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Latent heat fluxes during two contrasting years from a juvenile plantation established over a waste disposal landscape

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SUMMARY

Revegetation to restore hydrological function to highly disturbed landscapes used for waste disposal or mining is often constrained by the initial low rates of water-use during the early phases of the developing vegetation. This problem is especially pronounced for revegetation that relies on trees due to their prolonged lead-time to achieve canopy closure. Initial low rates of water-use can however be overcome if a groundcover of quick-growing herbaceous species is planted first. To demonstrate the significance of groundcover in the early phase of revegetation, we undertook an energy balance analysis using the Bowen ratio technique for a juvenile plantation growing over a heavy groundcover of herbaceous species on a waste disposal site in 2006/2007 and 2007/2008. Latent heat flux (λE) from the landscape (trees plus groundcover and soil) fluctuated widely between 0.5 and 22 MJ m^{-2} d^{-1} and accounted for between 60% and 90% of available energy at the site; this percentage exceeded 100% during periods with significant advection. The latent heat emanating from the tree canopy (λE_c), derived from sapflow measurements in the trees, accounted for only between 4% and 18% of daily λE with the balance arising from the groundcover that intercepted more than 90% of incident solar radiation. The λE_c was mostly smaller than the net radiation intercepted by the tree canopy (R_{nc}) with the excess energy expended by the canopy as sensible heat (H_c), which accounted for up to 18% of bulk sensible heat from the landscape. The λE expressed as ET was in excess (114%) of rainfall in the relatively dry first growing (September–May) season, when rainfall was only 87% of the long-term average. It was, however, smaller (80%) than rainfall during the second season, when the annual rainfall was close to the long-term average. We used these data to develop an empirical model for predicting λE from soil–water content and the prevailing evaporative demand.

1. Introduction

Water-use by young trees is generally constrained by the fact that their canopy is still developing and consequently intercept only small fractions of solar energy during the early years. This results in the transmission of the majority of incident solar radiation to the underlying understorey and/or bare soil. Where such vegetation is established primarily for restoring hydrological functions to landscapes, which have been highly disturbed due to waste disposal or mining, it is imperative to understand the relative contributions of the various evaporating surfaces to the bulk latent heat flux (λE). Such understanding is critical to developing improved land rehabilitation strategies with respect to identifying vegetation covers that are efficient in water-use and minimise deep drainage and hence risk of contaminating groundwater. Implementing partitioning of λE between the evaporating surfaces is often quite complicated. There are several techniques used to analyse the energy balance for individual component surfaces (tree canopy, groundcover and bare soil surface) in heterogeneous vegetation (Irvine et al., 1998; Kustasa and Norman, 1999; Scott et al., 2003).

The basic form of partitioning λE between component surfaces of the vegetation simply uses the fraction of incident radiant energy intercepted by the respective surfaces (Yunusa et al., 1995; Jahansooz et al., 2007; Zeggaf et al., 2008). This seemingly simple approach is, however, often inadequate where local advection of sensible heat enhances λE from a canopy (λE_c) that can exceed the energy absorbed. The patchy distribution of the projecting tree canopies over the more uniform understorey canopy creates aerodynamically rough surfaces; this often generate significant heat exchanges between the canopies of trees and that of the groundcover, including soil surface where present (Kustasa and Norman,

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1999). This is quite common when soil moisture is non-limiting and is accompanied with high levels of evaporative demand (McNaughton and Jarvis, 1983; Lindroth, 1985; Oke, 1987; Heilman et al., 1994; Stannard et al., 2004). Implementing an energy balance analysis for multiple surfaces is therefore often challenging and expensive.

Recent advances in remote sensing and spatial modelling, are proving to be useful tools in characterising energy dynamics above complex vegetation surfaces (Bartlett et al., 2003; Cleugh et al., 2007), and are increasingly employed in mapping latent heat fluxes from heterogeneous land surfaces (Bastiaanssen, 2000; Huete et al., 2006; Miglietta et al., 2009). The majority of these models are however, also limited in partitioning λE between under- and overstorey components with high precision. They also rarely include consideration of soil fluxes when there is a significant canopy cover. Thus there are considerable uncertainties over the precision with which many of the current models characterise the complex interactions inherent in the absorption of energy and it's partitioning between λE and sensible heat by the various surfaces (Campbell, 2003).

Increasingly sapflow techniques have facilitated direct quantification of λE_c especially for woody species (Eamus et al., 2006), and are gaining acceptance for quantifying λE from the woody component of the vegetation (Heilman et al., 1994; Yunusa et al., 2004; Mitchell et al., 2009). This technique is particularly apt for determining λE_c in juvenile plantations in which the tree canopy constitutes a small and discrete fraction of the total vegetation cover. In such landscapes, groundcovers and, where present, bare-ground, can constitute a major source of latent heat flux (Black and Kelliher, 1989; Yunusa et al., 1995; Irvine et al., 1998). Differences in stomatal physiology between trees and the groundcover (commonly herbaceous) species can also exert an influence on the λE from the two vegetation components.

There is a dearth of information on the energy balance of juvenile plantations of non-horticultural trees, and especially on those established as part of land rehabilitation strategies on landscapes used for waste disposal or mining. The capacity of the young trees to minimise saturation of the vadose zone, and subsequent deep drainage, is limited by their patchy canopy cover. In such cases the groundcover can easily assume the major source of λE_c. Despite the wide spread existence of such landscapes around the world, direct quantification of the various components of their vadose-zone hydrology is few; this is due to concern over disturbing the entombed waste. Techniques such as micrometeorology that cause minimum disruption offer the most practical alternative. Our aim in the current study was to undertake an energy balance analysis to assess the efficacy of a young plantation of mixed native tree species and its associated groundcover in dissipating rainfall through latent heat flux on a waste disposal site.

2. Materials and methods

2.1. The plantation

This study was undertaken on an 8 ha waste storage site at Castlereagh (33°39′41″S, 150°46′57″E), approximately 65 km northwest of Sydney, Australia. It is the same plantation used in a recent water-balance study (Yunusa et al., 2010b). The region has a mild temperate climate with cool winters (June–August) when mean daily temperature drops to 12.4 °C, and warm summers (December–February) with mean daily temperature of 23 °C. It receives about 810 mm rainfall annually that is distributed all year round with a monthly average of 58 mm, but with a slight peak that can exceed 90 mm from late spring through summer (November–March). The period September–April is the main growing season, when vegetation growth and water-use are highest. The original soil at the site had a duplex structure consisting of 0.7 m thick topsoil of loamy sand and a deep (>10 m) sub-soil of heavy clay. The topsoil has a mean bulk density of 1.3 Mg m^{-3} and the sub-soil 1.65 Mg m^{-3}. The dominant texture of the topsoil (<1.5 m) at the site could be broadly described as a silt loam. The site had a battery of storage cells (20 m length, 5 m wide and 5 m deep) spaced 2 m apart, which once filled with waste, were capped with the excavated soil that was returned in the reverse sequence of their removal. This provided a 2-m cap over the storage cells, but there were instances when it was necessary to augment the cap with additional soil sourced from elsewhere due to subsidence.

