transpiration</th>
<th>Method</th>
<th>Study duration</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Java</td>
<td>Secondary lowland</td>
<td>2-6 mm day⁻¹</td>
<td>Soil moisture depletion</td>
<td>25 days</td>
<td>(Calder et al., 1986)</td>
</tr>
<tr>
<td>Panama</td>
<td>Lowland</td>
<td>1-9 mm day⁻¹</td>
<td>Granier probes</td>
<td>10 days</td>
<td>(Phillips et al., 1999)</td>
</tr>
<tr>
<td>Manaus, Brazil</td>
<td>Lowland</td>
<td>2-8 mm day⁻¹</td>
<td>Eddy correlation</td>
<td>2 years</td>
<td>(Shuttleworth, 1988)</td>
</tr>
<tr>
<td>Venezuela</td>
<td>Lowland</td>
<td>2-8 mm day⁻¹</td>
<td>Tritiated water</td>
<td>6 weeks</td>
<td>(Jordan and Kline, 1977)</td>
</tr>
<tr>
<td>Kourou, French Guiana</td>
<td>Lowland</td>
<td>~1.3 – 3.8 mm day⁻¹</td>
<td>Granier probes</td>
<td>2 dry seasons</td>
<td>(Granier et al., 1996)</td>
</tr>
<tr>
<td>Manaus, Brazil</td>
<td>Lowland</td>
<td>2-3–4.6 mm day⁻¹</td>
<td>Porometry</td>
<td>Dry periods– 4 years</td>
<td>(Roberts et al., 1993)</td>
</tr>
<tr>
<td>Sarawak, Borneo</td>
<td>Lowland</td>
<td>2-7–3.5 mm day⁻¹</td>
<td>Eddy correlation</td>
<td>Dry and wet seasons</td>
<td>(Kumagai et al., 2004)</td>
</tr>
<tr>
<td>Peru</td>
<td>Floodplain Upland</td>
<td>&lt;0-6 mm day⁻¹</td>
<td>Granier probes</td>
<td>8 days</td>
<td>(Oren et al., 1996)</td>
</tr>
<tr>
<td>Queensland, Australia</td>
<td>Subtropical Upland</td>
<td>1-4 mm day⁻¹</td>
<td>Heat pulse probes</td>
<td>1 year</td>
<td>(Hutley et al., 1997)</td>
</tr>
<tr>
<td>Tat Hamlet, Vietnam</td>
<td>Subtropical Upland</td>
<td>1-0 mm day⁻¹</td>
<td>Granier probes</td>
<td>48 days</td>
<td>(Giambelluca et al., 2003)</td>
</tr>
<tr>
<td>Puerto Rico</td>
<td>Montane palm forest</td>
<td>1-3 mm day⁻¹</td>
<td>Eddy covariance</td>
<td>12 months</td>
<td>(Holwerda, 2005)</td>
</tr>
<tr>
<td>Puerto Rico</td>
<td>Eflin cloud forest</td>
<td>0.8 mm day⁻¹</td>
<td>Eddy covariance</td>
<td>11 months</td>
<td>(Holwerda, 2005)</td>
</tr>
<tr>
<td>Costa Rica</td>
<td>Cloud forest</td>
<td>1-0 mm day⁻¹</td>
<td>Eddy covariance</td>
<td>12 months</td>
<td>(Bruijnzel et al., 2006)</td>
</tr>
</tbody>
</table>
Figure 1. Location map showing Wet Tropics region and location of rainforest field sites (△). Altitudes of field sites are given in brackets.

Table II. Study duration, location, altitude, slope, geology, forest type, LAI, canopy gap, stem density, basal area, average canopy height, total precipitation, average annual precipitation, long-term annual precipitation (where available) and potential evaporation and heat pulse sample tree species for each study site

