The energy and water balance of a *Eucalyptus* plantation in southeast Brazil

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SUMMARY

The eddy covariance method was used to measure energy and water balance of a plantation of *Eucalyptus* (*grandis × urophylla*) hybrids over a 2 year period. The average daily evaporation rates were 5.4 (±2.0) mm day^{-1} in summer, but fell to 1.2 (±0.3) mm day^{-1} in winter. In contrast, the sensible heat flux was relatively low in summer but dominated the energy balance in winter. Evaporation accounted for 80% and 26% of the available energy, in summer and winter respectively. The annual evaporation was 82% (1124 mm) and 96% (1235 mm) of the annual rainfall recorded during the first and second year, respectively. Daily average canopy and aerodynamic conductance to water vapour were in the summer 51.9 (±38.4) mm s^{-1} and 84.1 (±25.6) mm s^{-1}, respectively; and in the winter 6.0 (±10.5) mm s^{-1} and 111.6 (±24.6) mm s^{-1}, respectively.

1. Introduction

Evaporation (the sum of the vegetation transpiration and intercepted rainfall) is one of the key processes through which vegetation influences the hydrological cycle and is a critical component of the water balance (Wilson et al., 2001; Kosugi and Katsuyama, 2007; Guyot et al., 2009). Evaporation can be derived from catchment data, but only at an annual time resolution and additional difficulties result from the inherent lags amongst the components of the system (Savenije, 1997). A soil water balance allows evaporation to be estimated at a daily time scale, but the technique is critically dependent on obtaining a representative spatial sample, and requires determination of the active rooting depth, drainage and capillary rise, leading to large uncertainties in the estimated fluxes (Wilson et al., 2001). In contrast, with a measurement footprint of several hectares upwind, the eddy covariance technique gives a direct measurement; integrating whole stand fluxes (Aubinet et al., 2000; Baldocchi et al., 2001; Kirschbaum et al., 2007).

Eddy covariance is now a viable technique for measuring evaporation at a hydrological time scale. It can operate continuously in remote locations for periods of a year or more, but measures fluxes at an hourly time scale. Eddy covariance data thus provides not only the overall water balance, but also insight into the processes controlling the coupled cycles of water and energy in ecosystems across seasons and under varying weather conditions (Leuning et al., 2005).

The area of *Eucalyptus* plantation in Brazil was 3.5 M ha in 2006, with 60% established in the southeast of the country. The main use (79%) is by the pulpwood industry, but 16% is used as fuel in pig-iron and steel manufacture (ABRAF, 2007), this bioenergy fuel demand is expected to increase in the next decades (FAO, 2008). The mean productivity has increased by approximately 37% in the past 10 years, and further increases in the above-ground net primary production associated with increases in rainfall have been observed by Stape et al. (2004). As high rates of productivity are often related with high rates of water use, there are concerns that eucalyptus production will adversely affect water resources, reducing yield from water-supply catchments (Whitehead and Beadle, 2004; Engel et al., 2005).

In this study we applied the eddy covariance technique to measure the water and energy fluxes of a *Eucalyptus* plantation. The objective was to establish the seasonal and inter-annual controls

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on eucalypt plantation water use in response to the fluctuations in the climatic variables (net all wave radiation and air humidity) as well the soil moisture storage conditions and surface bulk parameters, canopy conductance and decoupling factor, needed for modelling water use in the future. Two years of field data were collected.

2. Methods

2.1. Site

The *Eucalyptus* plantation (clonal *Eucalyptus grandis* × *Eucalyptus urophylla*) was located in São Paulo State, Brazil (21°35′S, 47°36′W, at an altitude 761 m). There was an eastward slope (3.5%) which was the predominant wind direction and whose fetch of approximately 1 km contained plants of the same hybrid and age. The fetch in the other directions was 2 km although the continuous vegetation had distinct ages. The average planting density was 1370 living trees per hectare (3 m × 2.4 m spacing). The period of measurements reported here begun in March 2006 (DoY 69) when the trees were 2 years old, and continued to March of 2008. The average canopy top height changed from 12 m at the start to 21 m at the end of the measurement period. The diameter at breast height (DBH) changed from 0.11 to 0.14 m over the same period. The maximum leaf area index (LAI) was achieved in the summer (3.4 $m^2 m^{-2}$) and was the same in both years. However the minimum LAI observed in the winter of 2006 (2.2 $m^2 m^{-2}$) was lower than that in 2007 (2.5 $m^2 m^{-2}$). These estimates were derived from hemispherical photographs (Schleppi et al., 2007).

The soil was a quartz sand (Typic Quartzipsamment), whose clay content was lower than 12% in all the profile (3.5 m depth), and the average global density and standard deviation was 1456 ± 97 $kg m^{-3}$. The available soil water (50 mm m^{-1} depth) is defined as the soil water content between the matric potentials of −33.4 and −1520 kPa.

The site long-term (30 year) mean annual precipitation (R) and standard deviation is 1498 ± 312 mm with the minimum occurring during the winter (June, 32 mm) and the maximum in the summer (January, 266 mm). The mean annual potential evaporation (EP) is 1049 mm and the cumulative R–EP between April and September is −196 mm. The average of the mean annual daily air temperatures is 22.1 ± 0.5 °C, varying between 19 and 24 °C.

2.2. Instrumentation

Turbulent fluxes were measured using an open-path infrared gas analyzer (IRGA, LI7500 LICOR) and a tri-dimensional sonic anemometer (CSAT3, Campbell SI), mounted on a vertical mast (3 m length) above the top of a triangular lattice tower (1 m cross-section), whose height was 24 m. The operation of both instruments and the recording of raw data at 20 Hz on a flash card were controlled by a datalogger (CR5000 or CR1000, Campbell SI).

The power was generated by 12 photovoltaic panels (80 W, Kyocera) mounted on top of a separate 30 m squared lattice tower (1 m cross-section), 100 m away from the eddy covariance tower, and six deep-discharge batteries (240 Ah each).

Radiation sensors were installed at 28 m height on a horizontal pole 3 m away from the power tower. They included: net all wave (R_n) radiation (NR LITE, Kipp and Zonen), the incident and reflected components of shortwave (CM3, Kipp and Zonen) and photosynthetic active radiation (PAR LITE, Kipp and Zonen). The air temperature and relative humidity above the canopy (28 m) were measured by an HMP45c probe (Vaisala) in a ventilated radiation shield, and the rainfall by a rain gauge installed at 30 m.

The soil heat flux (G) was measured by four heat flux plates (REBS) and two soil temperature thermocouples, all buried at 25 mm depth; a Sentek (Sentek Pty Ltd., Australia) probe was utilized to measure the soil moisture profile in the first metre. All sensor signals were sampled at 10 s interval with 10 min averages or totals being recorded by a CR10X datalogger and multiplexer (Campbell SI).

2.3. Data processing

Turbulent fluxes of water vapour (LE, where L is the latent heat of vaporisation and E is the mass flux of evaporation) and sensible heat (H) were obtained from the covariance of fluctuations calculated by subtracting the signals from the 30 min block averages (see Borma et al., 2009). The coordinate rotations forcing the mean vertical wind speed, w, to be zero (Kaimal and Finnigan, 1994) and the Webb et al. (1980) corrections were applied.

The average daytime cospectra of w and water vapour concentration exhibited a small attenuation above 1 Hz (data not shown), as the fall-off deviates from the −4/3 law (Kaimal and Finnigan, 1994). However, the energy in the integrated cospectra of w and sonic temperature above 1 Hz was less than 1% of the total; therefore frequency loss corrections (Moore, 1986) were not applied.