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 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 1050 stems per hectare and were irrigated as required during the first year, but left unirrigated thereafter. About the same time, a groundcover of perennial grasses and pasture legumes consisting of *Cynodon dactylon* (couch), *Axonopus affinis* (carpet grass), *Paspalum dilatatum* (paspalum), *Pennisetum clandestinum* (kikuyu grass), and *Trifolium repens* (white clover) was planted between the rows of woody species. These herbaceous species established quickly and were only slashed occasionally; they therefore provided an almost complete groundcover during the study period. The plantation was rain-fed during the time of this study. The trees had an average height of 0.57 m and diameter of 35 mm in spring of 2006 and grew to a mean height of 0.94 m in October 2007 and to 1.3 m in March 2008 (Table 1).

2.2. Measurements

2.2.1. Plants growth variables

Tree height was measured with a tape and stem diameter 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 Quickbird® image of the plantation. This involved importing the satellite image into IDRISI (Version I32.11, Clark Labs, Clark University, Worcester, Massachusetts), where it was separated into the three spectral bands (RGB) that were used to create a signature file and finally a classification image of the plantation. The new classified image was analysed using the HISTOGRAM routine in IDRISI to produce a frequency table of the numbers of pixels from which the young trees and groundcover were identified. These were then used to estimate the leaf area

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

Variables[a]	October 2007	March 2008
Planted stem density (trees ha^{-1})	1050	*na*
Actual plant density (trees ha^{-1})	*na*	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 for trees (LAI)[b]	0.74 ± 0.05	0.90 ± 0.071
Composite leaf area index (LAI)	3.1	4.0
Calculated canopy cover for tree canopy (i)	0.05	0.12
Canopy cover for whole plantation	0.90	0.95

[a] *na*, data not available.
[b] Estimates for the trees only, excluding groundcover.

indices and the fraction of light intercepted. Further details and verification of this technology have been reported elsewhere (Palmer et al., 2008).

2.2.2. Energy balance

This was undertaken over two growing seasons between September 2006 and end of May 2007, and between October 2007 and May 2008. Direct measurements were undertaken to solve the energy balance equation:

$$R_n - \lambda E - H - G = 0 \quad (1)$$

where R_n is net radiation, λE latent heat flux due to evapotranspiration, H sensible heat flux or energy transfer via conduction from a surface to heat the surrounding air, and G ground heat flux at the soil surface. Both R_n and G were measured directly. All the quantities were expressed in energy units (MJ m^{-2}) in this paper, except where stated otherwise. The λE was calculated from measurements of the Bowen ratio (β), described below, while H was obtained as the residual (Spronken-Smith et al., 2000). Measurements were made using a custom-made Bowen Ratio Energy Balance (BREB) unit (ICT International Ltd., Armidale, Australia). The unit was installed in an approximately 8 ha plantation in a position that produced a distance of at least 200 m from the edge of the plantation in all directions, except to the west where it was limited to 80 m due to the presence of a 6 m wide track. The BREB unit monitored R_n at 4 m height with a net radiometer (CN1-R, Middleton/McVan Instruments, Melbourne, Australia), and G with two heat flux plates (CN3, Middleton/McVan Instruments, Melbourne, Australia) installed at 50 and 100 mm depths into the soil. These are in addition to measurements at 1.5 and 2.5 m heights of vapour pressure and temperature of the air. The vapour pressure was monitored using wet- and dry-bulb thermometers in the first year and humidity-temperature sensors (HMP45A, Vaisala, Finland) in the second year. The two temperature-humidity sensors were compared against each other in the laboratory and at the same height in the field. The difference in temperature between the two sensors was about 0.001% and in humidity about 0.005%, and so the data logged in the field were adjusted accordingly (Tattari et al., 1995; Yunusa et al., 2004). On the rare occasions when R_n data were not available or unreliable due to sensor failure, it was estimated from global radiation (R_s) using an empirical equation reported by Yunusa et al. (2004):

$$R_n = 0.683R_s - 36.4\ \mathrm{Wm^{-2}} \quad (2)$$

$$G = 0.112R_s - 26.3\ \mathrm{Wm^{-2}} \quad (3)$$

Data from the two soil heat plates were used to calculate G for the soil surface as described by Snyder and Paw (2001):

$$G = G_{100} + \Delta S \quad (4)$$

in which G_{100} is flux measured with the plate at 100 mm depth, and ΔS is the difference in the readings between the two heat plates.

2.2.3. The Bowen ratio technique and its assumptions

The Bowen ratio technique was used to determine λE as:

$$\lambda E = \frac{R_n - G}{1 + \beta} \quad (5)$$

where β is the Bowen ratio (Stannard et al., 2004):

$$\beta = \gamma\left(\frac{\Delta T}{\Delta e}\right) \quad (6)$$

where γ is the psychrometric constant (0.066 kPa °C^{-1}), ΔT and Δe are the gradients in temperature and vapour pressure gradient (kPa) of the air between the two heights of measurements. Eq. (6) assumes that: (i) diffusion of water vapour and heat are equal and vertical, and (ii) horizontal gradients in the two variables are considered small enough to be ignored, i.e. temperature and vapour gradients are within the boundary of equilibrium of air flow (Oke, 1987; Stannard et al., 2004).

The first assumption is met when the height of the lower sensor is at least three times the roughness height (z_o) of the canopy, taken as 0.13 the mean canopy height (Monteith and Unsworth, 1990); the second is satisfied when the ratio of fetch to (upper) instrument height is at least 100 (Rosenberg et al., 1983). Taking average height attained by the trees during the study of 1.2 m produced z_o of 0.16 m, thereby fulfilling the first assumption. The second assumption was also fulfilled with the fetch:height ratio > 100:1, except in the western direction where it was 30:1. This minimum 30:1 ratio was similar to that which accounted for more than 80% of the flux from an 11 m tall Sitka spruce plantation (Irvine et al., 1998), and was at least 50% larger than the minimum of 20:1 recommended for a range of vegetation types including 1.2 m grapevines (Heilman et al., 1989). The dominant wind direction was mostly south-easterly in winter and north-westerly during warm periods. To further assess errors due to possible inadequacy of our fetch we undertook footprint analysis to calculate the degree of equilibrium of latent heat flux (λE_q) with our fetch lengths using the footprint analysis (Stannard, 1996):

$$\%\lambda E_q = 100^{-zU/xku} \quad (7)$$

where z is height of anemometer above displacement height (m), U assumed constant wind speed (m s^{-1}) approximated as mean of minimum wind speed recorded, x distance upwind from sensors, k von Karman's constant (0.4), and u variable wind speed (m s^{-1}). The displacement height was 0.67 the mean canopy height (Monteith and Unsworth, 1990).