<table>
<thead>
<tr>
<th>Study period</th>
<th>Oliver Creek</th>
<th>Upper Barron</th>
<th>Mt Lewis1</th>
<th>Bellenden Ker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration of study (days)</td>
<td>502</td>
<td>657</td>
<td>533</td>
<td>391</td>
</tr>
<tr>
<td>Latitude (S)</td>
<td>16°08-3</td>
<td>17°27-1</td>
<td>16°31-7</td>
<td>17°16-0</td>
</tr>
<tr>
<td>Longitude (E)</td>
<td>145°26-4</td>
<td>145°29-7</td>
<td>145°16-7</td>
<td>145°51-0</td>
</tr>
<tr>
<td>Altitude (m)</td>
<td>30</td>
<td>1050</td>
<td>1100</td>
<td>1560</td>
</tr>
<tr>
<td>Slope (%)</td>
<td>4</td>
<td>20</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>Geology</td>
<td>Mudstone</td>
<td>Basalt</td>
<td>Granite</td>
<td>Granite</td>
</tr>
<tr>
<td>Forest type</td>
<td>Complex Mesophyll</td>
<td>Complex Notophyll</td>
<td>Simple Notophyll</td>
<td>Simple Microphyll</td>
</tr>
<tr>
<td>LAI (m² m⁻²)</td>
<td>4-2 (±0-1)</td>
<td>4-1 (±0-1)</td>
<td>2-8 (±0-3)</td>
<td>6-4 (±0-5)</td>
</tr>
<tr>
<td>Canopy gap (%)</td>
<td>644</td>
<td>925</td>
<td>650</td>
<td>2019</td>
</tr>
<tr>
<td>Stem density (stems ha⁻¹)</td>
<td>64</td>
<td>69</td>
<td>62</td>
<td>74</td>
</tr>
<tr>
<td>Basal area (m² ha⁻¹)</td>
<td>3017</td>
<td>5699</td>
<td>3877</td>
<td>7898</td>
</tr>
<tr>
<td>Average canopy height (m)</td>
<td>27</td>
<td>25</td>
<td>32</td>
<td>8</td>
</tr>
<tr>
<td>Total precipitation (mm)</td>
<td>2484</td>
<td>2983</td>
<td>3040</td>
<td>7471</td>
</tr>
<tr>
<td>Average annual precipitation (mm)</td>
<td>3952</td>
<td>—</td>
<td>—</td>
<td>8100</td>
</tr>
<tr>
<td>Long-term annual precipitation (mm)</td>
<td>1139</td>
<td>1083</td>
<td>902</td>
<td>815</td>
</tr>
<tr>
<td>Average annual potential ET₀ (mm)</td>
<td>Idiospermum australiense</td>
<td>Acronychia crassipetala</td>
<td>Acronychia crassipetala</td>
<td>Balanops australiana</td>
</tr>
<tr>
<td>Heat pulse sample tree species</td>
<td>Endiandra microneura</td>
<td>Beilschmidea toorom</td>
<td>Beilschmidea toorom</td>
<td>Flindersia oppositifolia</td>
</tr>
<tr>
<td></td>
<td>Ristania pachysperma</td>
<td>Calophyllum costatum</td>
<td>Calophyllum costatum</td>
<td>Balanops australiana</td>
</tr>
<tr>
<td></td>
<td>Beilschmidea bancroftii</td>
<td>Doryphora aromatica</td>
<td>Canarium australaslicum</td>
<td>Musgravea stenostachya</td>
</tr>
<tr>
<td></td>
<td>Lindsayomurts racemoides</td>
<td>Elaeocarpus foveolatus</td>
<td>Doryphora aromatica</td>
<td>Elaeocarpus farraginiflorus</td>
</tr>
<tr>
<td></td>
<td>Cryptocarya murrayi</td>
<td>Melicope jonesii</td>
<td>Elaeocarpus foveolatus</td>
<td>Acmena hemilampra</td>
</tr>
<tr>
<td></td>
<td>Xanthophyllum fragrans</td>
<td>Melicope jonesii</td>
<td>Melicope jonesii</td>
<td>Rapanea sp.</td>
</tr>
<tr>
<td></td>
<td>Beilschmidea bancroftii</td>
<td></td>
<td></td>
<td>Cinnamomum propinquum</td>
</tr>
</tbody>
</table>
used to measure sapflow velocity of sample trees at each rainforest site for periods between 391 and 657 days. The first technique is known as the Heat Pulser system (Edwards Industries, Otaki, New Zealand) and the second was developed for this study to overcome electrical interference problems with the Heat Pulser system. This second custom built system is fully described by McJannet and Fitch (2004). Both systems work on the same principle and analysis of the data is identical. They use a heating probe, inserted into the trunk of a tree, to inject a heat pulse into the conducting tissue of the tree (sapwood). This pulse of heat is then used to infer the rate of movement of water up the trunk of the tree by the use of thermistor probes inserted into the tree above and below the heating probe. This monitoring arrangement compensates for the process of heat diffusion and allows heat convection to be isolated and measured. Heat convection can then be used to calculate sap velocity, which can in turn be used with measurements of the sapwood area of the tree to determine its volumetric sapflow rate. The heat pulse method is based on the compensation technique of Marshall (1958), which has been refined by Swanson and Whitfield (1981), Durham and Hatton (1989) and Hatton et al. (1990).

The heat pulse method produces point measurements of sap velocity at the depth of probe insertion, however, sapflow is known to vary rapidly within the sapwood of trees (e.g. Wullschleger and King, 2000; Ford et al., 2004). Accurate measurements of total sapflow therefore require heat pulse measurements to be made simultaneously at varying depths within the sapwood. To determine the depth of probe insertion in each tree we used the technique of Hatton et al. (1990), which specifies sensor depths that represent the midpoint within concentric rings of sapwood of equal area. Total sapflow for each tree was calculated as the sum of the area of each concentric ring multiplied by its associated sap velocity.

Sapflow measurements were made at 30 min intervals in nine trees at OC, seven trees at UB, nine trees at ML1 and eight trees at BK. The duration of measurement periods at each site is shown in Table II. Trees >50 cm diameter at breast height (DBH) were fitted with four probe sets and trees <50 cm DBH were fitted with two probe sets. This procedure was followed to ensure more accurate estimates of transpiration from the larger trees which dominate water use of the forests. The Heat Pulser system used 1-65 mm Teflon thermistor probes whereas the custom built system used 2-2 mm stainless steel thermistors. Following the methodology of Benyon (1999), wound size estimates, needed for correcting heat pulse velocity for disruption of sapwood capillaries during probe insertion (Swanson and Whitfield, 1981), were assumed to be equal to the thermistor diameter plus one vessel width (0-5 mm) on either side of the probe. Thermistor pairs and heaters were removed and reinstalled at ~2-month intervals so as to limit the possibility of reactions to probe implantation affecting sapflow measurements. To test if there was any such effect, we examined the ratio of sample tree water use to potential evaporation (see below) over a 100 day period (which included two probe reinstallations) where soil moisture was not limiting. There was no significant trend in this ratio over time, so we can assume that wound size remained stable during each installation period. If the upper and lower thermistors in each measurement pair failed to reach equilibrium within 10 min of heat pulse injection it was assumed that no sapflow was taking place.

Both heat pulse systems used a data logger (CR10X, Campbell Scientific, Logan, USA) to control a multiplexer (AM16/32, Campbell Scientific, Logan, USA or Heat Pulser, Edwards Industries, Otaki, New Zealand) capable of taking 32 simultaneous thermistor measurements (i.e. 16 thermistor pairs). Heat pulse systems at each site were powered using a single 120 Ahr deep cycle battery which was charged by a 64 W solar panel (Unisolar, Troy, MI).

