Partitioning of turbulent flux reveals contrasting cooling potential for woody vegetation and grassland during heat waves

Running title: *Turbulent flux over grassland and woody vegetation covers*

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Abstract

We compared the capacity of woody versus grassy vegetation covers to buffer high temperatures during heat waves by partitioning turbulent heat between latent (λE) and sensible (H) fluxes, and quantifying advection using the Priestley-Taylor coefficient (α), for a16-year old grassland and an adjoining 6-year old plantation of mixed woody species. We found that because λE

dominated (>65%) the turbulent flux in the plantation, and was at least twice as large as on the grassland on which λE was a small percentage (<35%) of the turbulent flux during heat waves, the ambient temperature over the plantation was up to 5 ^{o}C lower in the afternoon, and averaged about 1.2 ^{o}C for the whole day, compared with the grassland. Both vegetation covers emitted significant amounts of H that was a source of advective energy when soil-water availability was limited, and also in winter when canopy was mostly inactive because of dormancy in the grassland and mutual shading in the plantation due to low solar angle; advection of additional energy from surrounding vegetation suppressed λE and reduced α to <1.0 in both vegetation covers in winter. Advection enhanced λE during periods of frequent rainfalls in summer with mean α rising to 2.6 in the grassland and 3.4 in the plantation. Consistently low λE but high H made the grassland a source rather than a sink for advective energy, while the plantation was the opposite. The broadleaved evergreen woody vegetation consistently maintained a larger λE than the grassland in this mid-latitude environment, contrary to the smaller λE observed over mostly coniferous forests at high (northern) latitudes (>35^{o}). Annual evapotranspiration from the grassland (384 mm) was only 46% that from the plantation. Woody vegetation covers dominated by broadleaved-species are therefore preferred for buffering extreme high temperatures during heat waves, and recommended for land rehabilitation in populated landscapes. We also developed functions to approximate α for conditions when soil-water availability is limiting.

Key words: advection; Bowen ratio; evapotranspiration; heat wave; land-use change; Priestley-Taylor coefficient; sensible heat

1.0 Introduction

Maintaining suitable vegetation types can provide relief from heat stress by buffering extreme temperatures during heat waves or periods of excessively hot weather. Although the World Meteorological Organisation defines heat waves as periods during which daily maximum temperature on five consecutive days exceed the normal (1961–1990) average by 5 ^{o}C (Frich *et al.*, 2002), individual countries adopt their own threshold. For southern coastal cities in Australian, heat wave is any “five consecutive days with maximum temperature at or above 35 °C or three consecutive days at or above 40 °C” (Nairn and Fawcett, 2013). The frequency and severity of heat waves have been increasing and projected to intensify with adverse impacts on ecosystems and community welfare. Heat waves have become more frequent with climate-change and associated with increasing mortalities in human (Tong *et al.*, 2010) and avian (McKechnie *et al.*, 2010) populations, and in forests that are correlated with amplified temperatures and atmospheric dryness across forested continents (Allen et al 2010;-Eamus et al. 2013). Heat waves also impose enormous demand on power supply for cooling, which can be significantly alleviated by planting trees to provide evaporative cooling (Sawka *et al.*, 2013).

The relative efficacy of woody vegetation compared with grassy vegetation covers in providing respite from high temperature stress during heat waves has lately been questioned (Teuling *et al.*, 2010). The severity of the impact of heat waves on ecosystems and human communities depends on how net radiant energy (R_n) receipt at the land surface is dissipated between the two forms of turbulent heat transfer: f latent (λE) and sensible (H) heat fluxes:

$$R_n = \lambda E + H + G + S \quad (1)$$

in which G is the ground heat flux and S is the heat tied up in the biological processes of photosynthesis and respiration and is generally considered to be negligible at daily time-scales. In terrestrial ecosystems the relative magnitude of either λE or H depends on the availability of soil-water and the type and condition of the vegetation cover. Hence, maintaining large λE relative to H requires access to extractable supply of soil water.

When soil-water is limiting turbulent flux tends to be biased towards H at the expense of λE, because of the hydraulic limitation along the soil-plant continuum (Prior and Eamus, 2000) and the high atmospheric demand for water. Therefore vegetation types that retain active canopies, coupled with deep and extensive root systems, generally have a greater capacity to sustain larger rates of λE, thereby dampening the severity of heat waves compared to vegetation types that have seasonal growth and shallow root systems (Moore, 1976). Annual evapotranspiration for woody vegetation can range from 15% to up to a factor of three larger than for grasslands in cool sub-temperate and temperate environments (Eugster and Cattin, 2007; Yunusa *et al.*, 2010b; Yunusa *et al.*, 2012), and by more than 60% in the tropics (Priante-Filho *et al.*, 2004; Waterloo *et al.*, 1999). A larger canopy cover and a deeper, more extensive root system allows woody vegetation to sustain larger λE compared to grasses in arid environments and during hot and dry periods (Yunusa *et al.*, 2012). Hence it is expected that advective enhancement of λE is limited over grasslands compared with woodlands, especially during heat waves.

