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Latent heat fluxes from juvenile plantation of mixed native woody species on a waste disposal site in eastern Australia

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ABSTRACT

Energy balance analysis was undertaken during the growing seasons of 2006-07 and 2007-08 over a juvenile plantation established to dewater the soil on a waste disposal site. Latent heat flux over the whole plantation (λE) fluctuated widely but generally oscillated between 0.5 and 22 MJ m^{-2} d^{-1} and was the largest component of the energy balance accounting for between 60 and 170% of the available energy incident on the site; instances of λE exceeding available energy arose from advection of sensible heat during periods when volumetric water content exceeded 24% and the magnitude of the flux depended on net radiation receipts. With relatively dry soil ($q < 20\%$), λE declined linearly with θ. Limited measurements of sapflow in the first year allowed latent heat flux from the canopy (λE_c) to be quantified, and its rate was relatively stable between 0.20 and 0.38 MJ m^{-2} d^{-1} accounting for between 4 and 18% of daily λE, even though the tree canopy intercepted only 5% of the incident solar radiation. Canopy sensible heat flux (H_c) fluctuated widely in response to changing ambient available energy intercepted by the canopy. Evapotranspiration was less than the rainfall during each of the two years, which suggested deep drainage to the shallow watertable which rose by up to 57%. We concluded that effectiveness of the plantation in dewatering will only improve over time as the trees mature to intercept more of the available energy and their roots penetrate deeper.

Introduction

A thorough understanding of the hydrogeology of waste disposal sites and their vicinity is critical to the safe operation of such sites. This is especially important at the early stages when the juvenile trees barely provide any canopy cover and there is a high risk of runoff and drainage. Information on energy balance over juvenile plantations is scant in literature, but the sparse tree canopies over widely exposed understoreys produce energy flux profiles that somewhat resemble those over agroforestry systems. In such systems understorey species, and where present, bareground, are known to have dominant influence on energy balance, primarily because they intercept majority of the incident radiation (Black and Kelliher, 1989; Yunusa et al., 1995; Irvine et al., 1998). Physiological differences between the trees and the understorey, often herbaceous species, may also exert significant influence on the partitioning of available energy. Irvine et al. (1998) measured Bowen ratio (β) for a 15 year old Sitka spruce (*Picea sitchensis*) in agroforestry and found that latent heat flux (λE) increased with exposure of understorey through thinning of the trees, because the grasses had lower canopy resistance and hence higher transpiration than the trees. Earlier, Wicke and Bernhofer (1996) found lower β, and hence larger λE, over a grassland compared with an adjacent forest of Scots pine forest (*Pinus silvestris*). All these suggest that understorey species would even be more dominant of λE in much younger plantations.

In vegetations of multi-storey species, contribution of each stratum to λE is often scaled by the fraction of incident radiation it intercepts (Caylor et al., 2005; Jahanzooz et al., 2006). It is not uncommon however, for there to be a disparity between energy absorbed by given canopy and its latent heat flux, because λE from the canopy is strongly influenced by dynamics of the sensible heat fluxes in response to aerodynamic and soil moisture conditions (McNaughton and Jarvis, 1983; Granier et al., 1996; Heilman et al., 1994; Cleugh et al., 2007). Often λE from the canopy can exceed absorbed energy mostly when soil moisture is in abundant supply and stomatal conductance is largely unrestrained (Lindroth, 1985; Oke 1987; Yunusa et al., 2004). A reverse trend would generally be expected when soil-water is limiting since the leaf area index and the fraction of available energy would remain largely unchanged despite falls in rates of transpiration. Thus, while in the former case the canopy serves as a sink in gaining as sensible heat and dissipating it as latent heat, in the latter the canopy becomes a source of sensible heat. The latter scenario would dominate in a vegetation of Australian native woody species that are inherently parsimonious water-users by being conservative in their transpiration (Eberbach and Burrows, 2006; Zeppel et al., 2006). Instances of λE being smaller than intercepted energy have been commonly implied by several studies that showed water-use to be small fractions of evaporative demands even when soil-water is readily available (Zeppel et al., 2006; Cleugh et al., 2007). In such environments, the canopy can simultaneously be a significant source for both λE and sensible heat (Yunusa et al., 2004). For juvenile plantations not older than three years therefore, trees their small canopies would be expected to play limited, but significant role in the energy balance.

Removal of vegetation during commissioning of waste disposal sites causes substantial disruption to the hydrogeological processes that impact on ground and surface water. The situation is thus similar to that caused by land clearing for agriculture that has afflicted salinity and groundwater degradation on significant parts of Australian landscapes (Barr and Cary, 1992; Eamus et al., 2006). An additional challenge on waste disposal sites is the important need to isolate waste materials both from the environment and population, and to prevent movement of water into or out of the storage cell. i.e ensure hydrologic isolation (Freeze, 1972). Energy balance analysis of such sites provides an approach to assess the efficacy of young plantations in dewatering the soil with minimal disturbance of the soil. In the current study we used the Bowen Ration energy balance technique to quantify latent heat flux over a new waste disposal site with an objective to assess the effectiveness of young Australian native species in discharging much of the rainfall through evepotranspiration over a 2-year period of below-average rainfall.

Materials and methods

The plantation

This study was undertaken on a eight hectare waste storage site at the Castlereagh waste disposal depot (33° 39' 41"S, 150° 46' 57"E) approximately 65 km northwest of Sydney, Australia. The climate is subtemperate with cool winters (June –August) when mean daily temperature drops to 12.4 ^{o}C and warm summers (December –February) with average temperature of 23 ^{o}C. The region receives rainfall all year round with monthly average of 65 mm, but late summer to early autumn (January – March) are wetter with mean rainfall of about 90 mm. Thus the period of September – April is considered to be that of rapid growth. The original soil at the site had a duplex structure consisting of 0.5 m thick topsoil of loamy sand, and subsoil of clay soil. Following construction of storage cells, much of the original soil was replaced with thick caps of Londenderry clay that were topped with 0.4 m thick soil of light to medium texture obtained from a variety of sources, and can be generally classified as silt loam. Three year old seedlings of tree and shrub species of local provenance were planted during autumn (April –May) in 2004. The trees consisted of several species of *Eucalyptus* and *Angophora*, in addition to *Casuarina glauca*, *Melaleuca linarifolia* and *Syncarpia glommulifera*; these were mixed with shrubs species of *Acacia*, *Callistemon*, *Gravillea*, *Hakea*, *Kunzea* and *Leptospermum* that were planted in rows midway between alternate rows of the trees. Both trees and shrubs produced a density of 10,500 stems per hectare and were irrigated as required during the first year, but left unirrigated afterwards; thus, during the time of this study the trees were solely rainfed. At the commencement of this study, the trees had an average height of 5.8 m and diameter of 35.1 mm in (Table 1). There was moderate growth of short herbaceous grassy and broad-leafed weeds during the study period, and they accounted for about 50% of the vegetation cover.