Sapwood area was determined using a methodology similar to that of Dawson (1998). A single hole was drilled into the side of each tree at either breast height (1-3 m) or above buttressing. This hole was then fitted with a small hose filled with food dye from a reservoir above. Over time the dye was drawn through the sapwood by the tree and the region of the tree which was transporting dye was determined by taking a 0-5 mm increment core slightly above the drilled hole a couple of hours after installation. The sapwood was then easily identified by staining from the food dye. Increment cores were also used to determine wood and water fractions of the sapwood, which are necessary for converting heat pulse velocity to sapflow velocity.

Selection of sample trees was undertaken with the aim of representing the range of tree sizes found in a 1600 m² plot at each site, irrespective of tree species. Tree size distribution was determined by measuring the diameters of trees with a DBH >10 cm. The number of sample trees at each site was determined by the tree sizes selected and the measurement capability (16 thermistor pairs) at each site. Sample tree selection resulted in inclusion of a large range of tree species as shown in Table II. The methodology used for up-scaling from sample tree water use to stand transpiration is based on robust relationships between tree size and daily water use, which are described in detail in the results section.

Additional measurements

Temperature and humidity within the canopy of each site was monitored using a HOBO Pro RH/Temp Data Logger (Onset Computer Corporation, Massachusetts, USA). The logger was mounted in a weather shield to protect sensors from rain and direct sunlight. The logger was hoisted into the middle of the canopy (between 8 and 25 m) using a rope fixed over a high branch of an emergent tree. Temperature and humidity were measured at 30 min intervals and were used to calculate vapour pressure deficit (VPD).

Automatic weather stations, which monitored solar radiation, temperature, humidity and wind speed, were
installed at each site. Full descriptions of these stations are given in McJannet et al. (2007b). All weather station measurements were made at 30 min intervals. Rainfall ($P_g$) at each site was measured using tipping bucket rain gauges (see McJannet et al. (2007b) for details). The higher altitude rainforests (>1000 m) in the Australian Wet Tropics are often on steep slopes subject to frequent exposure to prevailing winds, therefore, to correctly estimate rainfall inputs theoretical corrections, which account for wind-losses from the rain gauge (Førland et al., 1996) and wind blown (near horizontal) rain being intercepted on sloping land (e.g. Sharon, 1980; de Lima, 1990; Holwerda et al., 2006), were applied. These theoretical corrections are described in detail by Holwerda et al. (2006). Analysis of the corrections applied to rainfall data from all sites in this study is given in McJannet et al. (2007b).

Total precipitation inputs at each site were determined from the combination of adjusted rainfall ($P_g$) and cloud interception measurements. At Oliver Creek precipitation occurred only as rainfall, but the other sites had significant inputs from cloud interception. Cloud interception estimates were made using the wet canopy water balance methodology described in McJannet et al. (2007a).

Using site specific parameters and weather station measurements for each site, daily potential evaporation ($E_T^0$) was calculated using the FAO version of the Penman–Monteith equation (Allen et al., 1998). On days where either relative humidity, solar radiation or wind speed measurements failed, $E_T^0$ was calculated using the temperature based methodology of Hargreaves and Samani (1985). Comparison of $E_T^0$ estimates made using both FAO (Food and Agriculture Organization) Penman–Monteith and Hargreaves and Samani methods revealed average differences of <5%.

RESULTS AND DISCUSSION

Weather overview

Measurements at different sites took place over varying time periods starting as early as August 2002 and all finishing before the end of June 2005 (Table II). During the years 2002 and 2003, rainfall in the region was well below average with the driest rainy seasons on record measured at many regional climate stations. During 2004 and 2005 rainfall was much closer to average conditions. The dry spell was due largely to the development of strong El Niño conditions during 2002. Annual precipitation totals during the measurement period at each site are shown in Table II. Total precipitation for the study period is a combination of rainfall and cloud water interception (see McJannet et al., 2007b) and for inter-site comparison purposes, average annual precipitation equivalent is calculated by totalling monthly averages.

Individual tree sapflow

Figure 2 shows the variation in sapflow rates of three different sized trees during a 5-day period towards the end of the dry season at OC. Also shown are the corresponding fluctuations in canopy VPD and solar radiation. Sapflow appears to be closely tied to solar radiation and VPD fluctuations. The two largest trees respond similarly during the 5 days whereas the smallest tree appears to reach maximum sapflow slightly later than the larger trees. This could be related to tree position

![Figure 2](image-url)
in the canopy, since the two larger trees have canopies in the overstorey whereas the smaller tree is in the understorey. It is interesting to note that the larger trees continue low sapflow rates (<1 L h\(^{-1}\)) throughout the night between 31 August 2003 and 3 September 2003, when canopy VPD was zero. These night-time sapflow rates may be due to tree sap continuing to flow after sunset through stomata remaining open or in order to replenish water stores within the tree that have been depleted during the day (Benyon, 1999). These low rates between 31 August 2003 and 3 September 2003 produce total nocturnal sapflow of 7.0 L, 9.9 L and 3.2 L for the 71.6 cm, 48.1 cm and 17.8 cm DBH trees, respectively. However, on the night of 4 September 2003 nocturnal VPD remained high and night-time sapflow increased. Sapflow totals of 82.3 L, 33.5 L and 15.7 L were recorded during this night by the 71.6 cm, 48.1 cm and 17.8 cm DBH trees, respectively. Nocturnal sapflow on this night has resulted from a combination of water storage replenishment and continued transpiration due to the high atmospheric saturation deficit.