The foregoing reasoning contradicts several recent studies that reported larger λE for grasslands than from forest vegetation covers, mostly at high (>35^o) latitudes (Baldocchi *et al.*, 2004; Rost and Mayer, 2006; Teuling *et al.*, 2010). An analysis of historical data coupled with more recent measurements in northern Europe by Teuling *et al.* (2010) found forests to have smaller λE, but larger *H*, than the grasslands despite the former having larger and deeper root systems. The authors argued that a strong stomatal control of transpiration in trees during unusually hot periods make forest conservative water-users. Rost and Mayer (2006) earlier reported λE to be 10% lower from Scotts pine (*Pinus sylvestris*) compared with nearby grassland. Both the woody and grassy vegetation in these studies had similar accessibility to soil-water supply such that differences in the soil-water was less than 10% between forests/woodlands and the grasses in the studies of Roberts *et al.* (2005) in the United Kingdom and that of Baldocchi *et al.* (2004) in the United States. As a result the woody vegetation generated more *H*, but lower λE, compared with the grassland during hot and dry periods when water-supply was limited (Baldocchi *et al.*, 2004; Teuling *et al.*, 2010). Also the differences in the leaf area indices between the grassland and the woody vegetation were often small, in some cases as little as 0.5 (Baldocchi *et al.*, 2004). Many of the forests and/or woodland in these studies were often dominated by, or contain a considerable proportion of, conifers. These are known for their high canopy resistance compared with broadleaved species (Wilson *et al.*, 2002) or grasslands (Kelliher *et al.*, 1993). Under these conditions therefore, the turbulent flux from grasslands would be dominated more by λE, and likely to benefit more from advection of additional energy than the conifer dominated woody vegetation. Contributions of advection on λE arising from transient and periodic changes in soil-water and meteorological dynamics can be analysed using evaporation coefficient (α) in the equation of Priestley and Taylor (1972).

Land-use change due to economic and/or social activities often results in significant degradation for which rehabilitation commonly involves revegetation to restore ecosystem and social functions (Eamus *et al.*, 2013; Gwenzi *et al.*, 2012). It is therefore important to consider the capacity of the vegetation in buffering extreme weather conditions to enhance community welfare and to also ensure that vegetation is able to perform the functions required, including dewatering of the soil profile, when choosing vegetation types for rehabilitation in urban and peri-urban environments. In this study we compared surface energy balance for a16-year old grassland and a 6-year old plantation of mixed native evergreen broadleaf woody species established over a rehabilitated waste storage site with shallow groundwater. Our objectives were to (1) apply the α to characterise advective impact on λE from the two vegetation covers, (2) explain how and when latent heat flux can be larger over the plantation than the grassland especially during heat waves, and (3) to close the annual water budget for the two vegetation covers.

2.0 Materials and methods

2.1 The site

This study was undertaken at the Waste Management Centre at Castlereagh (33° 39’ 41” S, 150° 46’ 57” E; 35 m asl) about 65 km north-west of Sydney’s Central Business District. The site covers approximately 357 hectares with the original soil classified as Chromosol, which is equivalent to Haplic Xerosol (FAO 1974). The soil has a duplex profile consisting of 0.7 m loamy sand topsoil over impermeable heavy clay referred to as Londonderry Clay, which in turn overlays conglomerate sandstone and shales. There are several groundwater systems that fluctuate in height, but the two main ones lay at about 3.0 m and the other about 17.0 m from the surface (Yunusa *et al.*, 2010b). Wastes were emplaced into cells (20 m x 5 m, and 5 m deep) constructed into the clay subsoil and spaced 2 m apart resulting in approximately 65 cells/ha. The cells were capped using the excavated soil that was returned in reverse order to provide a soil cap of 2 m over the cells. The reconstructed soil was then planted with either grassy or woody vegetation, and these have been described in detail earlier (Yunusa *et al.*, 2010b; 2012; Morales *et al.*, 2013).