Measurements

Plants growth variables

Plant height was measured with a tape and stem thickness with callipers in October 2006. The fraction of ground surface area covered by the canopy of the young trees was estimated from classification analysis of a satellite image of the plantation from Google Earth (Google Earth®, www.google.com), and then imported into IDRISI (Eastman, 1999), where it was separated into the three spectral bands (RGB). The resulting image was then digitized and used to create a signature file from the three spectral bands, which was then used to produce a new classified image that was analysed with the HISTOGRAM routine in IDRISI to produces a frequency table of the numbers of pixels from which the young trees were identified and their projection over the ground area estimated. This fraction of canopy cover was taken to be equivalent to fraction of light intercepted by the trees (*i*).

Energy balance

We used the Bowen Ratio Energy Balance (BREB) technique to determine latent heat flux. The technique consisted of monitoring net radiation at some height above the canopy, in addition to air temperature and vapour pressure at two heights above the vegetation. The Bowen ratio (β) was then determined as:

$$\beta = \gamma\left(\frac{\Delta T}{\Delta e}\right) \qquad (1)$$

In which g is psychrometric constant (0.066 kPa $^{o}C^{-1}$), ΔT is temperature gradient and Δe is vapour pressure gradient (kPa) of the air. Eq 1 assumes that diffusion of water vapour and heat are equal, diffusion is vertical, and In the current study both ΔT and Δe were monitored with two sets of wet-and-dry bulb thermometers installed at heights of 1.5 and 2.5 m. the b was then used to estimate the latent heat flux (λE) as;

$$\lambda E = \frac{R_n - G}{1+\beta} \qquad (2)$$

in which R_n is net radiation and G ground heat flux; all units are in MJ m^{-2}. The R_n was measured with a radiometer at 4 m height and G with two heat flux plates installed at 50 and 100 mm depths. Vapour pressure and temperature gradients were determined from a pair of dry- and wet-bulb thermometers at 1.5 m and 2.5 m. All the sensors used for the measurements of variables in eqn 1 and 2, were supplied as a package (ICT, Australia). The unit was installed more/less in the middle of the 8 ha plantation, this produced a fetch of at least 100 m to the west, while it was more than 200 m in the other directions. The persistent drought and the resulting growth did not warrant adjustment of the sensor heights during the study, in that the lower sensor was still 0.3 m above the topmost foliage at conclusion of the monitoring period. This provided a minimum fetch-to-height ratio based on the top sensors of 40:1, but extended to more than 100:1 in the north-westerly direction of the dominant wind. This minimum ratio was twice the 20:1 found for vineyards (Heilman et al., 1989) whose canopy height was similar to the mean height of our juvenile vegetation during the study (Table 1). Our minimum fetch was about the same achieved and accounted for more than 80% of the flux measured over a 11 m tall Sitka spruce plantation (Irvine et al., 1998). Moreover, any errors due to limited fetch in the westerly direction would be minimised by the similarity in relatively dry profile of the soil between the juvenile plantation and the grass paddock that was 150 m away, as explained by Stannard et al. (2004). Measurements were commenced in September and terminated at end of May during the first year (2006-07), and between October and May during the second year (2007-08), when the dry- and wet-bulb thermometers were replaced with temperature-humidity sensors (HMP45A, Vaisala, Finland, www.vaisala.com). The two temperature-humidity sensors were compared against each other at the same height in the field for two days and in the laboratory for one day. These comparisons showed that the difference in temperature was about 0.001% and in humidity about 0.005%, and so the data logged in the field were adjusted accordingly. Calculations of λE and measurements of G allowed the total energy balance for the site to be resolved:

$$R_n - \lambda E - H - G = 0 \qquad (3)$$

in which H is sensible heat flux and was obtained as the residual. On the rare occasions when R_n data were not available or unreliable due to sensor failure, Rn was estimated using an empirical equation reported by Yunusa et al. (2004).

Sap flow

Sap flow was monitored on six trees using the stem heat balance technique (Sakuratani, 1981; Baker and van Bavel, 1987) over a two month period (October to November) 2006. The trees were chosen to cover the size distribution (13 – 19 mm diameter) and each tree was supplied with a Dynagauge heater-thermistor unit (Dynamax, Inc., Houston) at a height of at least 0.3 m following the standard procedure (Steinberg et al., 1990). Each unit was provided with insulating collar consisting of white, reflective foam, which further covered with a heat insulator to minimize thermal perturbations caused by the ambient environment. The units were readjusted every fortnight to allow for growth and the signal scanned every 30 s and then averaged and logged at 30 min intervals until end of November. The volume of sapflow per tree was extrapolated to depth (mm) of water transpired using tessellation method by dividing the total plantation area by mean area allotted to each tree, i.e. 9.52 m^2. Transpiration (mm) was converted to latent heat flux from the canopy (λE_c), for which the latent heat of vaporisation of water was taken as 2.45 MJ kg^{-1}, and E_c was in volume of sap (litres) flowing the trunk expressed per unit land area.

To assess the degree of stress during periods of limited soil-water availability and relative influence of advection on evapotranspiration (ET) we calculated the equilibrium evapotranspiration (E_{eq}) as given by McNaughton (1976):

$$E_{eq} = \frac{s(R_n - G)}{s + \gamma} / \lambda \qquad (4)$$

where s is the slope of saturation vapour pressure–temperature curve (kPa $^{o}C^{-1}$). This equation is commonly used to approximate the upper limit for evapotranspiration in the absence of water-stress when the process is driven almost entirely by energy supply and aerodynamic resistance is much lower than the canopy resistance (Cleugh et al., 2007; Yunusa et al., 2008).

Watertable depths

Depths to watertable was monitored from two sets of piezometers installed at shallow (7.2 –8.9 m (shallow) and deep (17.4 –20.8 m) depth levels. These were monitored at least every six weeks.

Weather variables

The ambient weather variables of solar radiation (R_s), temperature, humidity, wind speed and rainfall were monitored at 1.5 m height with an automatic weather station installed over grassy paddock located about 100 m from the plantation. These data were used to calculate the vapour pressure deficit of the air (*D*) and potential evapotranspiration (E_o) based on the Priestley-Taylor equation (Priestley and Taylor, 1973).

Results and Discussion

The weather and plantation characteristics

Both years were characterised by warm and mostly dry conditions, but the main growing season (September –April) was cooler and wetter in 2007-08 than in the previous year (Fig. 1). The atmospheric conditions could be more extreme than suggested by the data in the figure, which are running averages. For instance, *D* of 3.1 kPa and E_o of 11 mm were observed on 24 November 2006. There were also days in winter such as 1 July 2007 that experienced a mean temperature of just 9 ^oC, *D* of 0.36 and E_o of just 0.6 mm. Total rainfall for the September – May period was 870 mm in 2006/07 and for October – May period in 2007/08 was 685; these were 10% and 13%, respectively, higher than the long-term means for the respective periods. Much of the rainfall in 2007-08 came in heavy storms between November and February when there were seven days that each experienced more than 20 mm of rain. The top 0.6 m of the soil profile remained relatively moist in both years with q remaining above 20% for most of time and reaching peaks of >35% during rainy periods. During the study period, the young trees increased their average height by 26% and their diameter by 30%, and light interception rose to 12% (Table 1).