We also calculated the equilibrium latent heat flux (λE_{eq}) as given by McNaughton (1976):

$$\lambda E_{eq} = \frac{s(R_n - G)}{s + \gamma} \quad (8)$$

where s is the slope of saturation vapour pressure–temperature curve (kPa °C^{-1}). Eq. (8) approximates the upper limit for λE from a saturated surface in the absence of advection, such that aerodynamic resistance is negligible relative to the canopy resistance (Cleugh et al., 2007; Yunusa et al., 2008). Thus, λE would always be $\leqslant \lambda E_{eq}$, except under significant local advection (Li and Yu, 2007).

2.2.4. Canopy energy balance

Energy balance for the site was implemented as:

$$R_{nc} - \lambda E_c - H_c = 0 \quad (9)$$

in which the terms represent the energy absorbed (R_{nc}), lost through transpiration (λE_c), and gained from or lost to the immediate surrounds by the canopy (canopy sensible heat flux, H_c). Thus, these terms are similar to those in Eq. (1). The ground heat flux is omitted in Eq. (9), because it is negligible for sites extensively covered by vegetation (Monteith and Unsworth, 1990). The R_{nc} was approximated by scaling R_n with fractional groundcover by the tree canopy (i), described in Section 2.2.1, as (Yunusa et al., 2004):

$$R_{nc} = iR_n \quad (10)$$

The λE_c was calculated from transpiration obtained from sapflow measured with the stem heat balance technique (Sakuratani, 1981; Baker and van Bavel, 1987). Sapflow was monitored over a 2 month period (October–November) in 2006 in six trees chosen to cover the size distribution (13–19 mm diameter). Each tree was supplied with a Dynagage® heater-thermistor unit (Dynamax, Inc., Houston, USA) at a height of at least 0.3 m from the ground surface as described by Steinberg et al. (1990). Each unit was covered with an insulating collar made of white, reflective foam to minimise thermal perturbations caused by the ambient conditions. The sensors were scanned every 30 s, but averaged and logged at 30 min intervals. The units were readjusted every fortnight to allow for growth. Latent heat flux from the canopy (λE_c, MJ m^{-2}) was obtained as:

$$\lambda E_c = 2.45(S_v/A) \tag{11}$$

in which S_v was sapflow per tree (kg) and λ the latent heat of vaporisation of water (2.45 MJ kg^{-1}), E_c was depth of water transpired per metre squared (mm), and A was land area allotted to each tree (m^2) estimated using a tessellation technique (Hatton et al., 1990). The A was 9.52 m^2 since the trees were uniformly spaced. Validation of this procedure for scaling transpiration from individual trees to stand levels has been reported recently (Zeppel et al., 2006; Yunusa et al., 2008).

2.2.5. Soil water content

Soil moisture was measured using three Frequency Domain Reflectometry (FDR) sensors (Theta probes, ML2x-UM-1.21, Delta-T Devices, UK) installed at depths of 0.1, 0.3 and 0.6 m. The readings from these sensors were scanned and data stored by the same logger used for the energy balance sensors.

2.2.6. 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 200 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, 1972).

3. Results and discussion

3.1. Site meteorology and plantation characteristics

Both years were characterised by warm and mostly dry conditions, but the main growing period (September–April) was cooler and wetter in 2007/2008 than in the previous year (Fig. 1). 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 °C, D of 0.36 kPa and E_o of 0.6 mm. Total rainfall for the September–May period was 517 mm in 2006/2007 and was 685 mm for October–May period in 2007/2008; these were 5% lower and 34% larger than the long-term (1900–2006) means for the same two periods, respectively. Much of the rainfall in 2007/2008 came in heavy storms between November and February when there were 7 days that each experienced more than 20 mm of rain. The top 0.6 m of the soil profile was relatively moist in both years with θ remaining above 20% for much of the time and reaching maxima of >35% in rainy periods. During the study period, the LAI for the trees increased from 0.40 in 2006 to 1.4 in early 2008. In the same period, tree height and diameter increased by 26% and 30%, respectively, while the fraction of light it intercepted rose to 12% from just 5% (Table 1). The total fraction of light intercepted by the whole plantation rarely fell below 85% and was mostly above 90%.

3.2. Quality check of the Bowen ratio data

Determination of latent heat flux from a juvenile plantation with patchy tree canopies does not satisfy the requirement for a large and uniform canopy cover to ensure one dimensional flow of energy (Oke, 1987; Stannard et al., 2004), but the heavy ground cover, which exposed not more than 10% of the bare soil even at the early stages of the study (Table 1), ensured a continuous canopy cover on the site. We however excluded those data for which $\%E_{eq}$ was <75% from a fetch of 80 m; this occurred almost entirely when β was small −0.2 to +0.2, mostly around sunrise and sunset. We also excluded data when β was negative; this occurred mostly around sunrise and at other times at night and constituted about 8% of the data collected during the two seasons. All the excluded data amounted to 11% of the total dataset for the 2 years. The results presented here, therefore, are restricted to daylight hours and when $\%E_{eq}$ was at least 75%. We therefore minimised major sources of potential errors. These checks improved the quality of our data with the result that the annual ET values (presented below) were consistent with those obtained using the water-balance technique (Yunusa et al., 2010b). The cumulative ET obtained with the two techniques during the 2 years were related thus: $ET_{water\ balance} = 0.93(ET_{Bowen\ ratio}) + 59.5, r^2 = 0.99$.

3.3. Latent heat flux from the plantation

Daily λE ranged between 0.45 MJ m^{-2} during the cool days of autumn in May 2006 and 21.7 MJ m^{-2} in the warm sunny days in spring following rainfall in October 2007. In order to enhance clarity and brevity, detailed data for the energy balance components were averaged for the same 3-day periods in 2006/2007 and 2007/2008 that are indicated with 'P' in Fig. 1a. These 3-day periods were in late spring (21–23 November), late summer (26–28 February) and early autumn (29–31 March) that experienced contrasting weather and soil–water conditions. In daylight hours of spring and summer λE was almost at par with R_n, the only exception was autumn in 2006/2007 (Fig. 2). The 3-day period in autumn of 2006/2007 was particularly windy, with an average wind run of 216 km d^{-1}. This coupled with the wet soil from the almost daily rainfall during the preceding week, and indeed March 2007, resulted in higher λE relative to R_n due to micro-advection of H. This is consistent with several studies that reported local advection of H produced flux patterns under wet conditions similar to those we present in Fig. 2c (Malek, 1992; Spronken-Smith et al., 2000). Malek (1992) reported that micro-advection of sensible heat sustained λE even during the night, accounting for 16% of the whole day's total ET, over a field of lucerne (*Medicago sativa*).

Differences in the partitioning of available energy between the two growing seasons were largely attributed to a better distribution of rainfall in 2007/2008 than in the previous year. The plants were highly sensitive to soil–water availability, such that the 2% fall in θ between summer of 2006/2007 and spring of the second year, resulted in an almost 30% decline in the $\lambda E/(R_n - G)$ term for spring, despite the two periods experiencing similar micrometeorological conditions (Table 2). Water-use by the plant species declined almost linearly with θ once the latter fell below 20% (Fig. 3). An asymptote of 2.45 for the $\lambda E/\lambda E_{eq}$ approximates the upper limit for the enhancement of λE through advection during the study. A two-and-half fold increase in λE due to advection is within the range of up to 3-fold observed over an irrigated wheat field (Li and Yu, 2007).