Despite high average annual rainfall across the region our field measurements suggest that the sapflow of rainforest trees can be periodically limited by soil moisture availability. This is illustrated in Figure 3 using sapflow data from a 91 cm DBH tree from ML1. Sapflow, canopy VPD and solar radiation for 3 days with very similar climatic conditions (i.e. temperature, wind speed, humidity, VPD and solar radiation) are shown. The \( ET_0 \) for these 3 days was 3-8, 3-3 and 3-9 mm for 29 October 2002, 10 September 2003 and 20 December 2003, respectively. Data from 29 October 2002 were recorded during a period of strong El Niño conditions, where rainfall in the previous 30 days was just 3 mm, whereas data from 10 September 2003 and 20 December 2003 had rainfall totals for the previous 30 days of 120 mm and 218 mm, respectively. On 29 October 2002 just 38 L of water were transpired, whereas on 10 September 2003 and 20 December 2003 107 L and 87 L were transpired, respectively. Despite similar nocturnal canopy VPD on 29 October 2002 to the other comparison nights, sapflow is very low, suggesting minimal transpiration at this time in response to drought stress. With all other controlling climatic factors held roughly constant these results provide strong evidence for occasional soil moisture stress, this observation is discussed further below.

### Scaling to stand transpiration

Figure 4 shows the relationship between DBH (cm) and average daily sap velocity (cm day\(^{-1}\)) for sample trees at all sites for example days that exhibit high and low transpiration rates. All sites exhibit a positive but weak relationship between tree size and sap velocity at both high and low transpiration rates. Sample trees represent different sized trees and also different species (Table II), but the weak positive trend in the relationship suggests that there is a tendency for larger trees to transpire faster than smaller trees, possibly as a result of their higher position in the canopy. Smaller trees tend to be sheltered from solar radiation and turbulent transfer processes, which are greatest at the top of the canopy (Shuttleworth et al., 1985; Roberts et al., 1993). Although the trends are positive, the relationships are weak because sap velocity shows a great deal of variation across tree size and species.

Sap velocity of sample trees was converted to daily transpiration by multiplying it by the cross-sectional area of conducting tissue of each tree. The relationship between tree DBH and sapwood area is shown in Figure 5. The linear fit to the data in this figure reflects the relatively constant sapwood thickness observed between species and tree size (Table III). Figure 6 shows the resultant relationships between tree size and transpiration for individual days representing examples of high and low transpiration conditions. It can be seen that these relationships are much stronger than between tree size and sap velocity (Figure 4) illustrating that the variations observed in tree water use are mainly driven by the strong relationship between sapwood area and DBH.

Despite the diversity of species and large ranges of tree sizes encountered at each site, the strength of relationships between tree size and transpiration made it possible to develop a simple scaling methodology, which allowed robust estimates of stand water use to be made.

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**Figure 3.** Diurnal sapflow rate fluctuations for a 91 cm DBH tree at ML1 over 3 days with similar climatic conditions. Measurements on 29 October 2002 were during strong El Niño drought conditions whereas measurements on 10 September 2003 and 20 December 2003 were during much wetter conditions. Corresponding VPD and solar radiation inputs are also shown for each day.

**Figure 4.** The linear fit to the data in this figure reflects the relatively constant sapwood thickness observed between species and tree size (Table III). Figure 6 shows the resultant relationships between tree size and transpiration for individual days representing examples of high and low transpiration conditions. It can be seen that these relationships are much stronger than between tree size and sap velocity (Figure 4) illustrating that the variations observed in tree water use are mainly driven by the strong relationship between sapwood area and DBH.

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**Figure 5.** The linear fit to the data in this figure reflects the relatively constant sapwood thickness observed between species and tree size (Table III). Figure 6 shows the resultant relationships between tree size and transpiration for individual days representing examples of high and low transpiration conditions. It can be seen that these relationships are much stronger than between tree size and sap velocity (Figure 4) illustrating that the variations observed in tree water use are mainly driven by the strong relationship between sapwood area and DBH.
For each day with measurements, relationships between tree size and daily transpiration were established (as in Figure 6). Then for any given day the total water use of the forest stand was estimated by applying the sample tree DBH versus transpiration relationship to each tree in a plot of 1600 m². The water use of all trees was then summed and divided by the plot area to determine stand transpiration rate (mm). Plot area was adjusted for slope angle so that transpiration was expressed on a horizontal surface.

Transpiration and stand characteristics

Using the scaling methodology presented above, a time series of stand level transpiration was derived, showing the seasonal variation in transpiration at each site (Figure 7). All sites show higher transpiration rates during the wet season months (Dec–May) than during the dry season months (Jun–Nov). The highest maximum daily transpiration was recorded at ML1 (3.8 mm), whereas the lowest was recorded at BK (2.2 mm). Over the entire study period the highest average daily transpiration rates were measured at OC and UB (1.7 mm) while the lowest was measured at BK (1.0 mm) (Table III). These average transpiration rates are at the lower end of the range reported in Table I (although some of these differences may be due to the duration of studies reported and conditions during the measurement periods). For subsequent monthly and season transpiration analysis missing daily transpiration values were estimated from the relationship between ET₀ (or total solar radiation when

Figure 4. Relationship between DBH of individual sample trees and daily sap velocity (v₁) at OC (a), UB (b), ML1 (c) and BK (d) for high (dashed line) and low (solid line) transpiration days. OC High v₁ = 0.40DBH + 90.5 (r² = 0.14), OC Low v₁ = 0.28DBH + 24.2 (r² = 0.21), UB High v₁ = 1.16DBH + 56.8 (r² = 0.17), UB Low v₁ = 0.23DBH + 27.3 (r² = 0.11), ML1 High v₁ = 0.43DBH + 136.6 (r² = 0.05), ML1 Low v₁ = 0.44DBH + 15.9 (r² = 0.37), BK High v₁ = 0.73DBH + 40.5 (r² = 0.13), BK Low v₁ = 0.30DBH + 14.7 (r² = 0.09)