The canopy conductance (g_c) to water vapour fluxes was calculated from the inverted Penman–Monteith equation (Monteith, 1965, also reproduced by Gash and Shuttleworth, 2007, see Shuttleworth et al., 1984; Rocha et al., 2004). The aerodynamic conductance (g_a) was calculated from the friction velocity and windspeed, following Gash et al. (1999). The degree of coupling between the canopy and the boundary layer was given by the omega (Ω) factor (McNaughton and Jarvis, 1983).

The components of the heat fluxes into storage (S) due to the changes in the sensible and latent heat in the canopy air were obtained from the time variation of air temperature and humidity above the canopy (Aston, 1985; Moore and Fisch, 1986; Michiles and Gielow, 2008). The changes in storage were determined from the vertical profiles of air temperature and humidity beneath the eddy covariance measurement height.

The changes in energy stored in the biomass were derived from the bark temperatures measured at different heights in a representative tree (Silberstein et al., 2001) and the specific heat of moist biomass (Moore and Fisch, 1986; Michiles and Gielow, 2008). The volumes and density of stems as functions of DBH, height and age were estimated by allometric equations (Stape et al., 2006; Ferreira, 2007) as well the biomass and moisture of branches and leaves which were measured at the site.

The amount of missing half hour LE fluxes was 21% which is a similar figure to that reported for other sites (Falge et al., 2001), and occurred mostly during rainfall due to wetting of the IRGA window. During those periods because the sensible heat fluxes (H) were available LE could be estimated as the residual (Amiro, 2009) from the energy balance equation ($LE = R_n − G − S − H$), where the energy used in photosynthesis and stored in the litter layer was neglected. The validity of this approach is addressed in the results section. When sensible heat flux was also missing, it was obtained from the relationship of H versus R_n, adjusted over 5 days preceding and 5 days after the faulty period.

3. Results and discussion

3.1. The flux footprint and energy balance closure

Flux footprint estimates were made using the method of Hsieh et al. (2000). During April–May 2006, when the observations begun, the footprints ranged from 1000 to 2000 m for unstable conditions, although the distance from measuring point to the maximum contributing source area (X_p) was less than 150 m. At

the end of the observational period (January–February 2008) the average footprint and X_p were 500 m and 26 m, respectively. This occurred because the measurement height above the zero-plane displacement decreased as the forest grew. The smaller fetch in this case should decrease the measurement error as the source area approaches the net radiometer limited field of view (see Lloyd et al., 1997) assuming there was no attenuation of fluxes due to the proximity of the surface. Thus adequate fetch conditions have been attained because the *Eucalyptus* surface extended across approximately 2 km in all tower directions.

The relationship between the available energy ($A_v = R_n - G - S$) and the sum ($H + LE$) is commonly used as an indicator of the accuracy of the measured fluxes H and LE (Wilson et al., 2001; Culf et al., 2004; Leuning et al., 2005; Foken, 2008). The closure of the original (not gap-filled) half-hourly fluxes is shown in Fig. 1; the slope (1.025) of the linear regression forced through the origin did not differ significantly from unity and produced a high R^2 (0.96).

The good quality of measured fluxes indicated by the energy balance closure supports the gap filling procedure outlined in the methods section, i.e. estimating LE as the residual in the energy balance equation. However this procedure still requires that the sonic anemometer performs under wet conditions (Gash et al., 1999). To test this Fig. 2 shows a plot of the standard deviation of vertical wind velocity (σ_w) versus the friction velocity (u_*) for rainy periods. For near-neutral conditions, Monin–Obukhov similarity theory predicts a straight line, the slope of which is a universal constant. The fitted slope of the linear regression (1.24) is very close to the typical value observed in neutral conditions (1.25) (see Garratt, 1992), indicating that the Campbell sonic anemometer was not adversely affected by the rain: either by water on the transducers or raindrops in the sonic path. Gash et al. (1999) and van der Tol et al. (2003) found a similar result for the Solent sonic anemometer.

3.2. Rainfall, H, LE and soil moisture

Flux measurement started in March of 2006: the first 12 months total of precipitation totalled 1377 mm, the second 12 months was 1280 mm. These totals accounted for 92% and 85% of the long-term average respectively. Notwithstanding the
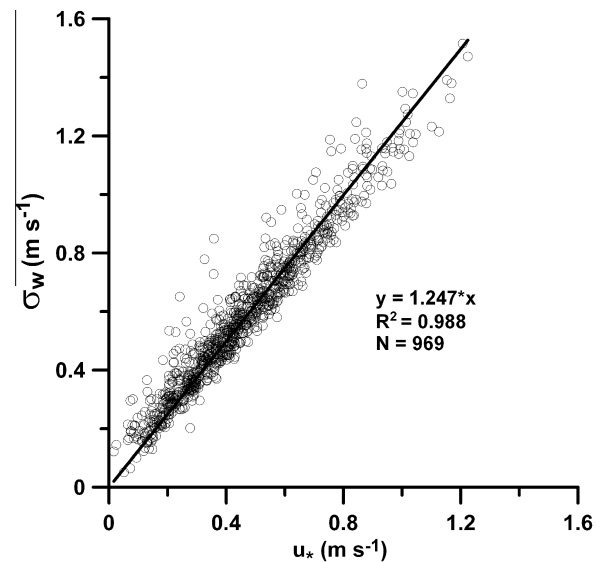

Fig. 2. Standard deviation of the vertical wind speed σ_w (m s^{-1}) versus friction velocity u_* (m s^{-1}) for half hourly periods when rainfall was greater than 0.5 mm.

small difference between years, 2006 showed a longer period with less rain from April to September (Day of Year 90–270) when 69 mm were recorded (Fig. 3a). During the same period in 2007 (DoY 90–287) the total rainfall was 244 mm, as the consequence of two cold fronts which produced substantial amounts of precipitation in May (DoY 142, $R = 93$ mm) and July (DoY 198, $R = 104$ mm).

The time series of daylight totals of LE and A_v presented in Fig. 3b also show indirectly the H fluxes as the area between the A_v and LE lines. Summer daily totals of LE above 5 mm day^{-1} and the water equivalent of H as low as 0.8 mm day^{-1} ($\sim$2 MJ m^{-2} day^{-1}) were common, indicating that more than 80% of the available energy was utilized in evaporation. In the winter the opposite was observed with the water equivalent H fluxes being higher than 4 mm day^{-1} ($\sim$10 MJ m^{-2} day^{-1}) and LE as low as 0.8 mm day^{-1}, under these conditions 74% of the available energy was directed to the sensible heat flux.

The LE fluxes and the soil moisture store were tightly coupled. The lowest values of LE and mean daily soil moisture store in the top 1 m layer (Fig. 3a) were observed during the winter in September of 2006 as the consequence of the almost continuous 3 months without rainfall. An evaporative fraction, given by the ratio LE/A_v, of approximately 0.85 was recorded as long as the soil moisture content was above 100 mm, even during the winter as in 2007 when there was sufficient rainfall, interrupting temporarily the progressive soil drying. Based on the available soil moisture for this sandy soil of 100 mm for a 2 m layer depth, the difference between the soil moisture store in March ($\sim$100 mm) and September (50 mm) of 2006 indicated the utilization of the all available moisture content down to 1 m depth.