The current study involved the grassland and juvenile plantation that were adjacent to each other but separated by a narrow dirt track of about 6 m (Figure 1). The grassland covered 12 ha and was established in 1994 with a mixture of *Cynodon dactylon* (couch grassland), *Axonopus affinis* (carpet grassland), *Paspalum dilatatum* (paspalum), *Pennisetum clandestinum* and *Trifolium repens* (white clover). The sward was often allowed to grow to heights of 0.8 –1.0 m before being mowed in spring (November) and late winter/early autumn (March/April). The plantation consisted of a 9 ha block established in autumn (April-May) 2004 with a mixture of native trees (mainly *Eucalyptus* spp, *Angophora* spp, *Casuarina glauca*, *Melaleuca linariifolia* and *Syncarpia glommulifera*) and shrubs (species of *Acacia*, *Callistemon*, *Grevillea*, *Hakea*, *Kunzea* and *Leptospermum*); these were planted in 5 m rows that were oriented in northeast – southwest direction. It had an average height of about 4.5 m at the start of the current study and grew to just over 5.0 m by mid-2010 when we concluded monitoring.

2.2 Surface energy balance

To quantify advective enhancement or suppression of λE we used the evaporation coefficient (α) in the Priestley-Taylor (1972) equation for determining reference evapotranspiration (E_o) where water supply is not limiting and/or enhanced by advection:

$$E_o = \left[\alpha \frac{s(R_n - G)}{s + \gamma} \right] / \lambda \qquad (2)$$

where s is the slope of saturation vapour pressure–temperature curve (kPa $^oC^{-1}$) and α is taken as 1.26 for saturated surfaces in which both aerodynamic and surface resistance are negligible (Priestley and Taylor 1972). When determining actual evapotranspiration on vegetated land surfaces the value for α is lower than the nominal 1.26 when the process is limited by soil-water availability, and is larger than the nominal value when the process is enhanced by advection (Agam *et al.*, 2010; Tabari and Talaee, 2011).

Partitioning of net radiation (R_n) between its components (eqn 1) was undertaken with Bowen Ratio Energy Balance (BREB) monitoring systems; one system was installed on each of the grassland and plantation sites and the two were separated by a distance of about 450 m (Figure 1). At each location R_n was measured at appropriate heights over the vegetation (see below), while G was measured with heat plates installed into the soil at 50 and 150 mm depths. Soil moisture content and temperature were also monitored at the same depths. The λE was calculated as follows:

$$\lambda E = \frac{R_n - G}{1 + \beta} \quad (3)$$

where β is calculated as:

$$\beta = \gamma\left(\frac{\Delta T}{\Delta e}\right) \quad (4)$$

in which γ is the psychrometric constant (0.066 kPa $^oC^{-1}$), while ΔT and Δe are gradients in temperature (^oC) and vapour pressure (kPa) between the two measurement heights over the respective vegetation covers.

The two measurement heights for T and e were 1.2 m and 1.6 m over the grass, and initially 5.0 and 6.0 m over the plantation but were later raised to 5.5 and 6.5 m due to tree growth. All the sensors and the masts were supplied together as a package (Campbell Scientific, Logan, USA). The remaining term (H) in eqn 1 was obtained as residual, assuming S = 0. The setup at both locations provided sufficient fetch: height ratio of at least 21:1 to the north of the BREB unit on the plantation and was more than the minimum of 20:1 recommended for a range of tall vegetation covers (Heilman *et al.*, 1989). Each pair of sensors over the two vegetation covers was mostly within the boundary layers above the respective canopies, which was taken as 0.13 times the canopy height (Monteith and Unsworth, 1990).

An automatic weather station was installed on the grassland to monitor ambient weather conditions comprising solar radiation (R_s), temperature, humidity, wind speed at 1.5 m height in addition to rainfall and soil-water content at 0.10 and 0.30 m depths. The evaporative demand for the site was calculated as E_o using eqn 2. Soil-water was also measured each month to a depth of six meters with a neutron probe using pre-installed aluminum access tube and since reported (Yunusa *et al.*, 2012). Fraction of available soil water (f_{wa}) was calculated for the topsoil (top 0.3 m layer) as follows:

$$f_{wa} = \left(\frac{S_t - S_w}{S_f - S_w} \right) \quad (5)$$

in which S storage of soil water with subscripts denoting its amounts at time of measurement (t) or permanent wilting (w) or field capacity (f); for this soil S_w was 0.158 and S_f was 0.434 (Yunusa *et al.*, 2012).