Latent heat flux from plantation

Daily λE fluctuated between 0.45 in the cool days of autumn in May 2006 and 21.7 MJ m^{-2} d^{-1} in warm sunny days following a rainy period in October in 2007. In order to enhance clarity and brevity, detailed data for the energy balance components are presented for the same dates in 2006/07 and 2007/08 and are indicated with 'P' in Figure 1a. These 3-day periods were in late spring (21 – 23 Nov), late summer (26 –28 Feb) and early autumn (29 –31 Mar) and they experienced contrasting weather and soil-water conditions as given in Table 2. Diurnal trends in heat fluxes (Fig. 2) show λE to be almost at par with, or in excess of, R_n for the three periods chosen in 2006-07. In the year 2007-08, λE for these periods was consistently less than R_n during much of the daylight hours between 0800 and 1700 hours. Differences in the partitioning of available energy between the two years could be primarily attributed to those in soil-water. This was well illustrated by comparing summer of the first year with spring of the second year, when R_n-G (available energy) and the other major micrometeorological conditions were similar (Table 2). In the summer λE was 99% of the available energy and β was <0.1, compared with the corresponding values of 70% and 0.24, respectively for the spring. The lower water supply for the three periods in 2006-07 meant a larger proportion of R_n had to be dissipated as H instead of λE.

To analyse this further, we expressed λE as a ratio of λE_{eq} as given in eq. 4 in order to normalise the λE for its responsiveness to micrometeorological conditions. This then allowed us to assess the influence of soil-water on λE by regressing $\lambda E/\lambda E_{eq}$ (relative λE or λE_r) on volumetric water content (θ). We obtained a significant relationship between λEr only with θ in the top 0.3 m of the soil profile (Fig. 3). The regression equation shows that λE_r attained a maximum mean value of 2.64 and θ of 16% is the point of inflexion below which λE_r declines linearly with θ. Thus it can be deduced that when θ exceeds 16% λE will increasingly be determined by the level of available energy and when advective enhancement of λE would be most common if the soil is sufficiently moist. This was the case in the selected 3-day period of autumn in 2006-07 (Fig. 2c) when the soil surface was still wet following a 5-day period of continuous rainfall that ceased only two days prior.

It had been established earlier that in addition to abundant supply of soil-water, unfettered canopy conductance and high evaporative demand conditions are essential for significant advective enhancement of λE to occur (Oke, 1987; McNaughton and Jarvis, 1983; Yunusa et al., 2004). Data presented here indicated that it can also occur under relatively mild micrometeorological conditions if the soil is sufficiently wet such as prevailed in the selected three days in autumn of 2006-07 (Table 2). The sum of H and λE balanced the available energy for the spring and summer periods in 2006-07 and all of the three periods in 2007-08 that experienced no advection. Lee et al. (2004) explained how local horizontal advection can contribute to vertical λE, and this can be picked up where measurements are made well above the ground. For the three periods in 2007-08, *H* constituted between 30 and 55% of the available energy, suggesting some measure of stress due to declining water supply causing dissipation of available energy as *H* instead of through λE. In this second year λE did not exceed 70% of the available energy and was as low as 40% during the three autumn days that had high energy receipt. A similar trend was observed in the very dry southern Portugal (Aires et al., 2008) where $\lambda E/\lambda E_{eq}$ over a grassland exceeded unity during the mild period that proceeded the growing seasons.

Latent heat flux from tree canopies

Although latent heat flux from the tree canopies (λE_c) was obtained over a 2-month period, we present diurnal data for only 20 days that experience a range of θ and micrometeorological conditions. The hourly λE_c attained peak of 0.018 MJ m^{-2} on most days and showed jagged patterns on cloudy days to reflect level of incident radiation (Fig. 4). By expressing λE_c as a ratio of net radiation intercepted by the tree canopy (R_{nc}) is was apparent that the energy absorbed by the canopy was greater than used for transpiration during much of the daylight hours except early in the morning and late afternoon when it could exceed 1.6. The low $\lambda E_c/R_{nc}$ was despite the mean q in the topsoil exceeding 20% during this period. It is a common adaptive feature amongst vast majority of terrestrial plant species, especially those that evolved in water-limited environments, to minimise transpiration through stomatal closure under high evaporative conditions even when soil moisture is temporarily abundant (Loveys et al., 1984; Yunusa et al., 2005). This is true of Australian native woody species for which E_c/E_o tend to be stable at between 0.2 and 03 even for mature forest during much of the season with only brief spikes following rainy periods (Zeppel et al., 2006). Hence, the apparent inability of the young trees to fully utilise intercepted energy for λE_c in this environment that is perennially water-limited.

A detailed analysis of canopy energy balance was undertaken for three consecutive days with high soil-water content in September and relatively lowers soil-water content in October. In September λE_c always commenced early even before receipt of R_{nc}, with the energy sourced from H_c which was always negative at this time (Fig. 5). A similar trend was observed, but with less prominence, in the last hours of the day light period. With reduced q in October, commencement of λE_c was delayed by at least an hour to around 0700 hrs, against 0600 hrs in the previous month. λE_c did not show a well-defined peak during either of the two periods considered. On the whole, less than half of R_{nc} was partitioned through λE_c with the balance given off as H_c (Table 3). Although R_{nc} was not measured directly, but approximated from satellite images and should be viewed with caution, the mean value of 0.057 for $\lambda E_c/\lambda E$ for the six days (Table 3) showed that a 5% estimate for R_{nc} in that first year was precise enough for this analysis.

Seasonal water use

The λE values were converted to evapotranspiration (ET) by taking λ as 2.45 MJ m^{-2}. To obtain continuous daily values, for gaps in data due to equipment failure, and also on rainy days when Bowen ratio technique is generally unreliable, we estimated λE based on the equation developed in Figure 3:

$$\lambda E = \left[\frac{2.64}{1 + \exp(-\theta - 16.0)/7.56} \right] E_{eq} \qquad (5)$$

in which θ is the mean volumetric water content (%) for the top 0.3 m of the soil. Mean daily ET oscillated between 0.5 and 5.5 mm d^{-1} (Fig. 6). The ET was particularly high in warm periods that experienced high amounts of and/or frequent rainfall, such as in summer of 2006-07 and early spring of 2007-08. These periods also coincided with when relative ET (ET/E_{eq}) exceeded unity suggesting significant contribution to latent energy through advection of sensible heat. For most of the time, ET was about 2.0 mm d^{-1}, and the corresponding ET/E_{eq} averaged 0.6. Total ET during the first year was in excess of rainfall suggesting that water-use was supported by antecedent soil-water (Table 4), which was plausible since the plantation was mostly bare in the preceding two years. Total ET was less than the rainfall in the second year, when several rainfall events were in the form of heavy storms (Fig. 1) and helped push the total rainfall well above the long-term average for the region. These large episodic rainfalls generated significant flooding events throughout the district. They however fully recharged the soil profile with excess draining into the groundwater and slightly raising the watertable (Table 4).