The rates of evaporation (Fig. 3b) contain the fraction of intercepted rainfall which was not measured separately. The interception loss (I) was estimated applying the Gash model (Gash et al., 1995). The eucalypt parameters from Valente et al. (1997) were used: the observed mean rainfall intensity (2 mm h^{-1}) was similar, and the canopy cover was changed proportionally to the greater stem density (1010 versus 1370 stems ha^{-1}), based on the results of Laclau et al. (2005) who obtained the average of 8% of the rainfall in a sparse stand (530 trees ha^{-1}). The monthly totals of modelled interception are shown in Fig. 4 where the maximum (48 mm) occurred in January 2007. The yearly totals accounted
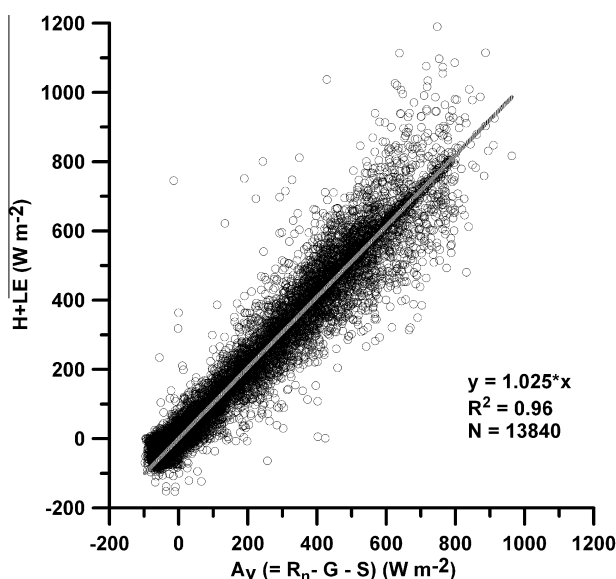

Fig. 1. Relationship between ($H + LE$) and available energy ($A_v = R_n - G - S$) data observed in 2007 (not gap-filled).
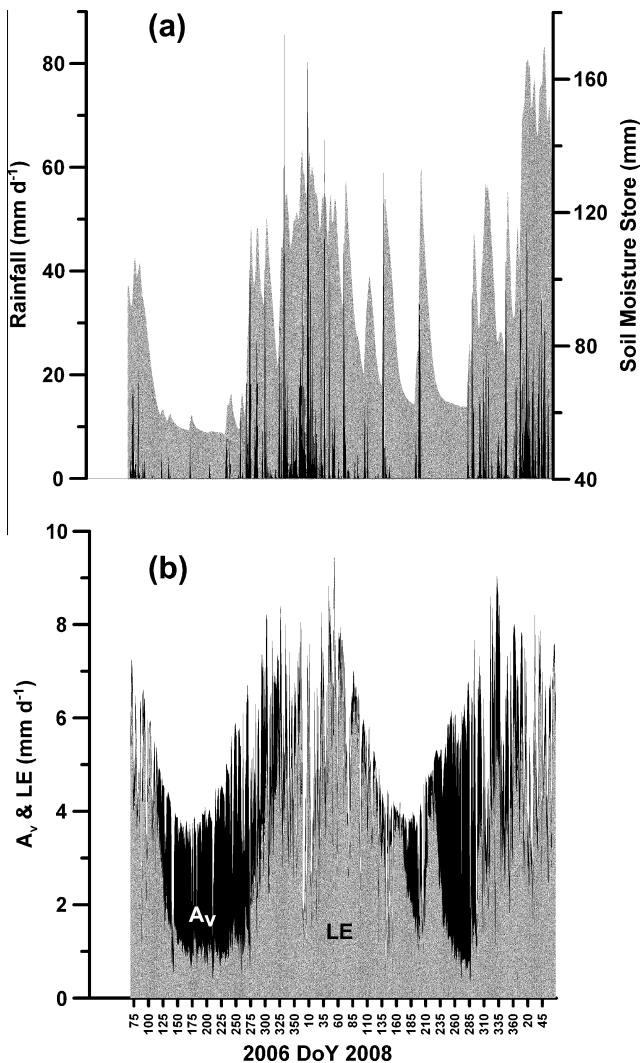
Fig. 3. (a) Daily water storage (grey area) in the top first metre of soil and rainfall (bars), (b) water equivalent (mm day^{-1}) of daylight totals of evaporation (*LE*) and available energy (*A$_v$*). The DoY is the day of year.

Fig. 4. Monthly totals (mm) of rainfall (*R*, circles), evaporation (*E*, diamonds), the evaporative equivalent of available energy (*A$_v$*, squares) and modelled interception loss (*I*, triangles).

for 12% of the rainfall in both years close to the average interception obtained by Almeida et al. (2007) and Valente et al. (1997) of 11% although Lane et al. (2004) found interception fractions between 18% and 24% and all them approximately within the range of 10–34% of annual rainfall reviewed by Whitehead and Beadle (2004).

The annual *E* accounted for 82% (1124 mm) and 96% (1235 mm) of the annual precipitation (*R*) for the first and second year, respectively, close to the 6 year mean ratio (*E/R*) of 95% obtained by Almeida et al. (2007) for eucalypts growing in similar climate. However the ratios *E/R* for the winter months (Fig. 4) were well above unity, indicating that water had been extracted from the soil in order to maintain the rates of transpiration (Almeida et al., 2007; Whitehead and Beadle, 2004). The evaporation in stands of eucalypts under a Mediterranean climate in Portugal (Pereira et al., 2007) was equal to rainfall in years of normal precipitation (~700 mm year^{-1}), but found to be 44% above annual precipitation in a dry year.

The cumulative difference between rainfall and evaporation (*R*–*E*) from March to September in 2006 was −270 mm (Fig. 4); this is the equivalent of all the available soil water down to approximately 5 m soil depth, based on the soil available moisture. The amount of rainfall recorded during the last 3 months of 2006
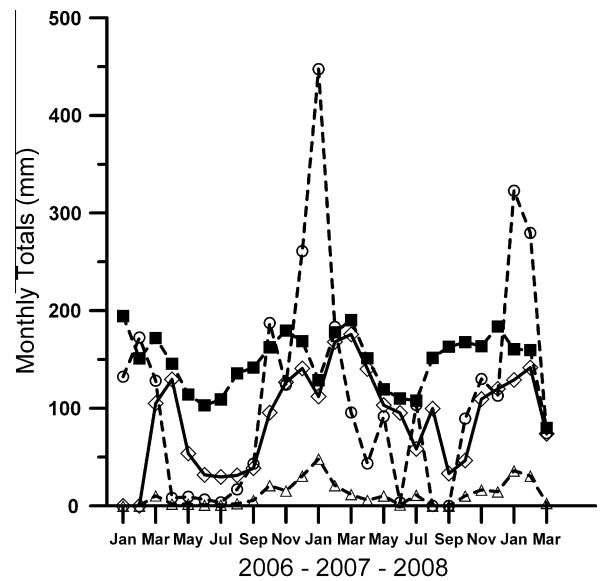
(OND = 573 mm) and beginning of 2007 (JFM = 727 mm) was enough to nearly recharge the soil moisture profile, because the first year cumulative *R*–*E* was 253 mm. The absolute value of the cumulative *R*–*E* between March and October of 2007 was much lower (−67 mm) than 2006 due to the cold-front rainfall recorded in 2007 (Fig. 3a), and explains why the highest soil moisture store (170 mm) was achieved in the summer of 2008 (Fig. 3a) although the amount of rainfall was lower than 2007.

The evaporative fraction, *LE/A$_v$*, was 0.85 during the summer months (JFM) of both years as well in the autumn of 2007 (AMJ), but the yearly minimum *LE* showed a decrease of 80% (Fig. 4). The minimum *A$_v$* was approximately 55% of the maximum, implying that the observed seasonal reduction in the evaporation rates was also a consequence of the LAI fall from 3.4 to 2.2 (35%) as well the lower soil moisture (Roberts and Rosier, 1993).

The estimated annual transpiration calculated as the difference between E and the rainfall interception, and not considering the soil evaporation, was 959 mm for the first year and 1081 mm for the second year. For comparison with studies such as Shuttleworth and Calder (1979) and Shuttleworth et al. (1984), the average Priestley–Taylor parameter, α (Priestley and Taylor, 1972), for the transpiration was 0.67, where α is calculated as the ratio of transpiration to the equilibrium evaporation. Although the rainfall was 7% lower in the second year (1280 versus 1377 mm), the transpiration increased 13% because of the winter rainfall episodes observed in 2007, which demonstrated the resilience of the vegetation through the water use increment, as observed in a natural Eucalyptus forest in Australia (Zeppel et al., 2008).