Table III. Average sample tree sapwood thickness (± standard deviation), plot sapwood area, plot LAI, LAI sapwood area ratio, average daily transpiration, average wet season transpiration, average dry season transpiration, maximum transpiration, percentage of precipitation lost through transpiration and normalized annual transpiration for the study duration at each site. Normalized annual transpiration was calculated from the total of monthly averages

<table>
<thead>
<tr>
<th></th>
<th>OC</th>
<th>UB</th>
<th>ML1</th>
<th>BK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average sample tree sapwood thickness (mm)</td>
<td>36(±8)</td>
<td>33(±6)</td>
<td>29(±2)</td>
<td>27(±4)</td>
</tr>
<tr>
<td>Plot sapwood area (m² ha⁻¹)</td>
<td>17.0</td>
<td>23.5</td>
<td>15.8</td>
<td>26.3</td>
</tr>
<tr>
<td>Plot LAI (m² m⁻²)</td>
<td>4.2</td>
<td>4.2</td>
<td>4.5</td>
<td>3.3</td>
</tr>
<tr>
<td>LAI: sapwood area (m² m⁻²) (m² m⁻²)</td>
<td>2970</td>
<td>1787</td>
<td>2848</td>
<td>1255</td>
</tr>
<tr>
<td>Average daily transpiration (mm)</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
<td>1.0</td>
</tr>
<tr>
<td>Average daily dry season transpiration (mm)</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
<td>0.8</td>
</tr>
<tr>
<td>Maximum daily transpiration (mm)</td>
<td>2.7</td>
<td>3.7</td>
<td>3.8</td>
<td>2.2</td>
</tr>
<tr>
<td>Percent of total precipitation transpired (%)</td>
<td>24</td>
<td>20</td>
<td>19</td>
<td>5</td>
</tr>
<tr>
<td>Average annual transpiration (mm)</td>
<td>587</td>
<td>591</td>
<td>589</td>
<td>353</td>
</tr>
</tbody>
</table>
$ET_0$ not available) and transpiration for complete data days (see below for details).

Analysis of the frequency of occurrence of transpiration classes also reveals some interesting information regarding the functioning of the different forest sites, Figure 8. The most frequent daily transpiration rate for OC was in the 1.5–2.0 mm range (39%), which was greater than all the other sites. The range of transpiration rates was greater at UB and ML1, however, over the duration of the study average transpiration rate was very similar to that of OC (Table III). The occurrence of some of the highest transpiration rates at ML1 and UB shows that when climatic conditions are favourable transpiration can exceed rates recorded at OC; the limiting factor at ML1 and UB is the number of days that favourable conditions occur. Compared with the low altitude OC site, both ML1 and UB experience cooler conditions, with frequent immersion in cloud. In particular, high daily transpiration rates at UB and ML1 correspond with periods of very high solar radiation in combination with high VPD. Maximum solar radiation values at ML1 and UB exceed those measured at OC and average daily VPD of these higher altitude sites can be as much as twice that observed at OC. At BK more than 50% of days had transpiration in the range of 0.5–1.0 mm reflecting the persistent low evaporative demand at this site.

Table III also shows the sapwood area and average transpiration rate for each site, illustrating that average transpiration is not solely determined by the total area of conducting tissue at any location. Total sapwood area of each plot was determined by applying the relationship between tree diameter and sapwood area of transpiration sample trees at each site (Figure 5) to all trees in a 1600 m$^2$ plot. Transpiration rates for different sites therefore result from a combination of stem size distribution, sapwood area, and local climatic and soil moisture conditions. To explore the influence that stem size distribution has on total transpiration an analysis of the distribution of stem size, sapwood area and transpiration across DBH size classes was undertaken.

![Figure 5](image-url) Relationship between DBH of individual sample trees and sapwood area (SA) at OC (a), UB (b), ML1 (c) and BK (d). OC SA = 10.83DBH - 27.0 ($r^2 = 0.77$), UB SA = 11.1DBH - 66.0 ($r^2 = 0.95$), ML1 SA = 9.53DBH - 57.7 ($r^2 = 0.96$), BK SA = 8.27DBH - 33.4 ($r^2 = 0.97$)

![Figure 6](image-url) Relationship between DBH of individual sample trees and daily sapflow ($Q$) at OC (a), UB (b), ML1 (c) and BK (d) for high (dashed line) and low (solid line) transpiration days. OC High $Q = 1.21DBH$ ($r^2 = 0.91$), OC Low $Q = 0.45DBH$ ($r^2 = 0.86$), UB High $Q = 1.13DBH$ ($r^2 = 0.76$), UB Low $Q = 0.38DBH$ ($r^2 = 0.84$), ML1 High $Q = 1.39DBH$ ($r^2 = 0.85$), ML1 Low $Q = 0.41DBH$ ($r^2 = 0.81$), BK High $Q = 0.50DBH$ ($r^2 = 0.78$), BK Low $Q = 0.19DBH^{1.15}$ ($r^2 = 0.72$)

Figure 5. Relationship between DBH of individual sample trees and sapwood area (SA) at OC (a), UB (b), ML1 (c) and BK (d), ML1 (c) and BK (d). OC SA = 10.83DBH - 27.0 ($r^2 = 0.77$), UB SA = 11.1DBH - 66.0 ($r^2 = 0.95$), ML1 SA = 9.53DBH - 57.7 ($r^2 = 0.96$), BK SA = 8.27DBH - 33.4 ($r^2 = 0.97$)