According to McNaughton and Jarvis (1983), advection can be inferred whenever H is negative, and is most likely when canopy conductance and evaporative demand are high (Oke, 1987; Yunusa et al., 2004). In the present study advection enhanced λE even under relatively mild micrometeorological conditions when the soil was sufficiently wet (Table 2). With declining availability of soil water, such as the three periods in 2007/2008, dissipation of available energy was increasingly through H rather than λE with the former constituting between 30% and 55% of the available energy. However, the sum of H and λE was consistent with the available

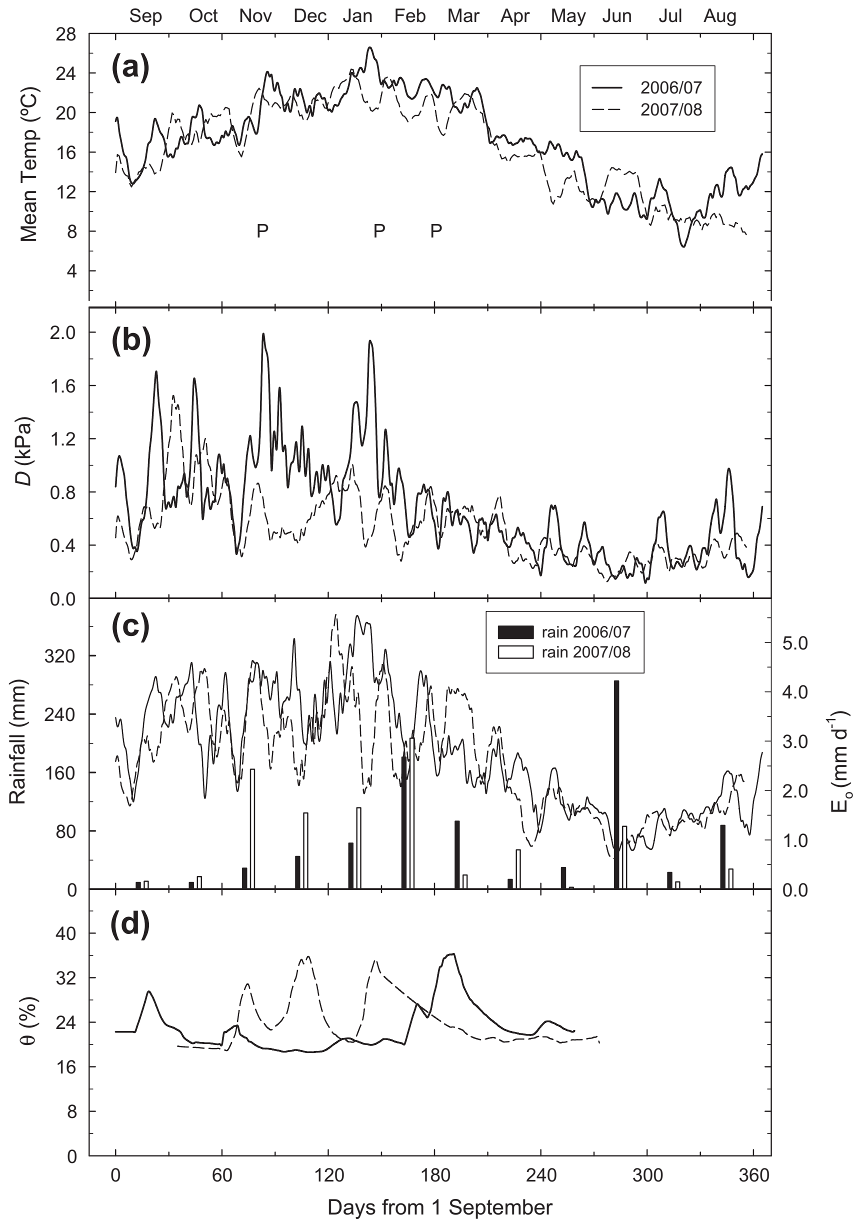

Fig. 1. Seven-day running averages for key weather and soil–water variables in 2006/2007 and 2007/2008 at Castlereagh: (a) daily means for temperature, (b) vapour pressure deficit (D), (c) rainfall and daily means for potential evaparotranspiration (E_o), and (d) volumetric water content (θ) for the top 0.6 m the of soil profile for the active growing period. The 3-day periods when detailed energy balance analyses were undertaken are marked in (a) as P.

energy ($R_n - G$) in spring and summer periods in 2006/2007 and all of the three periods in 2007/2008 that experienced no advection (Fig. 1).

3.4. Latent heat flux from the tree canopy

We present diurnal data for tree canopy latent heat flux derived from sapflow for a 20-day period that experienced variable volumetric soil–water content (θ and micrometeorological conditions. The hourly λE_c attained peak of 0.018 MJ m^{-2} on most days and also showed wide fluctuation in response to those in incident radiation on cloudy days (Fig. 4). By expressing λE_c as a ratio of net radiation intercepted by the tree canopy (R_{nc}), it became apparent that energy used in transpiration was smaller than was available to the canopy during much of the daylight hours; the exception being early in the morning and late afternoon when the ratio could exceed 1.6. The λE_c was driven by the advection of heat from the surrounding warming air to the canopy, which was yet to receive any incident radiation, during these early hours of the day. The low $\lambda E_c/R_{nc}$ was despite the mean θ in the topsoil exceeding 20% during this period. Low $\lambda E_c/R_{nc}$ is a common adaptive feature amongst most terrestrial plant species, especially those that evolved in water-limited environments. Instances of λE being smaller than intercepted energy are commonly implied by several studies that showed water-use to be limited even when soil–water is readily available (Cleugh et al., 2007). Furthermore the relative immaturity of the canopy suggests that root depth is likely to be relatively shallow thereby constraining water-use by the trees; no roots were found beyond 1.6 m depth under the trees in September 2009, 1 year after completion of the current study (Yunusa, unpublished data). Hence, the apparent inability of the young trees to fully utilise intercepted energy for λE_c was due partly to these native species being inherently adapted to prolonged drought and partly by the shallow rooting. These evergreen woody species