The average annual water balance for the 2 years of measurement is summarised in Table 1. Gash and Stewart (1977), McNaughton and Jarvis (1983) and Shuttleworth (1988) report that interception loss from forests may vary from 25% to 75% of overall evaporation, depending on climate and forest type. Our values of interception loss (*I* = 13% of *E*) are below the lower limit of this interval. Therefore, the evaporation from our Eucalyptus stand is strongly dominated by transpiration (87% of *E*).

Increases in eucalypt growth across a geographic gradient (in northeast Brazil) associated with increases in rainfall were reported by Stape et al. (2008), although other coexisting effects were also present such as soil fertility and air humidity. The results

Table 1
Summary of the average annual water balance over the 2 years of measurement.

	Equivalent water depth (mm year^{-1})	Percentage of rainfall (%)
Rainfall	1329	100
Measured evaporation	1179	88
Estimated interception	159	12
Transpiration (as residual)	1020	77

of da Rocha et al. (2009) about the controls on *E* seasonality of native vegetation along with a biome gradient in Brazil (from southeast to north) indicated that the net radiation (R_n) forcing was more important in the wetter forests (precipitation above 1900 mm and yearly average *E* of 4 mm day^{-1}) while soil moisture was the limiting factor in the drier savannah sites (precipitation lower than 1700 mm and yearly average *E* of 2.5 mm day^{-1}).

The sustainability of biomass production where exotic species have been adapted to the seasonality of high rainfall, as with the Eucalyptus in Brazil, requires managing a crucial trade-off between growth and recharge control in order to achieve a more efficient use of resources (White et al., 2003).

3.3. Seasonal changes in g_c, g_a and Ω

Fig. 5a shows the daily means of canopy conductance (g_c), whose averages and standard deviations for summer and winter were 51.9 ± 38.4 mm s^{-1} and 6.0 ± 10.5 mm s^{-1}, respectively. The seasonal variation in g_c followed the patterns of available energy and soil moisture (Fig. 3) as well the LAI variation which did not fully account for the decline in g_c suggesting that stomatal closure also occurred in winter in response to higher humidity saturation deficits *D* (Fig. 5b). The eucalypts generally tend to respond to soil water deficits through a reduction in conductance, however, this response is not straightforward as *D* and soil water deficit are often positively correlated seasonally (Whitehead and Beadle, 2004; Mitchell et al., 2009).
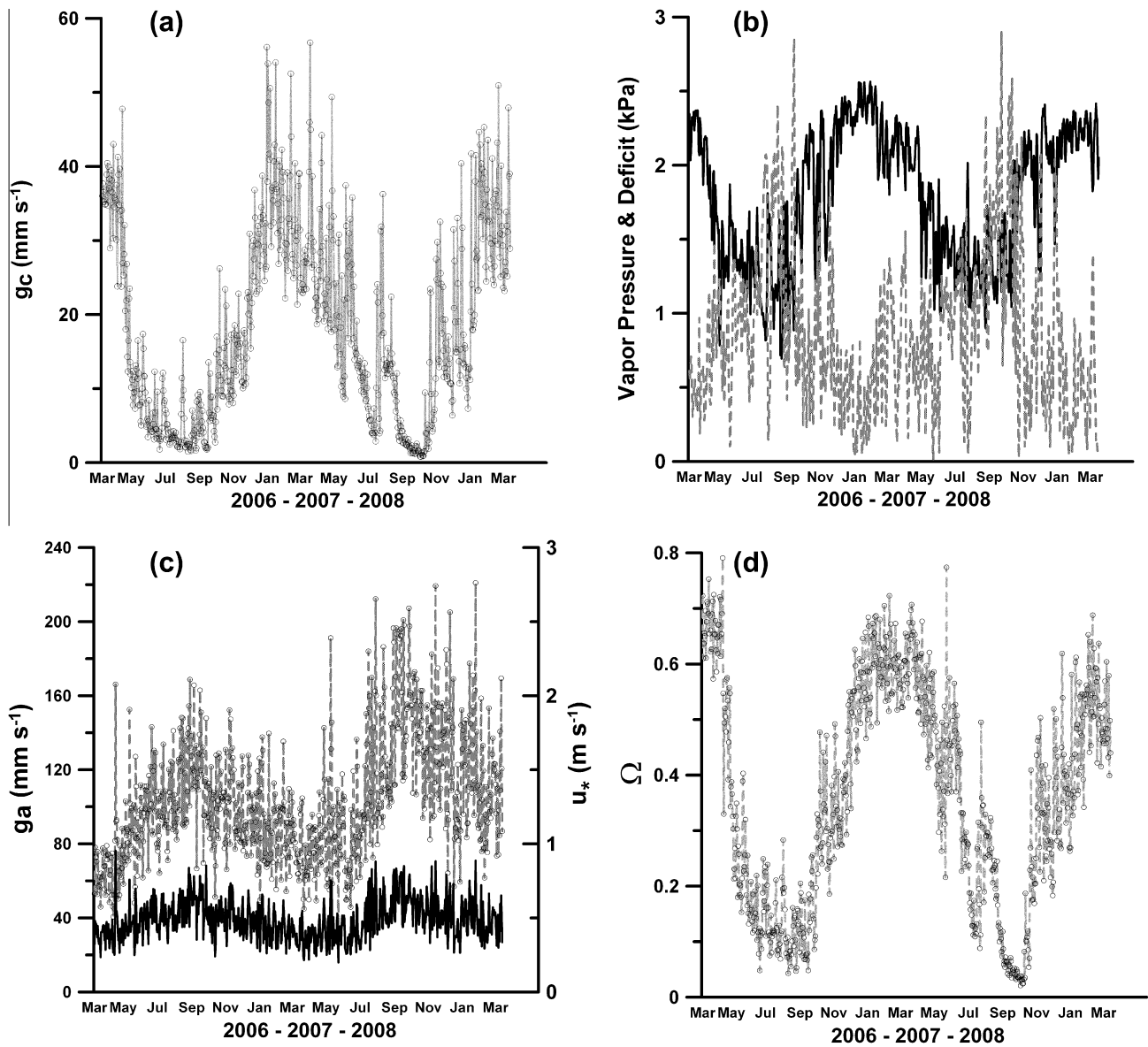

Fig. 5. Daily averages of: (a) canopy conductance (g_c); (b) air vapour pressure (thick line) and saturation deficit (dashed line); (c) aerodynamic conductance g_a (line and circles) and friction velocity (u_*); (d) decoupling coefficient (Ω).

The data of Mielke et al. (1999, 2000) from an older Eucalyptus hybrid plantation (9 years old, 32 m high and LAI = 2.3) exhibited a mean canopy stomatal conductance range from 17.3 to 5.8 mm s^{-1}, following the decrease in soil moisture. O'Grady et al. (2008) observed in young Eucalyptus plots (2.5 years, 7 m high and LAI = 3) a reduction in the maximum canopy conductance values from 5 to 1 mm s^{-1}, as the dry season progressed. David et al. (1997) reported for a eucalypt stand (8 years old, 18 m high and LAI = 3.2) in Portugal a decrease in daily maximum stomatal conductance from 15 to 4.5 mm s^{-1} as well as smaller diurnal variation, as the environmental conditions became warmer and drier. However, as the LAI is not constant these variations can produce the opposite effect to that which might be expected, for example higher leaf area results in increased shading of foliage in the lower canopy, therefore reducing the average canopy stomatal conductance per unit leaf area (Hubbard et al., 2004). All these previous data have been obtained with plant physiological methods which have inherent limitations in spatial and temporal coverage. Our data can be used to obtain g_c averages calculated over different time lengths and periods of the year as for example: 17.5 ± 13.9 mm s^{-1} in Apri–June and 5.5 ± 4.1 mm s^{-1} in September of 2006; 68.4 ± 35.1 mm s^{-1} in January and 2.3 ± 0.8 mm s^{-1} in September 2007. These results show the great advantage of the eddy covariance approach, demonstrating its capability to provide nearly continuous data records as can be seen in Fig. 5a, expanding the plant physiological level measurements both in time and space. Nevertheless, plant physiology is still a valuable tool where these results could not be achieved through the micrometeorological methods (Roberts, 2007).