In the first year, the trees accounted for 15% of the total estimated ET. Although E_c was not measured in 2007-08, assuming that its fraction increased in proportion to increase in canopy light interception between the two years a seasonal E_c of 199 mm was calculated for this year (Table 4). Thus between 65 and 85% of ET was accounted for by the groundcover, which much larger than an average of 60% found under a 3-year old agroforestry involving radiate pines (Yunusa et al., 1995). In this environment however, understorey transpiration is likely to remain high even as the trees attain maturity, and may account for up to 63% of λE as in mature natural forest (Zeppel et al., 2008).

Concluding remarks

In this juvenile forest, λE was the largest component of the surface energy balance, although much of it emanated from the groundcover. These woody species are known to be conservative in their water-use so that λE_c was always smaller than the energy absorbed by the canopy which then releases the excess as sensible heat. The trees were therefore a source of λE and H. The rate of λE from the whole plantation declined almost linearly with soil-water when θ was 20%, but when θ >30% the rate becomes a function of energy supply, and advection enhancement becomes common. This study provides a first approximation of the efficacy of a juvenile plantation to dewater a waste disposal site through transpiration. This plantation of Australian native species achieved this objective to large extent, even though much of water use was by the herbaceous annual species. The two years received above-average rainfall and it is plausible that even the marginal rise in watertable would have been avoided in a years close to average rainfall. Hence, it will be desirable to further analyse water balance as the trees progressively increase their contribution to ET over time and the regional rainfall returns to near normal situation.

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References

Aires LM, Pio CA and Pereira JS (2008). The effects of drought on energy and water vapour exchange above a mediterranean C3/C4 grassland in Southern Portugal. Agric. For. Meteorol. 148, 565-579.

Baker, J.M. and van Bavel, C.H.M., 1987: 'Measurement of mass flow of water in the stems of herbaceous plants' Plant Cell Environ., 10, 777-782.

Barr N F and Cary J 1992 Greening a brown land: the Australian search for sustainable land use. Macmillan Education Australia, South Melbourne.

Black TA and Kelliher FM (1989). Processes controlling understorey evapotranspiration. Phil Trans R Soc Lond B324, 207–231

Caylor KK, Shugart HH and Rodriguez-Iturbe I (2005). Tree canopy effects on simulated water stress in Southern African Savannas. Ecosystem 8, 19 –32.

Cleugh HA, Leuning R, Mu Q, Running SW (2007). Regional evaporation estimates from flux tower and MODIS satellite data. Remote Sensing of Environment 106, 285–304

Eamus, D., Hatton, T., Cook, P., Colvin, C., 2006. Ecohydrology: vegetation function, water and resource management. CSIRO Press, Melbourne, pp 348.

Eastman, J.R., (1999). IDRISI 32. (Worcester, MA: Clark University).

Freeze RA (1972). Subsurface hydrology of waste disposal sites. IBM Journal of Research and Development 16, 117 –129.

Eberbach PL and Burrows GE (2006). The transpiration response by four topographically distributed *Eucalyptus* species, to rainfall occurring during drought in south eastern Australia. Physiologia Plantarum 127: 483–493

Heilman, J.L., Britten, C.L., Neale, C.M.U., 1989. Fetch requirements of Bowen ratio measurements of latent and sensible heat fluxes. Agric. For. Meteorol., 44, 261–273.

Granier A, Biron P, Köstner B, Gay LW and Najjar G (1996). Comparisons of xylem sap flow and water vapour flux at the stand level and derivation of canopy conductance for Scots pine. Theoretical and Applied Climatology 53, 115-122

Irvine, MR, Gardiner BA and Morse AP (1998). Energy partitioning influenced by tree spacing. Agroforestry Systems 39: 211–224,

Lee X, Yu Q, Sun X, Liu J, Min Q, Liu Y and Zhnag X (2004). Micrometeorological fluxes under the influence of regional and local advection. Agric. For. Meteorol. 122, 111 – 124.

Lindroth A (1985). Seasonal and diurnal variation of energy balance components in coniferous forests. J Hydrol. 82, 1 –15.

Loveys, B.R., 1984. Diurnal changes in water relations and abscisic acid in field grown *Vitis vinefera* cultivars. III. The influence of xylem-derived abscisic acid on leaf gas exchange. New Phytol. 98, 563–573.

McNaughton, K. G. (1976). Evaporation and advection, I, Evaporation from extensive homogeneous surfaces. Quarterly Journal of the Royal Meteorolological Society, 25, 181–191.

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

Milne R (1979). Water loss and canopy resistance of a young Sitka Spruce plantation. Boundary-Layer Meteorol. 16, 67 – 81.

Oke, T.R., 1987. Boundary Layer Climates. 2nd edition, Rouledge, London. 435pp.

Priestley CHB, Taylor RJ (1972) On the assessment of surface heat flux and evaporation using large scale parameters. Monthly Weather Rev.100, 81–92.

Sakuratani T. 1981. A heat balance method for measuring water flux in the stem of intact plants. Journal of Agriculture Meteorology 37, 9–17.

Stannard DI, Rosenberry DO, Winter TC, and Parkhurst RS (2004). Estimates of fetch-induced errors in Bowen-ratio energy-budget measurements of evapotranspiration from a Praire wetland, Cottonwood Lake area, North Dakota, USA. Wetlands 24, 498 –513.

Steinberg, S.L., van Bavel, C.H.M. and McFarland, M.J., 1990: Improved sap flow gauge for woody and herbaceous plants. Agron. J., 82, 851-854.

Wicke W and Bernhofer Ch. 1996. Energy Balance Comparison of the Hartheim Forest and an adjacent grassland site during the HartX Experiment. Theor. Appl. Climatol. 53, 49 –58.

Yunusa IAM, Nuberg IK, Fuentes S, Lu P and Eamus D (2008). A simple field validation of daily transpiration derived from sapflow using a porometer and minimal meteorological data. Plant Soil 305, 15 – 24.

Yunusa IAM, Mead DJ, Pollock KM and Lucas RJ 1995a Process studies in a *Pinus radiata* - pasture agroforestry systems in a subhumid temperate environment. I. Water use and light interception in the third year. Agrofor. Systems 32, 163 – 183.