Figure 6. Relationship between DBH of individual sample trees and daily sapflow ($Q$) at OC (a), UB (b), ML1 (c) and BK (d) for high (dashed line) and low (solid line) transpiration days. OC High $Q = 1.21DBH$ ($r^2 = 0.91$), OC Low $Q = 0.45DBH$ ($r^2 = 0.86$), UB High $Q = 1.13DBH$ ($r^2 = 0.76$), UB Low $Q = 0.38DBH$ ($r^2 = 0.84$), ML1 High $Q = 1.39DBH$ ($r^2 = 0.85$), ML1 Low $Q = 0.41DBH$ ($r^2 = 0.81$), BK High $Q = 0.50DBH$ ($r^2 = 0.78$), BK Low $Q = 0.19DBH^{1.15}$ ($r^2 = 0.72$)
Although other studies of the hydrology of regenerating forest by Giambelluca (2002) and Kuczera (1987) report that evaporation from regenerating stands can be greater than that of mature forest, it should be noted that these studies refer to the regeneration of completely new forest stands where intense competition occurs across the entire stand; impacts of recolonization of cyclone or logging induced gaps is uncertain.

From this analysis it can be seen that the distribution of stem sizes is a more important determinant of stand transpiration than stand sapwood area. This is illustrated by comparing the annual transpiration of UB and ML1, which have similar climatic conditions and altitude. Despite having 50% more sapwood area than ML1 (Table III), average annual transpiration rates at UB (591 mm) are almost identical to those at ML1 (589 mm). Although UB has more sapwood area, most of this sapwood (55%) is found within trees <30 cm DBH, which are typically understory trees. Further evidence for the role that stem-size distributions play in controlling transpiration comes from comparing the LAI : sapwood-area ratio for each site (Table III). Both UB and BK have much lower ratios that the other two sites, indicating that they have less leaf area per unit sapwood. The cause of this observation is possibly related to the much higher stem densities (Table II) and larger representation of smaller trees (<20 cm DBH) at UB and BK (Figure 9). This suggests that smaller trees have less leaf area per unit sapwood area when compared with larger canopy trees. Direct evidence of such relationships is given by Vertessy et al. (1995) for temperate rainforests in Victoria, Australia.

Both OC and ML1 had measurements of transpiration during the dry El Niño conditions of late 2002, however, the impacts of these dry conditions are most pronounced at ML1. At this site transpiration during September–October 2002 was just 88 mm compared with 137 mm for the same period in 2003, similar observations at OC for the same period revealed differences

at each site and the results are shown in Figure 9. At OC about 40% of all stems fall in the 10–20 cm DBH class, this represents 19% of the total sapwood area but only 12% of total transpiration. At the other end of the scale trees in the >70 cm DBH class represent only 6% of the total number of stems on the plot but contribute 20% of the total plot transpiration. A similar case is shown for UB where 4% of all stems fall in the >70 cm DBH class, which is equivalent to 14% of plot sapwood area and 18% of plot transpiration. At ML1 trees in the >70 cm DBH class account for the greatest amount of transpiration (22%). The importance of these large trees to stand transpiration raises some issues as to the potential for removal of such trees through selective logging or cyclone damage to lead to short- to medium-term increases in catchment water yield.
in transpiration of just 4 mm. At ML1 $ET_0$ showed little variation for September–October 2002 (207 mm) and the same period during 2003 (201 mm), providing evidence that water availability was probably limiting transpiration at this site. Transpiration investigations by Kume et al. (2007) in the drier monsoonal climate of northern Thailand demonstrated that reduced stand transpiration during dry periods was largely due to drought stress in subcanopy trees. To see if similar effects were occurring at ML1, we compared the relative contributions of smaller subcanopy trees (DBH < 50 cm) to total water use at ML1 during the dry conditions of September–October 2002 with the same period during September–October 2003, and found no significant difference in contribution. This suggests that the drought stress affected all trees similarly and that the larger trees were not accessing deeper more permanent soil moisture stores.

Expressed as an annual transpiration equivalent, all sites except BK had very similar values (Table III). The annual transpiration rate at OC, UB and ML1 was 587 mm, 591 mm and 589 mm, respectively. These transpiration estimates are remarkably similar considering the variability in altitude, climate, species and stand characteristics at these sites. Annual transpiration values for these study sites are generally low when compared to the annual transpiration figures for tropical and warm temperate forests given in the review by Schellekens et al. (2000). In this review annual transpiration rates from coastal and lowland rainforests often exceed 1000 mm, almost double those found in this study, however, it should be noted that most of the transpiration rates compiled in this review are not direct measurements but estimates based on catchment water balance studies, which result in the inclusion of catchment leakage and measurement errors in other water balance terms.

It is possible that the low transpiration rates that we report in this study are underestimates due to measurement error, however, we believe that this is unlikely to explain the scale of the differences observed. Point estimates of sapflow measured with the heat pulse technique are susceptible to errors in probe alignment, wood and water fractions of the sapwood and corrections for wounding around probes. Hatton et al. (1995) and Olbrich et al. (1991) showed that sapflow measurement errors are dominated by errors in wound correction and probe alignment. In our field installations we rejected misaligned probes by testing alignment of drilled holes with blank probes, therefore, our largest potential source of error is likely to be related to wounding effects. The width of the wound that we used in our calculations is equivalent to the probe diameter (2-2 mm or 1-65 mm) plus 1 mm of tissue where flow is interrupted by probe installation (0.5 mm on either side). A review of the heat pulse literature found that the
The greatest wound width around probes was reported by Olbrich et al. (1991) (1-48 mm), although most studies report and use values within the range of 0-7 mm to 1-1 mm (e.g. Marshall, 1992; Cook et al., 1998; Eamus et al., 2000; Burgess et al., 2001) in addition to probe diameters. The wounding width that we used is therefore at the upper end of the range of values reported in the literature and reanalysis of our data suggests that doubling our wound size (to 2-0 mm plus probe diameter), would still only increase our annual transpiration estimates to ~850 mm. Although such wound widths seem unlikely given the values reported elsewhere, the size of wound widths in rainforest trees is unknown and direct comparison of heat pulse transpiration estimates against independently measured transpiration, for example, using cut tree experiments (e.g. Barrett et al., 1995; Vertessy et al., 1997) would be necessary to completely discount this potential source of error.