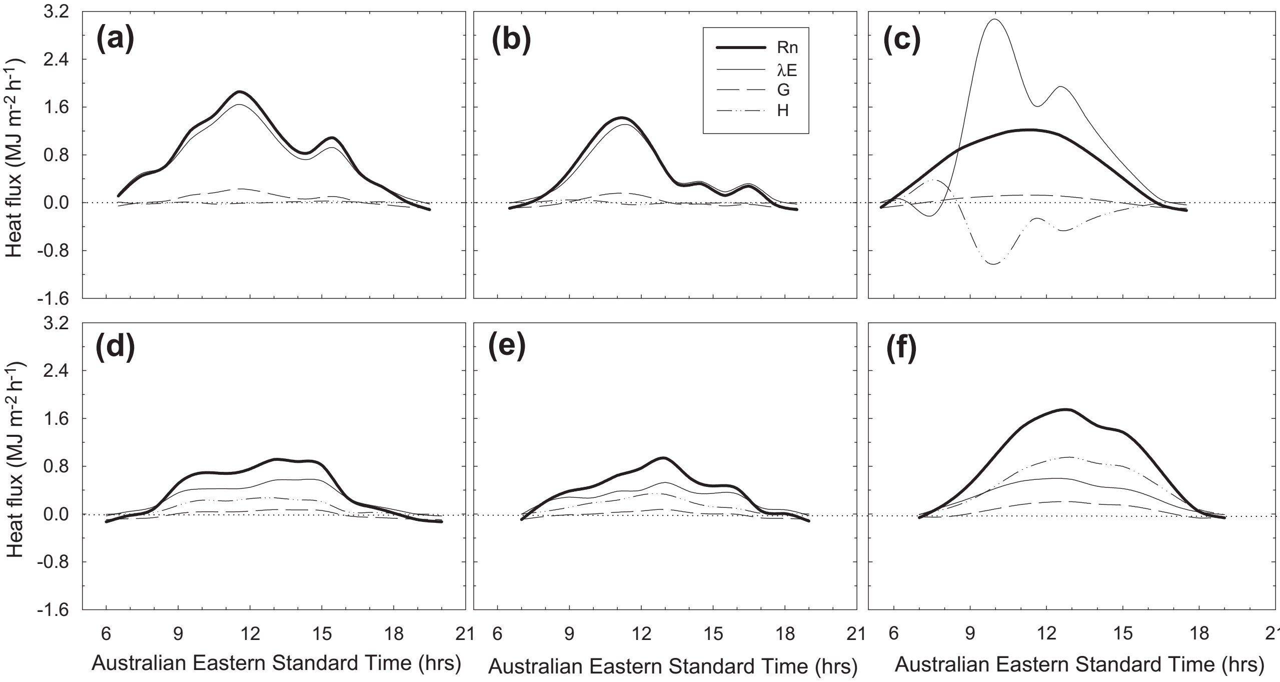

Fig. 2. Daytime trends in the energy balance components over a juvenile plantation during three contrasting 3-day periods in spring (a and d), summer (b and e) and autumn (c and f) in 2006/2007 (a–c) and 2007/2008 (d–f) at Castlereagh, Australia. The dotted lines represent zero value.

Table 2
Daytime mean values for the components of energy balance, 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})	$\lambda E/(R_n - G)$	Mean θ (%)	Mean soil temp (°C)	Mean air temp (°C)	Mean D (kPa)	Mean R_s (MJ m^{-2})
2006/2007	Spring	10.14	10.00	0.10	0.99	24.0	30.2	23.1	3.08	18.6
	Summer	5.57	5.50	0.07	0.99	34.4	25.0	17.1	0.64	10.6
	Autumn	7.41	12.57	−5.16	1.70	25.3	21.2	17.0	0.90	13.8
2007/2008	Spring	5.52	3.98	1.68	0.70	22.6	23.2	21.8	0.68	10.6
	Summer	4.76	3.28	1.67	0.66	22.2	*na*	20.8	0.54	9.3
	Autumn	10.70	3.89	5.96	0.40	20.9	19.4	20.3	1.09	17.7

na, data not available.

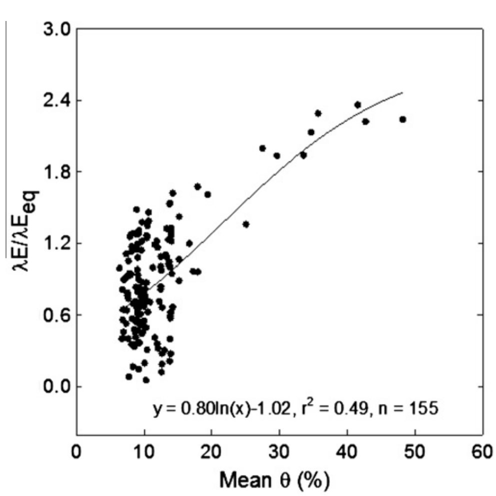

Fig. 3. Relationship between relative λE ($\lambda E/\lambda E_{eq}$) and mean volumetric water content of the top 0.3 m of soil for a juvenile plantation during the growing season of 2006/2007 at Castlereagh, Australia.

rely heavily on stomatal conductance to control transpiration in response to changes in soil–water availability such that E_c/E_o tends to commonly fluctuate between 0.2 and 0.3 most of the year even for pre-existing woodlands in southern Australia (Zeppel et al., 2006; Yunusa et al., 2010a).

A detailed analysis of canopy energy balance for the tree canopy is presented for three consecutive days when θ was relatively high (September) or relatively low (October) in 2006. In September λE_c always commenced early, even before receipt of R_{nc}, with the energy derived 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. With relatively low θ in October, commencement of λE_c was delayed by at least an hour to around 0700 h, while λE_c did not show any well-defined peak, during either of the two periods. Typically less than half of R_{nc} was partitioned through λE_c with the balance lost as H_c (Table 3). R_{nc} was approximated (Eq. (8)) and not measured directly, and should be viewed with caution; the mean value of 0.057 for $\lambda E_c/\lambda E$ for the 6 days (Table 3) showed that the 5% estimate for R_{nc} in the first year was precise enough for this analysis. These young trees are therefore minor contributors to latent heat flux from the plantation. Their daily transpiration was below 0.3 mm when their LAI was less than 0.5. Measurements on