Yunusa IAM, Thomson SE, Pollock KP, Youwei L and Mead DJ (2005). Water potential and gas exchange did not reflect performance of *Pinus radiate* D. Don in an agrofrestry system under conditions of soil-water deficit in a temeperate environment. Plant Soil 275, 195 – 206.

Yunusa IAM, Walker RR, Lu P (2004) Evapotranspiration components from energy balance, sap-flow and microlysimetry techniques for an irrigated vineyard in inland Australia. Agric. For. Meteorol. 127, 93–107.

Zeppel MJB, Macinnis-Ng CMO, Yunusa IAM, Whitley RJ, Eamus D (2008). Long term trends of stand transpiration in a remnant forest during wet and dry years. J Hydrol. 349, 200-213.

Zeppela MJB, Yunusa IAM and Eamus D (2006). Daily, seasonal and annual patterns of transpiration from a stand of remnant vegetation dominated by a coniferous *Callitris* species and a broad-leaved *Eucalyptus* species. Physiologia Plantarum 127: 413–422.

Table 1. Basic characteristics for a juvenile plantation during third year of growth on a waste disposal site at Castlereagh, Australia.

Variables	October 2006	March 2008
Planted stem density (trees ha^{-1})	1050	*na*
Actual plant density (trees ha^{-1})		896 ± 137
Mean stem diameter (mm)	16.6 ± 1.2	21.5 ± 0.1
Mean tree height (m)	1.04 ± 0.06	1.30 ± 0.004
Estimated mean leaf area index	0.37 ± 0.05	1.43 ± 0.071
Calculated canopy cover (*i*)	0.05	0.12

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[1] Estimates for the trees only, excluding groundcover

Table 2. Daytime mean values for the components of energy balance, Bowen ratio (β), mean volumetric water content (θ) in the top 0.6 m of the soil, temperature of the top 50 mm of soil, air temperature, vapour pressure deficit (D) and solar radiation (R_s) for the same selected 3-day periods in spring, summer and autumn for juvenile plantation during the growing seasons of 2006/2007 and 2007/2008 at Castlereagh, Australia.

Year	Season	R_n-G (MJ m^{-2})	λE (MJ m^{-2})	H (MJ m^{-2})	$\lambda E/(R_n-G)$	β	Mean θ (%)	Mean soil temp (°C)	Mean air temp (°C)	Mean D (kPa)	Mean R_s (MJ m^{-2})
2006/07	Spring	10.14	10.00	0.10	0.99	0.06	24.0	30.2	23.1	3.08	18.6
	Summer	5.57	5.50	0.07	0.99	0.06	34.4	25.0	17.1	0.64	10.6
	Autumn	7.41	12.57	-5.16	1.70	-0.02	25.3	21.2	29.7	0.90	13.8
2007/08	Spring	5.52	3.98	1.68	0.70	0.24	22.6	23.2	21.8	0.68	10.6
	Summer	4.76	3.28	1.67	0.66	0.25	22.2	*na*	20.8	0.54	9.3
	Autumn	10.70	3.89	5.96	0.40	1.60	20.9	19.4	20.3	1.09	17.7

na, data not available

Table 3. Daytime values for the components of canopy energy balance young trees, mean volumetric water content (θ) of the top 0.6 m of the soil, temperature of the top 50 mm of soil, air temperature, vapour pressure deficit (*D*) and solar radiation (R_s) for two 3-day periods during the growing seasons of 2006/2007 Castlereagh, Australia.

Dates	R_{nc} (MJ m^{-2})	λE_c (MJ m^{-2})	H_c (MJ m^{-2})	$\lambda E_c/R_{nc}$	$\lambda E_c/\lambda E$	H_c/H	Mean θ (%)	Mean soil temp (^oC)	Mean air temp (^oC)	Mean *D* (kPa)
22 Sept	0.69	0.32	0.36	0.46	0.08	0.05	26.1	20.2	21.8	2.01
23 Sep	0.65	0.36	0.29	0.55	0.04	0.18	24.7	23.0	21.0	1.90
24 Sept	0.74	0.36	0.33	0.49	0.04	0.09	24.0	23.0	14.9	1.02
7 Oct	0.69	0.31	0.38	0.45	0.05	0.18	21.7	27.4	18.9	0.95
8 Oct	0.62	0.25	0.38	0.40	0.10	0.07	20.5	26.6	17.6	0.88
9 Oct	0.74	0.24	0.50	0.32	0.03	-25	18.8	26.3	14.5	0.81

Table 4. Summary of water use variables during the third year of growth by mixed tree species during growing seasons of 2006/2007 and 2007/2008 at Castlereagh, Australia.

Variables	2006 –2007 Season		2007 –2008 Season	
	Sept – May	Sept – Aug [1]	Oct – May	Sept – Aug [1]
Total potential evapotranspiration (E_o, mm)	869	1004	711	
Rainfall (mm)	474	870	685	
Long term average rainfall (1900-2006) (mm)[2]	650	796	607	-
Equilibrium evaporation (E_{eq}, mm)	642	758	565	
Evapotranspiration (ET, mm)	589	675	554	
Transpiration by trees (E_c, mm)[3]	85	102	199	*na*
Mean changes to depth of water table (m)				
Shallow	*na*	+1.10 (34%)	+1.53 (57%)	
Deep	*na*	+0.35 (2%)	+0.20 (1.2%)	

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[1] Estimates for ET and transpiration based on mean ET/E_{eq} and E_c/E_{eq} obtained for the duration of measurements for the respective years, *na*, data not available

[2] Source:

[3] E_c for 2007-08 based on scaling E_c/E_{eq} for the previous year by the change in fraction of light intercepted by the tree canopy