The daily mean aerodynamic conductance (g_a) shown in Fig. 5c, exhibited an annual cycle whose peaks occurred in September following the decrease in LAI and the wind speed seasonality, represented by friction velocity (u_*), more intense during the winter. The overall mean g_a was 112 ± 24 mm s^{-1} and there was a difference between years, from 105 ± 25 mm s^{-1} in 2006 to 132 ± 38 mm s^{-1} in 2007, due to the forest growth and the path length reduction between the canopy top and the sonic anemometer, not a consequence of changes in the aerodynamic characteristics of the canopy. Roberts and Rosier (1993) obtained similar results 73–229 mm s^{-1} considering the LAI of 2.2 and windspeeds between 1.5 and 3.0 m s^{-1}, and Mielke et al. (1999) estimated the mean g_a as 192 mm s^{-1}. Whitehead and Beadle (2004) noticed the scarcity of boundary layer conductance data for Eucalyptus species in contrast with the number of g_c measurements in the literature.

The time series of the mean daily decoupling coefficients (Ω) are shown in Fig. 5d. The average and standard deviation in the summer and winter were 0.6 ± 0.08 and 0.13 ± 0.07, respectively. According to Jarvis (1985), intermediate Ω values as those obtained in the summer (0.6) imply that the evaporation was driven by R_n, saturation deficit and to some extent to the canopy conductance, whereas in winter it was largely controlled by plant physiological regulation and saturation deficit.

Results for the cool boreal forests in Japan (Matsumoto et al., 2008) exhibited g_c values one order lower than g_a leading to the conclusion that the evaporation rate was largely controlled by plant physiological regulation and surface water conditions, rather than by the regulation of wind speed and surface roughness conditions. In the aspen forest work of Blanken and Black (2004) they choose Ω = 0.5 as the limit to define forests as rough surfaces with a large g_a tending to be well coupled (Ω < 0.5) to the air within the convective boundary layer, whilst smooth surfaces with a small g_a are poorly coupled (Ω > 0.5), their Ω values were not constant throughout the year similarly to the results obtained here for the eucalypts under distinctly different conditions.

Generally the Eucalyptus forests have been defined as strongly coupled to the atmosphere, i.e. have low decoupling coefficients Ω (Mielke et al., 1999; Whitehead and Beadle, 2004; O'Grady et al., 2008). The seasonal variations in Ω obtained here indicate the relative importance of both g_c and g_a contradicting to some extent previous findings for Eucalyptus forests as noticed by White et al. (2000). However, despite the large temporal variations observed in LE on annual basis the mean evaporative fraction was 0.66.

3.4. Mean daily cycles of g_c

The average daily cycle of canopy conductance (g_c) in the summer is shown in Fig. 6a. g_c exhibited a morning peak as the saturation deficits (D) were lower than 0.5 kPa and declined afterwards. However, the LE fluxes closely followed the available energy (A_v) throughout the day and D was lower than 1.5 kPa.
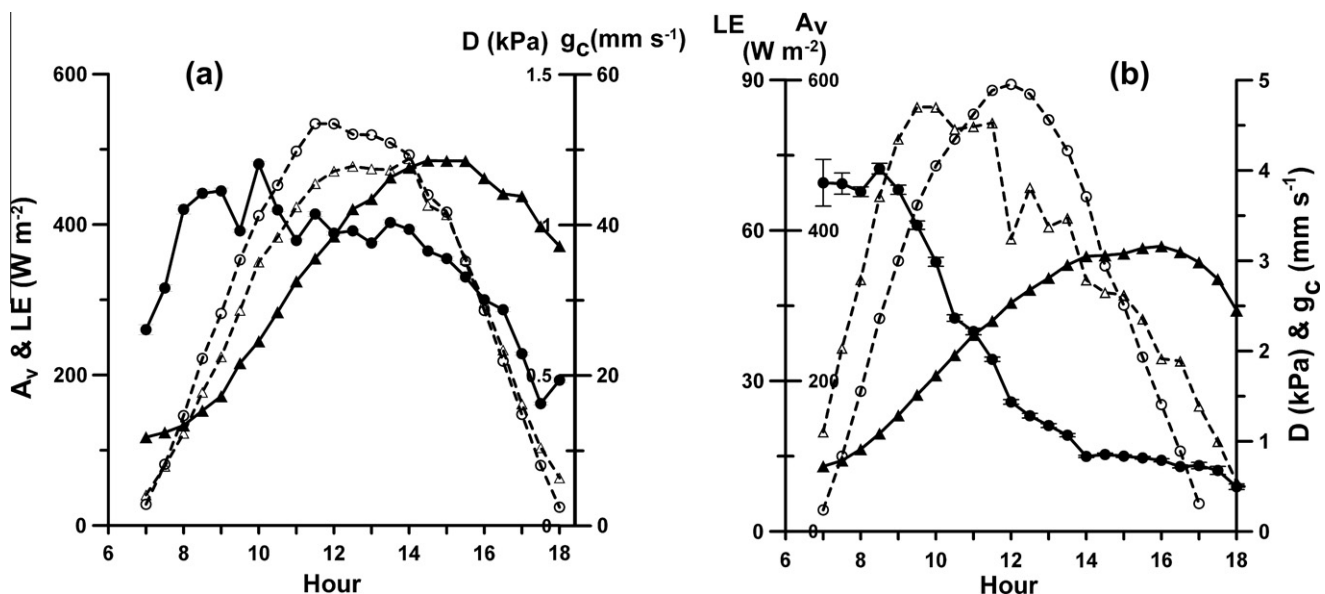

Fig. 6. Summer (a) and winter (b) hourly averages of: LE (empty triangles); A_v (empty circles); D (filled triangles) and g_c (filled circles). The bars represent the standard errors of g_c.
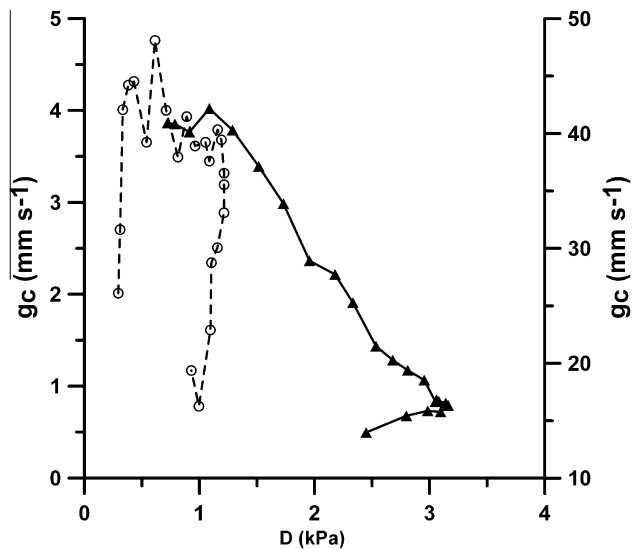
Fig. 7. Hourly averages of canopy conductance (g_c) in summer (empty circles, right axis) and winter (filled triangles, left axis) versus saturation deficits (D).