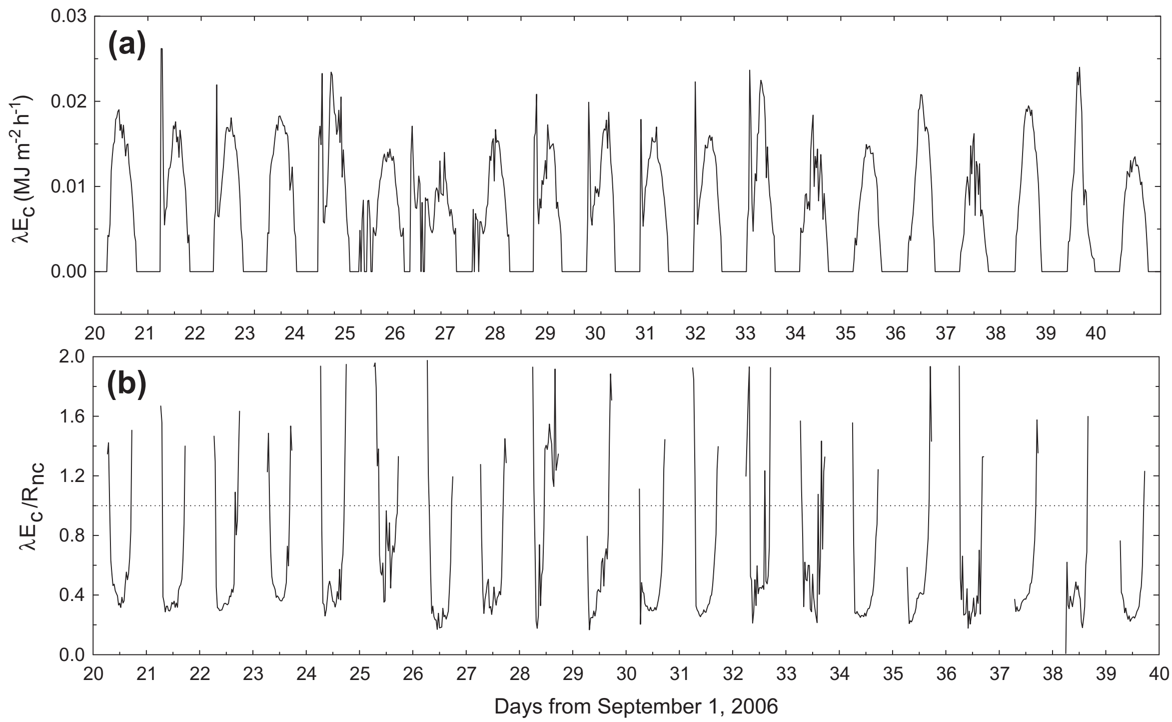

Fig. 4. Diurnal pattern for the water-use through the canopy of the young trees at Castlereagh, Australia: (a) diurnal rates of latent heat flux from the canopy (λE_c), and (b) ratio of λE_c to intercepted available energy (R_{nc}). The dashed line in (b) represents the ratio 1:1.

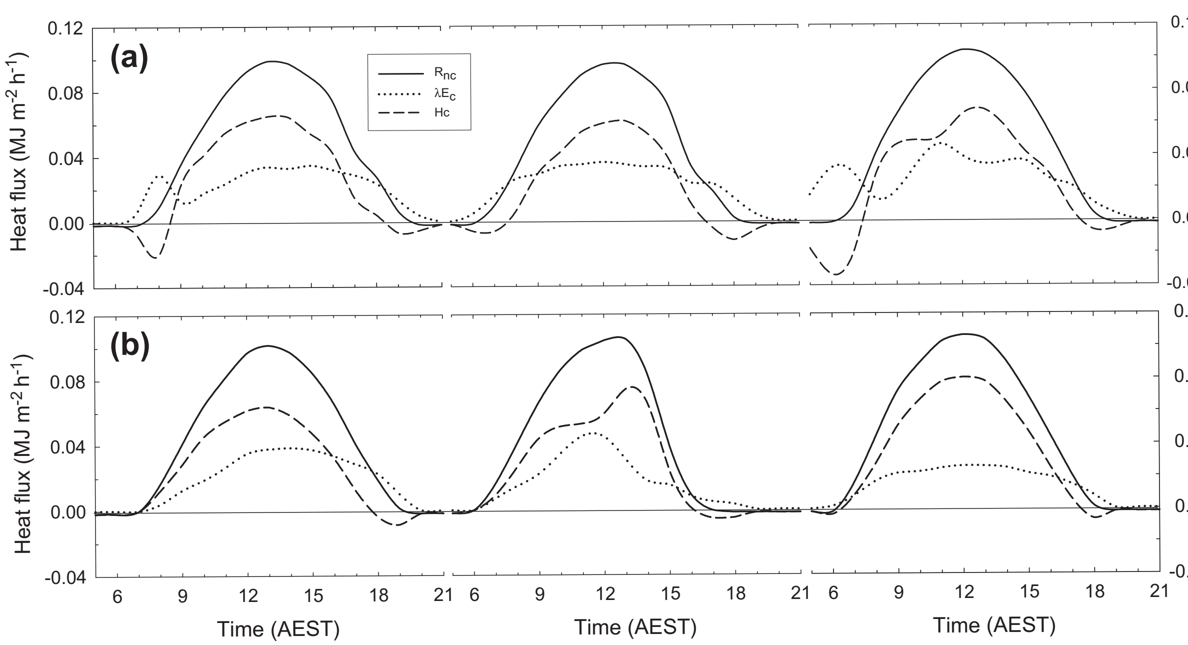

Fig. 5. Daytime trends in the energy balance components for the juvenile tree canopy during two contrasting 3-day periods during the growing season of 2006 at Castlereagh, Australia: (a) 22–24 September, and (b) 14–16 October.

this plantation in late 2008, found transpiration by the trees averaged just 0.7 mm d^{-1}, or 31% of total ET for the plantation (Yunusa et al., 2010b). This daily rate of transpiration was only 15% of what is attainable from a mature eucalyptus forests (4.5 mm) having a leaf area index >3.0 in the southern parts of Australia (Dunin and Aston, 1984; Hookey et al., 1987).

The contribution of the bare soil surface to the λE was considered to be negligible due to the heavy groundcover. The exposed soil surface constituted not more than 10% of the plantation area, and this was halved by the start of the second year (Table 1). This, along with the persistent drought especially in 2006/2007 (Fig. 1), meant that overwhelming majority of λE ($\geqslant$90%, Table 3) emanated from the herbaceous groundcover canopy.

3.5. Seasonal water-use

Mean daily λE was expressed as ET in mm/d for the whole two seasons. The missing data due to equipment failure, and also for

Table 3
Daytime values for the energy balance components of the tree canopy: 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 (°C)	Mean air temp (°C)	Mean D (kPa)
22 September	0.69	0.32	0.36	0.46	0.08	0.05	26.1	20.2	21.8	2.01
23 September	0.65	0.36	0.29	0.55	0.04	0.18	24.7	23.0	21.0	1.90
24 September	0.74	0.36	0.33	0.49	0.04	0.09	24.0	23.0	14.9	1.02
7 October	0.69	0.31	0.38	0.45	0.05	0.18	21.7	27.4	18.9	0.95
8 October	0.62	0.25	0.38	0.40	0.10	0.07	20.5	26.6	17.6	0.88
9 October	0.74	0.24	0.50	0.32	0.03	−25	18.8	26.3	14.5	0.81

rainy days when the Bowen ratio technique is unreliable, were approximated using the following equation from Fig. 3:

$$ET = \frac{E_{eq}}{\lambda}[0.80\ln(\theta) - 1.02] \quad (12)$$

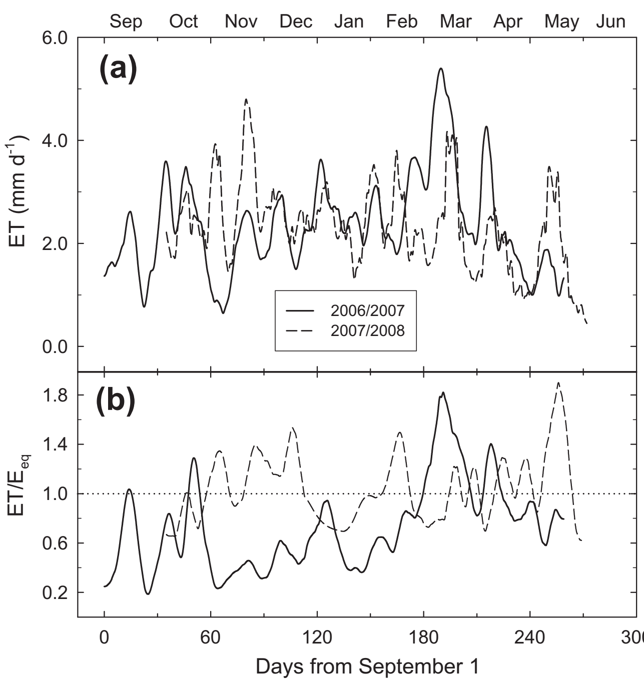

Fig. 6. Seven-day running averages for daily values for water-use variables from a juvenile plantation in 2006/2007 and 2007/2008 at Castlereagh, Australia: (a) evapotranspiration (ET), and (b) normalised evapotranspiration. The dotted line in (b) represents the ratio 1:1.

in which θ is the mean volumetric water content (%) for the top 0.3 m of the soil. Mean daily ET varied between 0.5 and 5.5 mm d^{-1} (Fig. 6). The ET was particularly high in wet warm periods when soil moisture content was high such as in the summer of 2006/2007 and early spring of the 2007/2008 year. These periods also coincided with high values for relative ET (ET/E_{eq}), which occasionally exceeded unity suggesting a significant contribution to latent energy through local advection of sensible heat. For most of the times, ET was approximately 3.0 mm d^{-1}. The corresponding ET/E_{eq} averaged 0.6, and although it occasionally exceeded unity due to advection that could enhance ET by as much as 300% (Li and Yu, 2007). Total ET during the first growing season of study (September–May) exceeded rainfall by 11% suggesting that water-use was supported by soil moisture stored in the profile prior to the start of the study (Table 4). The plantation was mostly bare in the preceding 2 years and there was 91 mm of rainfall in the 3 months preceding the commencement of this study. In the second year, however, total ET was 20% less than rainfall; the year received above-average rainfall with several events occurring in the form of heavy storms (Fig. 1). In both years, approximated ET averaged 1.2 mm d^{-1} in winter (June–August) that experienced good rainfall. For instance, monthly rainfall for these 3 months averaged 88 mm during the 2 years compared with 40 mm for the E_o. Winter therefore is a period with high risk of generating drainage, which may also occur anytime there is a heavy downpour.

In the first year, the trees accounted for 15% of the total estimated ET. Although E_c was not measured in 2007/2008, but assuming that its fraction of ET increased in proportion to that of light intercepted by its canopy between the 2 years, a seasonal E_c of 199 mm was approximated for the second year (Table 4). The majority of ET (between 65% and 85%) was accounted for by the groundcover, similar to an average of 81% found with a water-balance approach, and was credited with preventing drainage from this site during these early years (Yunusa et al., 2010b).

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

Water-use variables[a]	Monitoring period		Annual estimates[b] (September–August)	
	2006/2007 (September–May)	2007/2008 (October–May)	2006/2007	2007/2008
Long-term average rainfall (1900–2006) (mm)[c]	545	510	810	
Total potential evapotranspiration (E_o, mm)	869	711	1004	864
Rainfall (mm)	517	685	870	796
Equilibrium evaporation (E_{eq}, mm)	642	565	758	686
Evapotranspiration (ET, mm)	589	531	675	652
Transpiration by trees (E_c, mm)[d]	85	199	102	*na*
Ratios:				
ET/rainfall	1.14	0.77	0.78	0.82
ET/E_{eq}	0.92	0.94	0.89	0.95
E_c/ET	0.14	0.38	0.15	*na*

[a] *na*, data not available.
[b] Estimates for ET and transpiration based on mean ET/E_{eq} or E_c/E_{eq} obtained from measurements during the respective years.
[c] Source: Bureau of Meteorology (http://www.bom.gov.au/climate/averages/tables/cw_067033.shtml).
[d] E_c for 2007/2008 based on scaling E_c/E_{eq} for the previous year by the change in fraction of light intercepted by the tree canopy.

4. Conclusions

The λE was the largest component of the surface energy balance in this juvenile plantation forest, although much of it emanated from the groundcover. The relatively high ET, therefore, was due in large part to the contribution from groundcover of herbaceous species. The woody species that constituted the upper canopy intercepted less than 5% of incident radiation, which along with their inherent conservative water-use resulted in λE_c being low. The λE_c was always smaller than the energy absorbed by the canopy with the excess energy released as sensible heat, and the tree canopy was thus a simultaneous source of λE and H. The rate of λE from the whole plantation declined almost linearly with soil–water when $\theta < 20\%$, but increased with energy supply when $\theta > 25\%$ and when advective enhancement of the process was common. These data thus prove the efficacy of this juvenile plantation, with an extensive groundcover, in dewatering a waste disposal site through transpiration. Although quality of the groundwater was not the primary objective of this paper, the lack of evidence for drainage suggested a minimal risk of groundwater contamination on this site. The roots of the young trees were still shallow during this study and it is therefore imperative to repeat these measurements, along with those of water in the deeper layers of the soil profile, as the trees grow older.