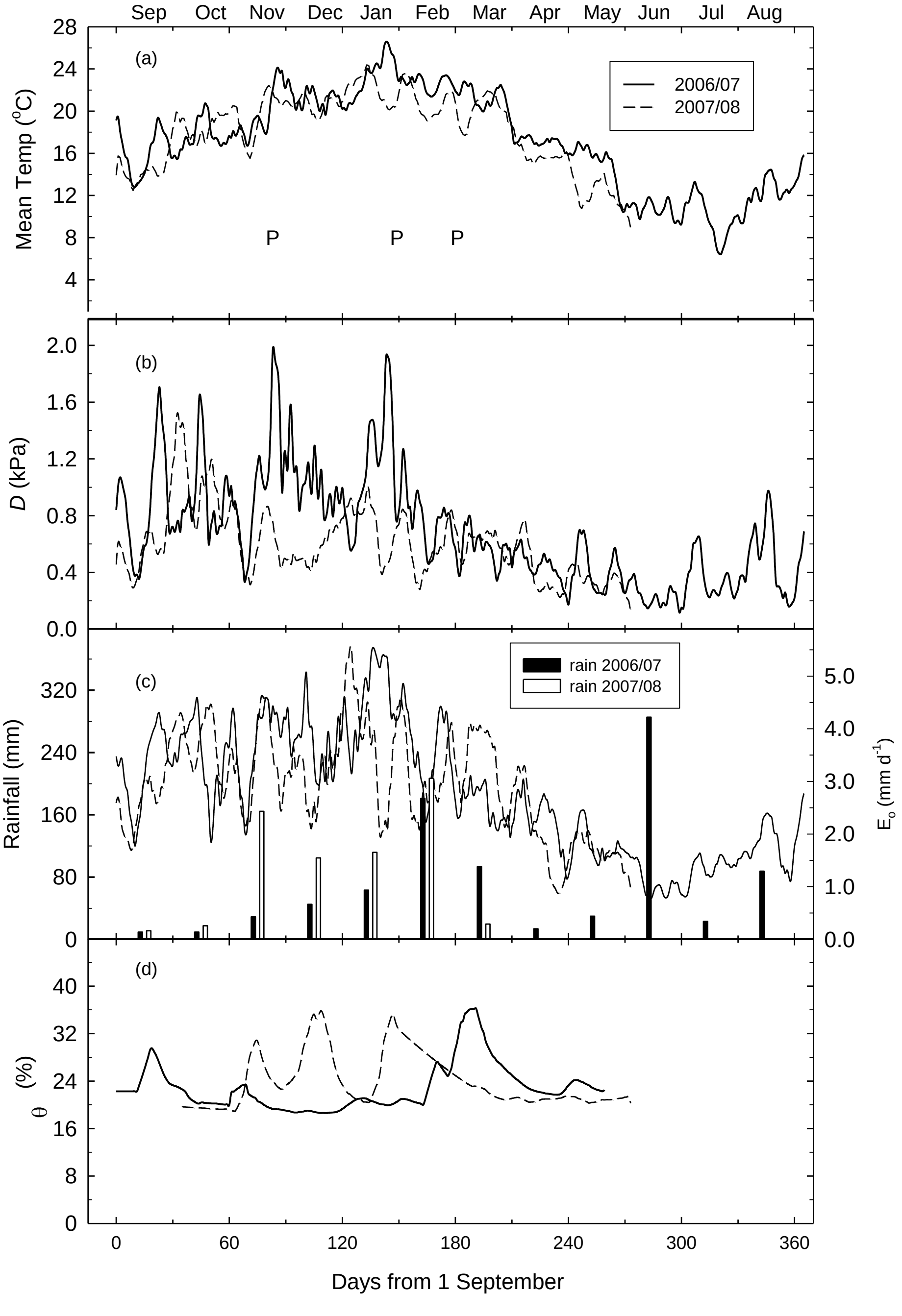

Fig. 1. Seven-day running averages for key weather and soil-water variables during growing seasons of 2006/2007 and 2007/2008 at Castlereagh: (a) daily means for temperature, (b) vapour pressure deficit (*D*), (c) rainfall and daily means for potential evaporatranspiration (E_0), and (d) volumetric water content (θ) for the top 0.6 m the of soil profile for the active growing period. The periods when detailed energy balance analyses were undertaken are marked in (a) as P.

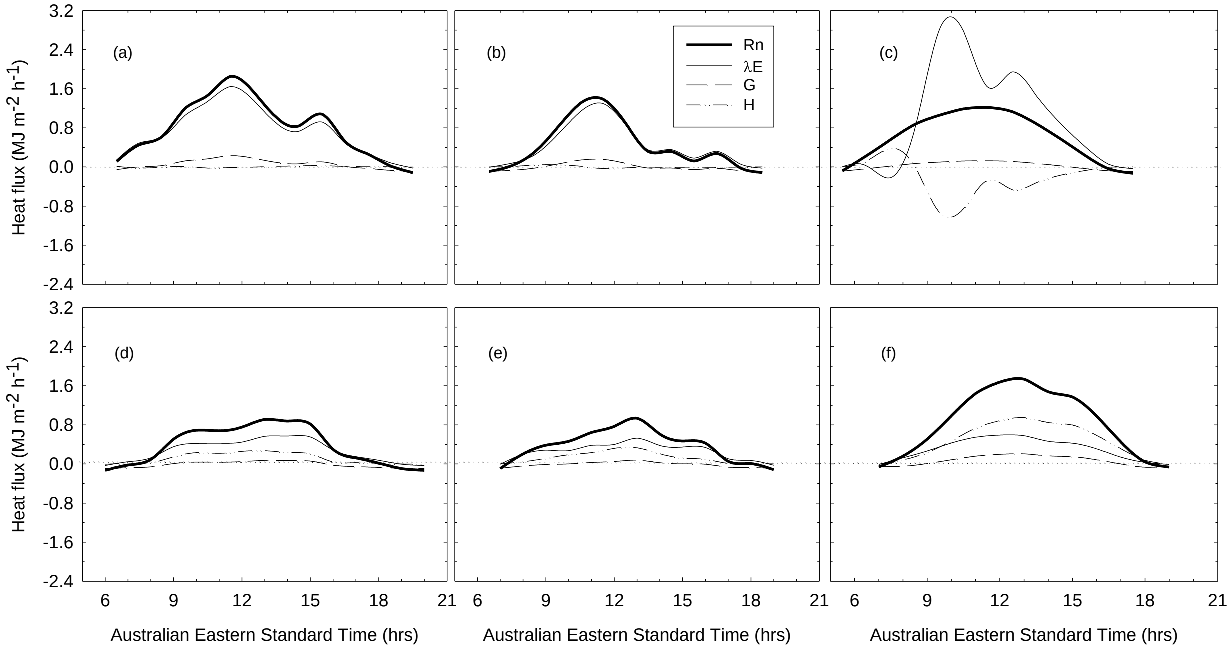

Fig. 2. Daytime trends for the energy balance components for a juvenile plantation during three contrasting 3-day periods in spring (a, d), summer (b, e) and autumn (c, f) in the growing seasons of 2006/2007 (a – c) and 2007/2008 (d – f) at Castlereagh, Australia. The dotted lines represent zero value.