The diel patterns in winter are shown in Fig. 6b. The early morning LE fluxes followed the increase in A_v, while g_c was nearly constant (3.7 mm s^{-1}) and D was lower than 1.5 kPa. For the rest of the morning LE was constant (80 W m^{-2}), although g_c dropped to 1.9 mm s^{-1} and D reached 2.3 kPa. In the afternoon both g_c and LE decreased while D increased. This suggests the apparent feed-forward response of g_c to vapour pressure deficit (Franks et al., 1997) in which evaporation reached a maximum rate at D = 1.5 kPa and then declined with further increases of D (MacFarlane et al., 2004), as well the three-phase behaviour in conductance observed at leaf and canopy scales by Whitley et al. (2008), although there is reasonable evidence that transpiration rate rather than D constitutes the over-riding g_c control (Roberts, 2007).

The summer and winter hourly averages of canopy conductance versus saturation deficit (Fig. 7) exhibited a clear hysteresis which was larger during the summer, contrary to the observations of O'Grady et al. (1999) in Eucalyptus trees in the savannas of northern Australia. The hysteresis has been attributed to the asymmetry in the daily cycle of D whose peak occurs in the mid-afternoon as well the uneven distribution of soil water potential with distance from the roots (Tuzet et al., 2003), or the result of changing stomatal sensitivity to D, which may become more sensitive to D with increasing D (Mitchell et al., 2009), possibly in response to changes in leaf resistance rather than the result of changes in the hydraulic conductance of the soil-to-root-to-leaf pathway (O'Grady et al., 2008).

The increased evaporation in the summer, closely matching the diurnal cycle of A_v and D, while in the winter the evaporation followed the g_c curve, due to the strong stomatal control, imply that water vapour exchange was limited by atmospheric demand during summer and by supply in winter (O'Grady et al., 2008). Isohydric plants, which maintain constant minimum leaf water potential are expected to have high stomatal sensitivity (Tuzet et al., 2003) and the control of transpiration is advantageous in woody plants as it prevents water potentials falling to dangerous levels and risking serious xylem dysfunction, where the cost of recovering hydraulic function may be high (O'Grady et al., 2008).

4. Conclusions

The site long-term average annual precipitation (R = 1498 mm year^{-1}) is approximately equal to 85% of the evapo-rative equivalent of A_v (1527 mm year^{-1}). Consequently, due to the rainfall seasonality the vegetation's capability to delay water stress through the use of the water in a large volume of soil was mainly dependent on the regularity of summer precipitation to recharge soil water, as noticed in the year 2006 whose total rainfall was 27% lower than the average, and eventually by winter cold-front generated rainfall, as observed in year 2007.

The summer rainfall lowered the surface atmosphere vapour pressure deficit and increased the LAI (3.4 m^2 m^{-2}), changing the microclimate and physiology which promoted evaporation rates controlled by the available energy. Conversely in the winter the decline in ecosystem water content and LAI (2.2 m^2 m^{-2}) led to increased sensible heat fluxes, evaporative demand and decline in g_c, which limited the rates of LE to less than 20% of the available energy. Notwithstanding, the mean E/R ratio was 89% and the mean annual evaporative fraction was 66%.

The estimated transpiration in the second year was 13% greater besides the 7% reduction in rainfall, therefore the physiologically productive water flow (Pereira et al., 2006), was more efficient when compared with the first year as the proportion of the canopy interception loss (non-productive water flux) was the same (12% of R). However as pointed out by Hubbard et al. (2010) it is important to observe the balance between the increased productivity and higher water use mainly with respect to drier areas or as a consequence of climatic variability. The impacts of Eucalyptus afforestation on water yield are documented elsewhere (Engel et al., 2005; Nosetto et al., 2005; Silveira and Alonso, 2009) as well the acknowledgement of time scale effects (Brown et al., 2005; Scott and Prinsloo, 2008), although according to Vanclay (2009) the evidence presented remains equivocal and suggests the alternative of management control of forest plantations to deliberately increase water use efficiency.

The observed evaporation data demonstrate the importance of knowing about the water balance–vegetation interactions at the stand scale which, when extended over the landscape, allow groundwater recharge to be estimated. This understanding can be incorporated in operational estimates of groundwater recharge made by applying the daily values of canopy and aerodynamic conductance derived here in a simple water balance model such as that by Finch (1998) which calculates recharge from standard meteorological data. Environmentally sustainable land management can then be achieved by managing the trade-offs between economic viability and water resources security (Zhang et al., 1999; Dye and Versfeld, 2007).

References

ABRAF, 2007. Abraf Statistical Yearbook 2007: Base Year 2006. Brazilian Association of Forest Plantation Producers, Brasília, 80 p (ISSN 1980-8569).

Almeida, A.C., Soares, J.V., Landsberg, J.J., Rezende, G.D., 2007. Growth and water balance of *Eucalyptus grandis* hybrid plantations in Brazil during a rotation for pulp production. Forest Ecol. Manage. 251, 10–21.

Amiro, B., 2009. Measuring boreal forest evapotranspiration using the energy balance residual. J. Hydrol. 366, 112–118.

Aston, A.R., 1985. Heat storage in a young eucalypt forest. Agric. Forest Meteorol. 35, 281–297.

Aubinet, M., Grelle, A., Ibrom, A., Rannik, U., Moncrieff, J.B., Foken, T., Kowalski, A.S., Martin, P.H., Berbigier, P., Bernhofer, C.H., Clement, R., Elbers, J., Granier, A., Griinwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., Vesala, T., 2000. Estimates of the annual net carbon and water exchange of forests: the EUROFLUX methodology. Adv. Ecol. Res. 30, 113–175.

Baldocchi, D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Evans, R., Fuentes, J., Goldstein, A., Katul, G., Law, B., Lee, X., Malhi, Y., Meyers, T., Munger, W., Oechel, W., Paw U, K.T., Pilegaard, K., Schmid, H.P., Valentini, R., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2001. FLUXNET: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor and energy flux densities. Bull. Am. Meteorol. Soc. 82, 2415–2434.

Blanken, P.D., Black, T.A., 2004. The canopy conductance of a boreal aspen forest, Prince Albert National Park, Canada. Hydrol. Process. 18, 1561–1578.

Borma, L.S., da Rocha, H.R., Cabral, O.M., von Randow, C., Collicchio, E., Kurzatkowski, D., Brugger, P.J., Freitas, H., Tannus, R., Oliveira, L., Rennó, C.D., Artaxo, P., 2009. Atmosphere and hydrological controls of the evapotranspiration over a floodplain forest in the Bananal Island region, Amazonia. J. Geophys. Res. 114, G01003. doi:10.1029/2007JG000641.

Brown, A.E., Zhang, L., McMahon, T.A., Western, A.W., Vertessy, R.A., 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. J. Hydrol. 310, 28–61.

Culf, A.D., Foken, T., Gash, J.H.C., 2004. The energy balance problem. In: Kabat, P., Claussen, M., Dirmeyer, P.A., Gash, J.H.C., Bravo de Guenni, L., Meybeck, M., Pielke Sr, R.A., Vörösmarty, C.J., Hutjes, R.W.A., Lütkmeier, S. (Eds.), Vegetation, Water, Humans & the Climate. Springer-Verlag, Berlin (ISBN 3-540-42400-8: 159-166).

da Rocha, H.R., Manzi, A.O., Cabral, O.M., Miller, S.D., Goulden, M.L., Saleska, S.R., Coupe, N.R., Wofsy, S.C., Borma, L.S., Artaxo, P., Vourlitis, G., Nogueira, J.S., Cardoso, F.L., Nobre, A.D., Kruijt, B., Freitas, H.C., von Randow, C., Aguiar, R.G., Maia, J.F., 2009. Patterns of water and heat flux across a biome gradient from tropical forest to savanna in Brazil. J. Geophys. Res. 114, G00B12. doi:10.1029/2007JG000640.