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References

Baker, J.M., van Bavel, C.H.M., 1987. Measurement of mass flow of water in the stems of herbaceous plants. Plant Cell and Environment 10, 777–782.
Bartlett, P.A., McCaughey, J.H., Lafleur, P.M., Verseghy, D.L., 2003. Modelling evapotranspiration at three boreal forest stands using the CLASS: tests of parameterizations for canopy conductance and soil evaporation. International Journal of Climatology 23, 427–451.
Bastiaanssen, W.G.M., 2000. SEBAL-based sensible and latent heat fluxes in the irrigated Gediz Basin, Turkey. Journal of Hydrology 229, 87–100.
Black, T.A., Kelliher, F.M., 1989. Processes controlling understorey evapotranspiration. Philosophical Transactions of the Royal Society London B324, 207–231.
Campbell, G.S., 2003. Modeling sensible and latent heat transport in crop and residue canopies. Agronomy Journal 95, 1388–1392.
Cleugh, H.A., Leuning, R., Mu, Q., Running, S.W., 2007. Regional evaporation estimates from flux tower and MODIS satellite data. Remote Sensing of Environment 106, 285–304.
Dunin, F.X., Aston, A.R., 1984. The development and proving of models of large scale evapotranspiration: an Australian study. Agricultural Water Management 8, 305–323.
Eamus D., Hatton T., Cook, P., Colvin, C., 2006. Ecohydrology: Vegetation Function, Water and Resource Management. CSIRO Press, Melbourne. 348 p.
Hatton, T.J., Catchpole, E.A., Vertessey, R.A., 1990. Integration of sapflow velocity to estimate plant water use. Tree Physiology 6, 201–209.
Heilman, J.L., Brittin, C.L., Neale, C.M.U., 1989. Fetch requirements of Bowen ratio measurements of latent and sensible heat fluxes. Agricultural and Forest Meteorology 44, 261–273.
Heilman, J.L., McInnes, K.J., Savage, M.J., Gesch, R.W., Lascano, R.J., 1994. Soil and canopy energy balances in a west Texas vineyard. Agricultural and Forest Meteorology 71, 99–114.
Hookey, G.R., Loh, I.C., Bartle, J.R., 1987. Water Use of Eucalypts above Saline Groundwater. Report No. WH 32, Water Authority of Western Australia, Perth. 39 p.
Huete, A.R., Didan, K., Shimabukuro, Y.E., Ratana, P., Saleska, S.R., Hutyra, L.R., Yang, W.Z., Nemani, R.R., Myneni, R., 2006. Amazon rainforests green-up with sunlight in dry season. Geophysical Research Letters 33, Article Number L06405.
Irvine, M.R., Gardiner, B.A., Morse, A.P., 1998. Energy partitioning influenced by tree spacing. Agroforestry Systems 39, 211–224.
Jahansooz, M.R., Yunusa, I.A.M., Coventry, D.R., Palmer, A.R., Eamus, D., 2007. Radiation- and water-use associated with growth and yields of wheat and chickpea in sole and mixed crops. European Journal of Agronomy 26, 275–282.
Kustasa, W.P., Norman, J.M., 1999. Evaluation of soil and vegetation heat flux predictions using a simple two-source model with radiometric temperatures for partial canopy cover. Agricultural and Forest Meteorology 94, 3–29.
Li, L., Yu, Q., 2007. Quantifying the effects of advection on canopy energy budgets and water use efficiency in an irrigated wheat field in North China Plain. Agricultural Water Management 89, 116–122.
Lindroth, A., 1985. Seasonal and diurnal variation of energy balance components in coniferous forests. Journal of Hydrology 82, 1–15.
Malek, E., 1992. Night-time evapotranspiration vs. daytime and 24 h evapotranspiration. Journal of Hydrology 138, 110–129.
McNaughton, K.G., 1976. Evaporation and advection. I. Evaporation from extensive homogeneous surfaces. Quarterly Journal of Royal Meteorological Society 25, 181–191.
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. Academic Press, New York, pp. 1–47.
Miglietta, F., Gioli, B., Brunet, Y., Hutjes, R.W.A., Matese, A., Sarrat, C., Zaldei, A., 2009. Sensible and latent heat flux from radiometric surface temperatures at the regional scale: methodology and evaluation. Biogeosciences 6, 1975–1986.
Mitchell, P.J., Veneklaas, E., Lamber, H., Burgess, S.O., 2009. Partitioning of evapotranspiration in a semi-arid eucalypt woodland in south-western Australia. Agricultural and Forest Meteorology 149, 25–37.
Monteith, J.L., Unsworth, M.H., 1990. Principles of Environmental Physics. Edward Arnold, London. 291pp.
Oke, T.R., 1987. Boundary Layer Climates, second ed., Rouledge, London. 435pp.
Palmer, A.R., Fuentes, S., Taylor, D., Macinnis-Ng, C., Zeppel, M., Yunusa, I., February, F., Eamus, D., 2008. The use of pre-dawn leaf water potential and MODIS LAI to explore seasonal trends in the phenology of Australian and southern African woodlands and savannas. Australian Journal of Botany 56, 557–563.
Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large scale parameters. Monthly Weather Review 100, 81–92.
Rosenberg, N.J., Blad, B.L., Verma, S.B., 1983. Microclimate: The biological Environment. Wiley, New York. 495 pp.
Sakuratani, T., 1981. A heat balance method for measuring water flux in the stem of intact plants. Journal of Agricultural Meteorology 37, 9–17.
Scott, R.L., Watts, C., Payan, J.G., Edwards, E., Goodrich, D.C., Williams, D., Shuttleworth, W.J., 2003. The understory and overstory partitioning of energy and water fluxes in an open canopy, semiarid woodland. Agricultural and Forest Meteorology 114, 127–139.
Snyder, R.L., Paw U, K.T., 2001. Soil Heat Flow and Temperature. <http://biomet.ucdavis.edu/biomet/SoilHeatFlow/SoilHF.htm> (accessed 02.05.10).
Spronken-Smith, R.A., Oke, T.R., Lowry, W.P., 2000. Advection and the surface energy balance across an irrigated urban park. International Journal of Climatology 20, 1033–1047.
Stannard, D.I., 1996. A theoretically based determination of Bowen-ratio fetch requirements. Boundary-Layer Meteorology 83, 375–406.
Stannard, D.I., Rosenberry, D.O., Winter, T.C., Parkhurst, R.S., 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., McFarland, M.J., 1990. Improved sapflow gauge for woody and herbaceous plants. Agronomy Journal 82, 851–854.
Tattari, S., Ikonen, J.P., Sucksdorff, Y., 1995. A comparison of evapotranspiration above a barley field based on quality tested Bowen ratio data and Deardoff modelling. Journal of Hydrology 170, 1–14.
Yunusa, I.A.M., Mead, D.J., Pollock, K.M., Lucas, R.J., 1995. Process studies in a *Pinus radiata* – pasture agroforestry systems in a subhumid temperate environment. I. Water use and light interception in the third year. Agroforestry Systems 32, 163–183.
Yunusa, I.A.M., Walker, R.R., Lu, P., 2004. Evapotranspiration components from energy balance, sap-flow and micro-lysimetry techniques for an irrigated vineyard in inland Australia. Agricultural and Forest Meteorology 127, 93–107.
Yunusa, I.A.M., Nuberg, I.K., Fuentes, S., Lu, P., Eamus, D., 2008. A simple field validation of daily transpiration derived from sapflow using a porometer and minimal meteorological data. Plant and Soil 305, 15–24.
Yunusa, I.A.M., Aumann, C., Rab, M.A., Merrick, N., Fisher, P.D., Eberbach, P.L., Eamus, D., 2010a. Topographical and seasonal trends in transpiration by two co-occurring Eucalyptus species during two contrasting years in a low rainfall environment. Agricultural and Forest Meteorology 150, 1234–1244.
Yunusa, I.A.M., Zeppel, M.J.B., Fuentes, S., Macinnis-Ng, C.M.O., Palmer, A.R., Eamus, D., 2010b. An assessment of the water budget for contrasting vegetation covers associated with waste management. Hydrological Processes 24, 1149–1158.
Zeggaf, A.T., Takeuchib, S., Dehghanisanijc, H., Anyojid, H., Yano, T., 2008. A Bowen ratio technique for partitioning energy fluxes between maize transpiration and soil surface evaporation. Agronomy Journal 100, 988–996.
Zeppel, M.J.B., Yunusa, I.A.M., 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.