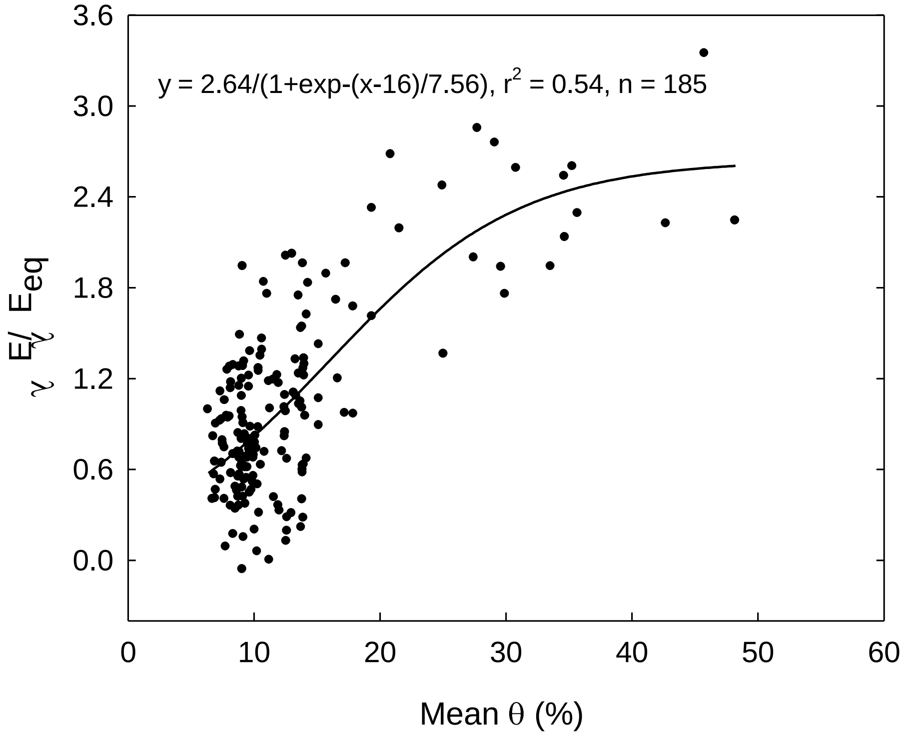

Fig. 3. Relationship between relative λE (λE/λE_{eq}) and mean volumetric water content of the top 0.3 m of soil for a juvenile plantation during the growing season of 2006/2007 at Castlereagh, Australia. Data for rainy days were excluded from the plot.

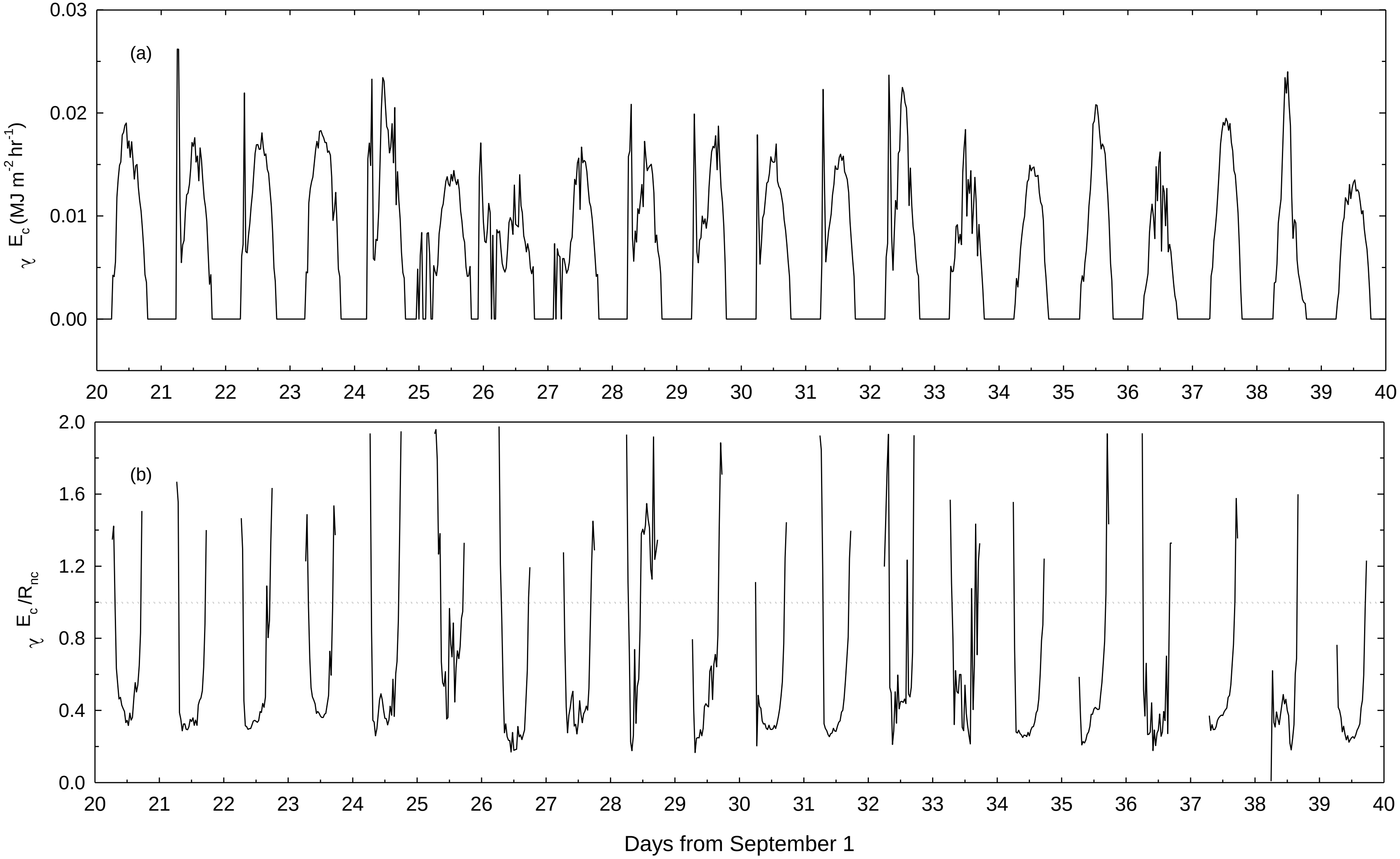
(a)
0.03
0.02
0.01
0.00
γ E_c (MJ m^{-2} hr^{-1})
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
(b)
2.0
1.6
1.2
0.8
0.4
0.0
γ E_c/R_{nc}
Days from September 1

Fig. 4. Diurnal pattern for latent heat flux from tree canopies (λE_c) (a) and for the ratio of latent heat flux to intercepted available energy (b) in a juvenile plantation of native species in 2006 at Castlereagh, Australia. The dashed line in (b) represents ratio on one.