David, T.S., Ferreira, M.I., David, J.S., Pereira, J.S., 1997. Transpiration from a mature Eucalyptus globulus plantation in Portugal during a spring–summer period of progressively higher water deficit. Oecologia 110, 153–159.

Dye, P., Versfeld, D., 2007. Managing the hydrological impacts of South African plantation forests: an overview. Forest Ecol. Manage. 251, 121–128.

Engel, V., Jobbágy, E.G., Stieglitz, M., Williams, M., Jackson, R.B., 2005. Hydrological consequences of Eucalyptus afforestation in the Argentine Pampas. Water Resour. Res. 41, W10409.

FAO, 2008. Forests and Energy: Key Issues. FAO Forestry Paper 154, Rome, 56 pp (ISBN 978-92-5-105985-2).

Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H., Granier, A., Gross, P., Grunwald, T., Hollinger, D., Jensen, N.O., Katul, G., Keronen, P., Kowalski, A., Lai, C.T., Law, B.E., Meyers, T., Moncrieff, J., Moors, E., Munger, J.W., Pilegaard, K., Rannik, U., Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. Agric. Forest Meteorol. 107, 43–69.

Finch, J.W., 1998. Estimating direct groundwater recharge using a simple water balance model-sensitivity to land surface parameters. J. Hydrol. 211, 112–125.

Franks, P.J., Cowan, R., Farquhar, G.D., 1997. The apparent feed forward response of stomata to air vapour pressure deficit: information revealed by different experimental procedures with two rainforest trees. Plant Cell Environ. 20, 142–145.

Ferreira, J.M.A., 2007. Productivity Gains in Eucalyptus urophylla Clonal Plantations and its Correlation with Soil, Climate and Stand Variables. MSc Thesis ESALQ-USP, Piracicaba, São Paulo, Brasil 84 pp (Portuguese).

Foken, T., 2008. The energy balance closure problem – an overview. Ecol. Appl. 18, 1351–1367.

Gash, J.H.C., Stewart, J.B., 1977. Evaporation from Thetford forest during 1975. J. Hydrol. 35, 385–396.

Gash, J.H.C., Lloyd, C.R., Lachaud, G., 1995. Estimating sparse forest rainfall interception with an analytical model. J. Hydrol. 170, 79–86.

Gash, J.H.C., Shuttleworth, W.J., 2007. Benchmark Papers in Hydrology: Evaporation. IAHS Press, Wallingford. 521 p.

Gash, J.H.C., Valente, F., David, J.S., 1999. Estimates and measurements of evaporation from wet, sparse pine forest in Portugal. Agric. Forest Meteorol. 94, 149–158.

Garratt, J.R., 1992. The Atmospheric Boundary Layer. Cambridge University Press, Cambridge. 316 pp (ISBN 0-521-46745-4).

Guyot, A., Cohard, J.M., Anquentin, S., Galle, S., Lloyd, C.L., 2009. Combined analysis of energy and water balances to estimate latent heat flux of a sudanian small catchment. J. Hydrol. 375, 227–240.

Hsieh, C.I., Katul, G., Chi, T., 2000. An approximate analytical model for footprint estimation of scaler fluxes in thermally stratified atmospheric flows. Adv. Water Resour. 23, 765–772.

Hubbard, R.M., Ryan, M.G., Giardina, C.P., Barnard, H., 2004. The effect of fertilization on sap flux and canopy conductance in a Eucalyptus saligna experimental forest. Global Change Biol. 10, 427–436.

Hubbard, R.M., Stape, J., Ryan, M.G., Almeida, A.C., Rojas, J., 2010. Effects of irrigation on water use and water use efficiency in two fast growing Eucalyptus plantations. Forest Ecol. Manage. 259, 1714–1721.

Jarvis, P.G., 1985. Coupling of transpiration to the atmosphere in horticultural crops: the omega factor. Acta Hortic. 171, 187–205.

Kaimal, J.C., Finnigan, J.J., 1994. Atmospheric Boundary Layer Flows: Their Structure and Measurement. Oxford University Press. 289 pp.

Kirschbaum, M.U.F., Keith, H., Leuning, R., Cleugh, H.A., Jacobsen, K.L., van Gorsel, E., Raison, R.J., 2007. Modelling net ecosystem carbon and water exchange of a temperate Eucalyptus delegatensis forest using multiple constraints. Agric. Forest Meteorol. 145, 48–68.

Kosugi, Y., Katsuyama, M., 2007. Evapotranspiration over a Japanese cypress forest. II. Comparison of the eddy covariance and water budget methods. J. Hydrol. 334, 305–311.

Laclau, J.P., Ranger, J., Deleporte, P., Nouvellon, Y., Saint-André, L., Marlet, S., Bouillet, J.P., 2005. Nutrient cycling in a clonal stand of Eucalyptus and an adjacent savanna ecosystem in Congo 3. Input–output budgets and consequences for the sustainability of the plantations. Forest Ecol. Manage. 210, 375–391.

Lane, P.N.J., Morris, J., Ningnan, Z., Guangyi, Z., Guoyi, Z., Daping, X., 2004. Water balance of tropical eucalypt plantations in south-eastern China. Agric. Forest Meteorol. 124, 253–267.

Leuning, R., Cleugh, H., Zegelin, S., Hughes, D., 2005. Carbon and water fluxes over a temperate Eucalyptus forest and tropical wet/dry savanna in Australia. Agric. Forest Meteorol. 129, 151–173.

Lloyd, C.R., Bessemoulin, P., Cropley, F.D., Culf, A.D., Dolman, A.J., Elbers, J., Heusinkveld, B., Moncrieff, J.B., Monteny, B., Verhoef, A., 1997. A comparison of surface fluxes at the HAPEX-Sahel fallow bush sites. J. Hydrol., 400–425.

MacFarlane, C., White, D.A., Adams, M.A., 2004. The apparent feed-forward response to water vapour pressure deficit of stomata in droughted, field-grown Eucalyptus globules Labill. Plant Cell Environ. 27, 1268–1280.

Matsumoto, K., Ohta, T., Nakai, T., Kuwada, T., Daikoku, K., Iida, S., Yabuki, H., Kononov, A.V., van der Molen, M.K., Kodama, Y., Maximov, T.C., Dolman, A.J., Hattori, S., 2008. Responses of surface conductance to forest environments in the Far East. Agric. Forest Meteorol. 148, 1926–1940.

McNaughton, K.G., Jarvis, P.G., 1983. Predicting effects of vegetation changes on transpiration and evaporation. In: Kozlowski, T.T. (Ed.), Water Deficits and Plant Growth, vol. 7. Academic Press, New York, pp. 1–47.

Michiles, A.A.S., Gielow, R., 2008. Above-ground thermal energy storage rates, trunk heat fluxes and surface energy balance in a central Amazonian rainforest. Agric. Forest Meteorol. 148, 917–930.

Mielke, M.S., Oliva, M.A., Barros, N.F., Penchel, R.M., Martinez, C.A., Almeida, A.C., 1999. Stomatal control of transpiration in the canopy of a clonal Eucalyptus grandis plantation. Trees 13, 152–160.

Mielke, M.S., Oliva, M.A., de Barros, N.F., Penchel, R.M., Martinez, C.A., da Fonseca, S., de Almeida, A.C., 2000. Leaf gas exchange in a clonal eucalypt plantation as related to soil moisture, leaf water potential and microclimate variables. Trees 14, 263–270.

Mitchell, P.J., Veneklaas, E., Lambers, H., Burgess, S.S.O., 2009. Partitioning of evapotranspiration in a semi-arid eucalypt woodland in south-western Australia. Agric. Forest Meteorol. 149, 25–37.