In contrast to studies elsewhere in the tropics, comparison of our results with transpiration rates from other rainforest water balance studies in Australia reveal much more similar results. For example, Gilmour (1975) undertook water balance estimates for coastal rainforest in the Wet Tropics of north Queensland and estimated annual transpiration of 420 mm (10% of precipitation) by subtracting measured interception from evapotranspiration derived from the difference between catchment precipitation and yield, while Hutley et al. (1997) working in the subtropical forest of south-east Queensland estimated total annual transpiration of 513 mm (39% of precipitation) based on heat pulse measurements made on one large tree subject to fog. Despite the potential errors in these Australian estimates similarity to annual transpiration estimates from this study suggests that Australian tropical rainforests transpire less than rainforests in some other parts of the world. Assuming that our measurement errors are minimal, the reasons for this could be related to forest structural differences (i.e. fewer large trees), climatic differences (i.e. different rainfall characteristics), very high wet canopy evaporation (22–29%, see McJanet et al., 2007b) or differences in tree physiology. Forest structural differences, particularly the possibility of Australian rainforest containing fewer larger trees, could be attributed to the frequent occurrence of cyclones on the Wet Tropics coast. Such cyclones often result in destruction of larger trees, which could, in turn, be preventing the formation of tall canopies with large-crowned trees. This could also explain the low LAI estimates for these sites. To illustrate this point, by simply doubling the number of trees larger than 70 cm DBH at OC (seven extra trees), ML1 (seven extra trees) and UB (five extra trees), average stand transpiration increases by 20%. This translates to an average annual transpiration of around 700 mm; somewhat closer to the values reported in Schellekens et al. (2000).

The site with by far the lowest annual transpiration rate of 253 mm was BK. This estimate is slightly higher than annual transpiration estimates of between 250 and 285 mm in a review of similar forest types compiled by Bruijnzeel (2005) but is very similar to recent reports of transpiration for cloud forest in Puerto Rico at 1010 m (~300 mm) (Holwerda, 2005) and Costa Rica at 1500 m (365 mm) (Bruijnzeel et al., 2006).

Transpiration and precipitation

Figure 10 shows a comparison of monthly transpiration and precipitation inputs for each site. On this figure arrows indicate months in which transpiration losses exceed precipitation. At OC this occurred during four months of the study period towards the end of the dry seasons (Sep–Nov). This was the time of the year when transpiration occurred at its highest rates due to dry canopy conditions and high solar radiation inputs. During the wet season months precipitation was far in excess of transpiration. At UB transpiration only exceeded precipitation during October 2003. At ML1 transpiration exceeded precipitation for three months during the study period. Interestingly, transpiration during September–October 2002 was only 65% of that for the same months during 2003, largely as a result of the much drier El Niño conditions during late 2002. Similar trends were not seen at other field sites. The extremely wet conditions at BK meant that precipitation was always far in excess of transpiration. In fact, transpiration at this site was only 5% of precipitation. At OC, UB and ML1 transpiration accounted for 24%, 20% and 19% of precipitation, respectively (Table III).

Environmental controls on transpiration

The relationship between total daily solar radiation and stand transpiration for each site is shown in Figure 11. All sites exhibited reasonably good correlations (r² > 0.61) between solar radiation and stand transpiration. At BK the slope of the regression is less than that at other sites, reflecting the smaller amount of transpiration from the forest at this site. At ML1 the data were initially found to exhibit a large degree of scatter, more in-depth analysis showed that much of this scatter was related to a period of strong El Niño conditions in the second half of 2002 and, once separated, data points formed two distinct groups (Figure 11c). This provides further evidence that water supply may have been restricting transpiration during the 2002 period. Splitting the data from OC (the other site with measurements during 2002) into the same groupings revealed no distinct differences. The reason for this is believed to be the close proximity (<50 m) to Oliver Creek (which flows year round), the gently sloping land (4%) and the shallow nature of the local groundwater table. A groundwater observation well was installed at OC in early 2003, but it was only possible to auger to a depth of 2-0 m due to the rocky nature of these mudstone-derived soils. Observations in the well during 2003 showed that for much of the year water remained within 2-0 m of the surface, occasionally rising to as close to 0-4 m below the surface for short periods in the height of the wet season and falling below the bottom of the well for only a couple of months later in the dry season.
Transpiration (mm) and Precipitation (mm)

(a) Oliver Creek
(b) Upper Barron
(c) Mount Lewis1
(d) Bellenden Ker

Figure 10. Monthly stand transpiration and precipitation totals for (a) OC, (b) UB, (c) ML1 and (d) BK. Arrows indicate months where transpiration losses exceed precipitation inputs. Precipitation is the combination of corrected rainfall and cloud interception. Wet season shaded in grey.

Daily stand transpiration (mm)

(a) Oliver Creek
(b) Upper Barron
(c) Mount Lewis1
(d) Bellenden Ker

Figure 11. Relationship between total daily solar radiation ($R_s$) and plot transpiration ($T$) at (a) OC, (b) UB, (c) ML1 and (d) BK. The ML1 site shows two data sets; one for 2002 (open circles and dashed regression line) illustrating impacts of El Niño conditions, and one for the remainder of the study duration (black circles). OC ($r^2 = 0.61$), UB ($r^2 = 0.74$), ML1 (El Niño) ($r^2 = 0.84$), ML1 ($r^2 = 0.84$), BK ($r^2 = 0.74$).