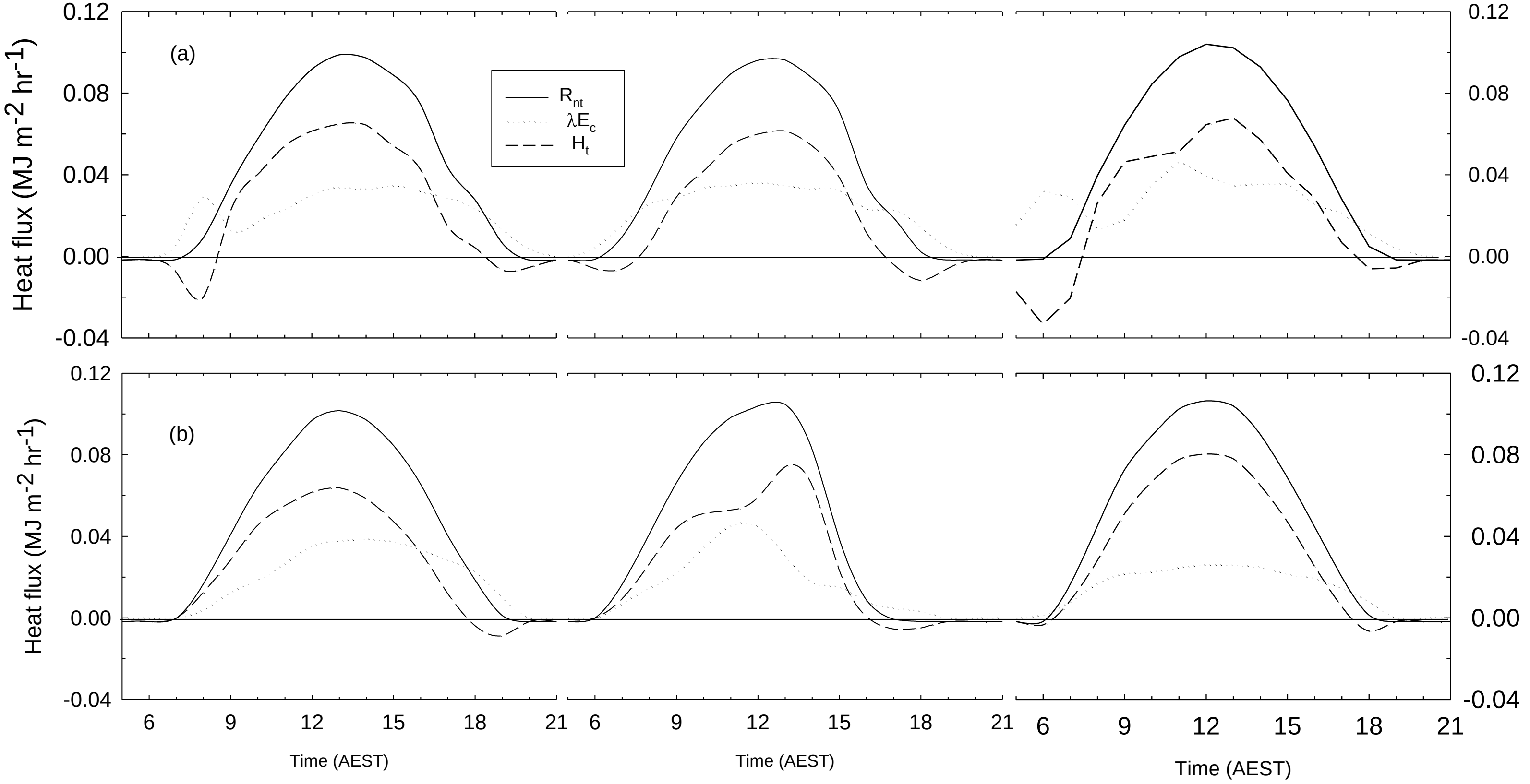

Fig. 5. Daytime trends for the energy balance components for the canopies of juvenal native trees during two contrasting periods in the third year of growth during the growing season of 2006 at Castlereagh, Australia: (a) 22 – 24 September, and (b) 14 – 16 October.

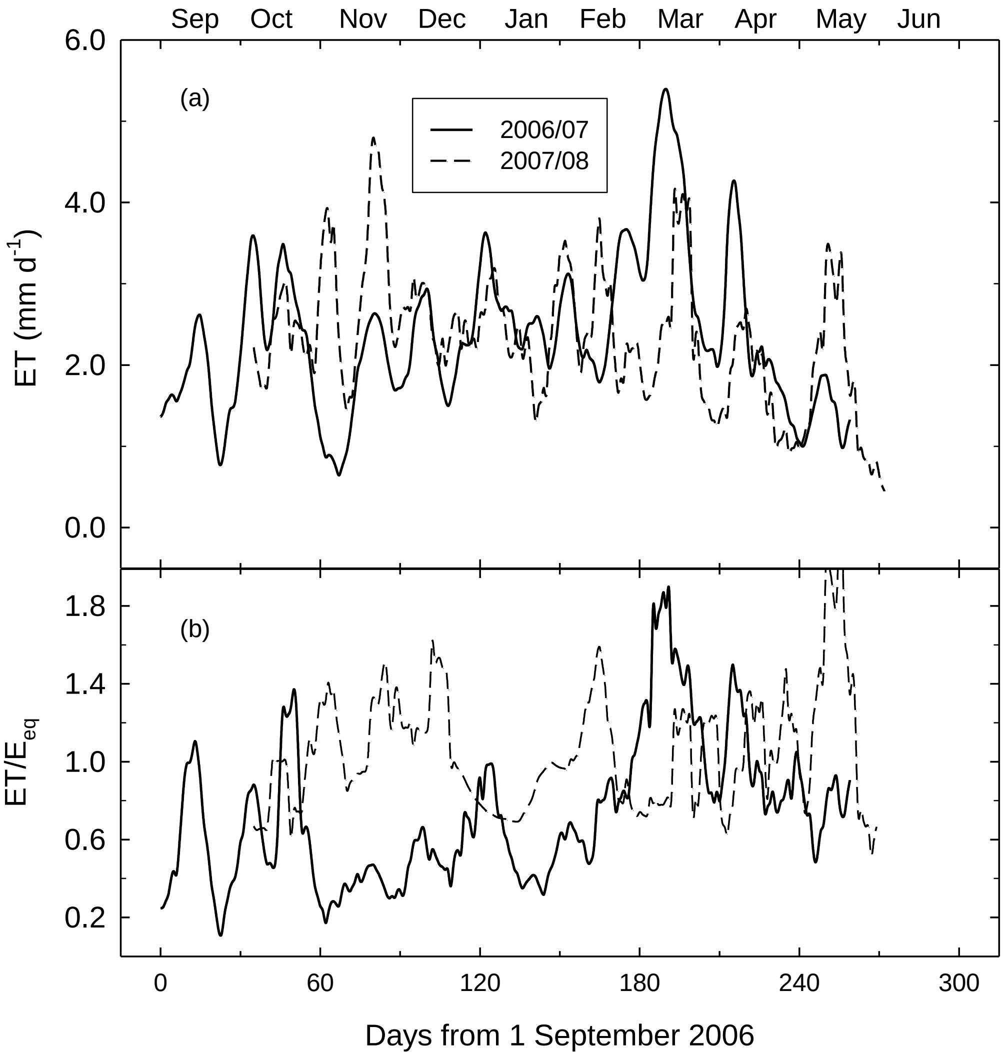

Fig. 6. Seven-day running averages for daily values for water use variables from a plantation during the growing seasons of 2006/2007 and 2007/2008 at Castlereagh, Australia: (a) evapotranspiration (ET), and (b) normalised evapotranspiration. The dotted line in (b) represents ratio of one.