Monteith, J.L., 1965. Evaporation and environment. In: The State and Movement of Water in Living Organisms. Proc. 19th Symp. Soc. Exp. Biol., Swansea 1964. Cambridge University Press, Cambridge, pp. 205–234.

Moore, C.J., 1986. Frequency response corrections for eddy correlation systems. Bound. Layer Meteorol. 37, 17–35.

Moore, C.J., Fisch, G.F., 1986. Estimating heat storage in Amazonian tropical forest. Agric. Forest Meteorol. 38, 147–169.

Nosetto, M.D., Jobbagy, E.G., Paruelo, J.M., 2005. Land-use change and water losses: the case of grassland afforestation across a soil textural gradient in central Argentina. Global Change Biol. 11, 1101–1117.

O'Grady, A.P., Eamus, D., Hutley, L.B., 1999. Transpiration increases during the dry season: patterns of tree water use in eucalypt open-forests of northern Australia. Tree Physiol. 19, 591–598.

O'Grady, A.P., Worledge, D., Battaglia, M., 2008. Constraints on transpiration of Eucalyptus globules in southern Tasmania, Australia. Agric. Forest Meteorol. 148, 453–465.

Pereira, J.S., Chaves, M.M., Caldeira, M.C., Correia, A.V., 2006. Water availability and productivity. In: Morrison, J.I.L., Morecroft, D. (Eds.), Plant Growth and Climate Change. Blackwell Publishers, London, pp. 118–145.

Pereira, J.S., Mateus, J.A., Aires, L.M., Pita, G., Pio, C., David, J.S., Andrade, V., Banza, J., David, T.S., Paço, T.A., Rodrigues, A., 2007. Net ecosystem carbon exchange in three contrasting Mediterranean ecosystems – the effect of drought. Biogeosciences 4, 791–802.

Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large scale parameters. Mon. Weather Rev. 100, 81–92.

Roberts, J., Rosier, P.T.W., 1993. Physiological studies in young Eucalyptus stands in southern India and derived estimates of forest transpiration. Agric. Water Manage. 14, 103–118.

Roberts, J., 2007. The role of plant physiology in hydrology: looking backwards and forwards. Hydrol. Earth Syst. Sci. 11, 256–269.

Rocha, H.R., Goulden, M.L., Miller, S.D., Menton, M.C., Pinto, L.D.V.O., Freitas, H.C., Figueira, A.M.S., 2004. Seasonality of water and heat fluxes over a tropical forest in eastern Amazonia. Ecol. Appl. 14, S22–S32.

Savenije, H.G., 1997. Determination of evaporation from catchment water balance at a monthly time scale. Hydrol. Earth Syst. Sci. 1, 93–100.

Schleppi, P., Conedera, M., Sedivy, I., Thimonier, A., 2007. Correcting non-linearity and slope effects in the estimation of the leaf area index of forests from hemispherical photographs. Agric. Forest Meteorol. 144, 236–242.

Scott, D.F., Prinsloo, F.W., 2008. Longer-term effects of pine and eucalypt plantations on streamflow. Water Resour. Res. 44, W00A08. doi:10.1029/2007WR006781 (printed 45(7), 2009).

Shuttleworth, W.J., Calder, I.R., 1979. Has the Priestley–Taylor equation any relevance to forest evaporation? J. Appl. Meteorol. 18, 639–646.

Shuttleworth, W.J., Gash, J.H.C., Lloyd, C.R., Moore, C.J., Roberts, J.M., Marques Filho, A.O., Fisch, G., Paula, S., Filho, V., Góes Ribeiro, M.N., Molion, L.C.B., Abreu De Sa, L., Nobre, C.A., Cabral, O.M.R., Patel, S.R., De Moraes, C., 1984. Eddy correlation measurements of energy partition for Amazonian forest. Quart. J. Royal Meteor. Soc. 110, 1143–1162.

Shuttleworth, W.J., 1988. Evaporation from Amazonian rainforest. Proc. Royal Soc. Lond. B 233, 321–346.

Silberstein, R., Held, A., Hatton, T., Viney, N., Sivapalan, M., 2001. Energy balance of a natural Jarrah (Eucalyptus marginata) forest in Western Australia: measurements during the spring and summer. Agric. Forest Meteorol. 109, 79–104.

Silveira, L., Alonso, J., 2009. Runoff modifications due to the conversion of natural grasslands to forests in a large basin in Uruguay. Hydrol. Process. 23, 320–329.

Stape, J.L., Binkley, D., Ryan, M.G., 2004. Eucalyptus production and the supply, use and efficiency of use of water, light and nitrogen across a geographic gradient in Brazil. Forest Ecol. Manage. 193, 17–31.

Stape, J.L., Binkley, D., Jacob, W.S., Takahashi, E.N., 2006. A twin-plot approach to determine nutrient limitation and potential productivity in Eucalyptus plantations at landscape scales in Brazil. Forest Ecol. Manage. 223, 358–362.

Stape, J.L., Binkley, D., Ryan, M.G., 2008. Production and carbon allocation in a clonal Eucalyptus plantation with water and nutrient manipulations. Forest Ecol. Manage. 255, 920–930.

Tuzet, A., Perrier, A., Leuning, R., 2003. A coupled model of stomatal conductance, photosynthesis and transpiration. Plant Cell Environ. 26, 1097–1116.

Valente, F., David, J.S., Gash, J.H.C., 1997. Modelling interception loss for two sparse eucalypt and pine forests in central Portugal using reformulated Rutter and Gash analytical models. J. Hydrol. 190, 141–162.

van der Tol, C., Gash, J.H.C., Grant, S.J., McNeil, D.D., Robinson, M., 2003. Average wet canopy evaporation for a Sitka spruce forest derived using the eddy correlation-energy balance technique. J. Hydrol. 276, 12–19.

Vanclay, J.K., 2009. Managing water use from forest plantations. Forest Ecol. Manage. 257, 385–389.

Webb, E.K., Pearman, G.I., Leuning, R.G., 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. Quart. J. Royal Meteor. Soc. 106, 85–100.

White, D.A., Beadle, C.L., Worledge, D., 2000. Control of transpiration in an irrigated Eucalyptus globulus Labill. plantation. Plant Cell Environ. 23, 123–134.

White, D.A., Battaglia, M., Macfarlane, C., Mummery, D., McGrath, J.F., Beadle, C.L., 2003. Selecting species for recharge management in Mediterranean south western Australia – some ecophysiological considerations. Plant Soil 257, 283–293.

Whitehead, D., Beadle, C.L., 2004. Physiological regulation of productivity and water use in Eucalyptus: a review. Forest Ecol. Manage. 193, 113–140.

Whitley, Rhys, Zeppel, M., Armstrong, N., Macinnis-Ng, C., Yunusa, I., Eamus, D., 2008. A modified Jarvis–Stewart model for predicting stand-scale transpiration of an Australian native forest. Plant Soil 305, 35–47.

Wilson, K.B., Hanson, P.J., Mulholland, P.J., Baldocchi, D.D., Wullschleger, S.D., 2001. A comparison of methods for determining forest evapotranspiration and its components: sap-flow, soil water budget, eddy covariance and catchment water balance. Agric. Forest Meteorol. 106, 153–168.

Zeppel, M.J.B., Macinnis-Ng, C.M.O., Yunusa, I.A.M., Whitley, R.J., Eamus, D., 2008. Long term trends of stand transpiration in a remnant forest during wet and dry years. J. Hydrol. 349, 200–213.

Zhang, L., Dawes, W.R., Walker, G.R., 1999. Predicting the Effect of Vegetation Changes on Catchment Average Water Balance. CRC for Catchment Hydrology Technical Report 99/12, Canberra.