Total daily transpiration had a plateau-shaped relationship with canopy vapour pressure deficit (VPD), at all sites (Figure 12). Transpiration rate increased sharply with VPD at low levels (VPD < 0.5 KPa), but then tended to level off at higher canopy VPD levels. Similar relationships between transpiration rates and VPD have been observed for rainforest trees in studies by Granier et al. (1996), and Meinzer et al. (1993). These authors conclude that levelling off of transpiration at higher VPD levels is a result of stomatal closure. Being closely tied to solar radiation, VPD explains 70% of the variation in transpiration at OC, 71% at UB, 56% at ML1 and 57% at BK. Data points for the 2002 El Niño at ML1 are plotted separately on Figure 12c, and clearly show that transpiration was limited by soil moisture during this time. As with the comparison with solar radiation OC transpiration showed no obvious effects of El Niño conditions, with the comparison with solar radiation OC transpiration was limited by soil moisture during this time. As a further measure of the control that environmental factors have over transpiration, the canopy decoupling coefficient (Ωc) of Jarvis and McNaughton (1986) was calculated at each site. This factor describes the strength of the coupling between the forest canopy and the atmosphere. The decoupling coefficient varies between 0 (perfect coupling) and 1 (complete isolation). Daily average Ωc was calculated using the methodology outlined in Granier et al. (1996). Average Ωc over the duration of the study period was 0.19, 0.14, 0.22 and 0.30 at OC, UB, ML1 and BK, respectively. This indicates a higher degree of canopy coupling to the atmosphere. Granier et al. (1996) report similar values with a Ωc of 0.2 for 19 bright days in rainforest in French Guiana and Roberts et al. (1990) reported 0.28 for canopy trees in Brazil. Vourlitis et al. (2002) report Ωc of 0.1–0.3 for transitional tropical forest in Brazil. Much higher values of Ωc have been reported for other studies of tropical trees (see Wullschleger et al., 1998), however, it would appear that transpiration of tropical forests is generally well coupled with atmospheric conditions.

Transpiration and potential evaporation

Comparison of ET₀ and actual transpiration for each site is shown in Figure 13. At OC transpiration rises rapidly with ET₀ at low levels and then flattens off at higher levels once again, suggesting that stomatal closure is occurring under conditions of high evaporative demand. A similar type of relationship may be occurring at BK. This type of relationship between ET₀ and transpiration has also been noted by Granier et al. (1992, 1996), who conclude that the cause is high VPD reducing stomatal conductance. At UB and ML1 the relationships are slightly more linear, except at very low ET₀.

Over the entire study period actual transpiration at OC was only 51% of ET₀ (wet season –48%, dry season –53%) and at UB transpiration was 54% of ET₀ (wet season –29%, dry season –38%).
season –57%, dry season –50%). At ML1 data were split into the 2002 El Niño period and the remainder of the study period. During the El Niño conditions transpiration was 45% of $ET_0$, however, this value increased to 68% for the remainder of the study period. At BK transpiration accounted for 44% of $ET_0$ with no variations between the wet and dry seasons. Investigations by Granier et al. (1992) found low ratios of stand transpiration to $ET_0$ for rainforest trees in a plantation in French Guyana. Their measurements showed that for bright days transpiration accounted for 50% of $ET_0$. In contrast to these findings transpiration of Brazilian rainforest is reported as 70% of $ET_0$ on bright days (Shuttleworth et al., 1984) and transpiration of natural rainforest in French Guyana is reported as 75% of $ET_0$ (Granier et al., 1996). It is not clear why actual transpiration is such a low fraction of potential evaporation, especially when soil moisture supply is generally not limiting.

**CONCLUSIONS**

Measurements of sapflow in the rainforest of north Queensland, Australia, revealed strong relationships between tree size and daily transpiration despite the diversity of species and complex canopy architecture of the rainforest systems studied. The strength of these relationships provided a robust way by which to scale heat pulse measurements of sapflow in sample trees to stand transpiration. Thus, transpiration of rainforest trees was found to be more a function of canopy position that the species.

Transpiration was shown to be strongly coupled to energy inputs and the atmospheric demand for moisture. Over the duration of measurements, ML1 was the only field site that showed any evidence of transpiration being limited by soil moisture. The cause of this soil moisture deficit was an extended period with very little rain during strong El Niño conditions of 2002. Soil moisture supplies did not appear to influence transpiration at other sites where soil profiles were deeper and access to groundwater was available.

Whereas the rate of transpiration was found to be closely tied to local climatic conditions, total stand transpiration was controlled by local forest characteristics such as stem density, tree size distribution and sapwood area. Large trees (>70 cm DBH), although small in number, contributed a large proportion (~20%) of forest transpiration at all sites except the stunted cloud forest at BK. Hence, removal of such trees through selective logging or cyclone damage could have a significant impact on forest transpiration and water yield in the region on a short to medium timescale as canopy gaps are recolonized.

Particularly low rates of annual transpiration (353 mm) were measured at BK where a combination of persistent wet conditions and low solar radiation inputs restricted transpiration to 5% of precipitation input. Transpiration of all rainforest sites studied was far less than potential evaporation despite sufficient energy inputs and soil moisture availability. In comparison to the international literature, transpiration rates of Australian rainforests reported in this study and studies of Hutley et al. (1997)
and Gilmour (1975) are relatively low. The reasons for this are unclear, but could be related to a combination of differences in forest structure (i.e. fewer large trees), climatic conditions, very high wet canopy evaporation and the physiological functioning of trees. A possible explanation could be that tropical rainforests in the otherwise dry continent of Australia have evolved to survive through periods of desiccation which favour the survival of trees that transpire at more moderate rates.

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