The BREB unit was deployed on February 25, 2009 on the plantation and in July 2009 on the grassland and data logging commenced immediately at 20 min intervals. Technical problems forced a premature termination of monitoring on the grassland in mid-January 2010 following a lightning strike, but monitoring on the plantation was concluded in April in 2010.

2.3 Quantifying advective effects on the energy balance

The α for non-saturated surfaces (α') can be calculated by combining eqns 2 and 3:

$$\alpha' = \frac{s+\gamma}{s(1+\beta)} \tag{6}$$

The α' thus accounts for the effects of soil-water availability, especially soil drying, on surface resistance. From eqn 2 the energy driven fraction of observed latent heat flux (λE_{eo}) was determined as: $\lambda E_{eo} = \lambda E/\alpha'$. Hence the proportion of λE due to advection (*%Adv*) was obtained as:

$$\%Adv = \left[\frac{\lambda E - \lambda E_{eo}}{\lambda E}\right]\cdot 100 \tag{7}$$

2.4 Energy balance during heat waves

The mean maximum daily temperature between 1961 and 1990 for the Hawkesbury district during late spring/summer was 26.9 ^{o}C in November, 28.9 ^{o}C in December and 29.4 ^{o}C in January (Australian Bureau of Meteorology, www.bom.gov.au). These were much lower than observed during the two heat waves in this study of 29.9–37.1 ^{o}C (median of 36.2 ^{o}C) in late 2009 (November 21–27) and 30.1–40.1 ^{o}C (35.6 ^{o}C) in early 2010 (January 9–13). These two periods were compared with a cool period of July 27–August 2, 2009, when maximum temperature range was 15.6 –18.8 ^{o}C.

3.0 RESULTS AND DISCUSSION

3.1 Weather conditions and latent heat flux

Weather conditions during the one-year study period were typical of a mild temperate climate (Figure 2a, b) with the mean maximum temperature rising from around 17 ^{o}C in winter (June – August) to highs of around 32 ^{o}C in summer (December–February) during which two heat waves were identifiable in November and January. Trends in minimum temperature and evaporative demand followed a similar pattern with the latter increasing from around 2.0 mm d^{-1} to 6.0 mm d^{-1}. The first half of the study period was relatively dry with only a few rainfall events that exceeded 10 mm, but the second half was relatively wet with many large rainfall events (>10 mm) during January–March 2010. The variability in rainfall distribution was reflected in the availability of soil moisture, with the topsoil being drier in the grassland than plantation, but this trend was reversed in the subsoil.

Daily λE from both vegetation covers increased as the conditions became warmer from winter through spring (September – November) to summer (Figure 2e). Flux of λE was always lower from the grassland than from the plantation with the difference increasing by as much as a factor of 3 as the season became warmer in summer. This was because (a) the leaf area index was larger for the plantation (mean of 3.2) than the grassland (mean 2.01), and (b) the amount of roots in the grassland was just 40% that of the plantation (Yunusa *et al.*, 2012). Consequently large amounts of soil-water remained unused in the grassland under which the soil was consistently wetter than the plantation (Figure 2d).

3.2 Trends in the calculated Priestley-Taylor coefficient and λE

Except during winter to early spring period when it was lower, α' remained well above 1.26 for both vegetation covers, reaching maxima in November/December (Figure 2f). The α'<1.26 in winter suggested advective suppression of λE due to stomatal closure during a substantial part of the day. A similar situation occurred with the plantation during cloudy and humid conditions in April/May 2010. At all times α' was larger for the plantation than the grassland despite R_n being mostly lower for the plantation than the grassland (Figure 3a). The higher R_n over the grassland compared with the plantation was contrary to expectation since the oft-reported higher albedo from grassland would lower R_n compared with woody vegetation (Moore, 1976; Teuling *et al.*, 2010). It is not clear why R_n was lower for the plantation, but Waterloo *et al.* (1999) reported albedo for a 6-year old regenerating forest, similar to our plantation site, to be up to 30% (13% *vs* 10%) smaller than for a mature 15-year old pine forest, while albedo could be up to 56% higher from the pine forest than from the grassland. Mowing the grassy groundcover, which constituted at least half of the land area in the plantation, in November, thus caused rapid declines in ΔR_n. Similarly, Wilson *et al.* (2002) recorded higher R_n for grassland compared with woody vegetation at several sites.

A combination of limited soil-water supply, winter dormancy and occasional mowing suppressed λE from the grassland such that the air above the canopy was warmer, by more than 1.0 ^{o}C on several occasions, when compared with that above the plantation (Figure 3b). During periods of frequent rainfall (November–January) the difference in temperature between the two vegetation covers was negligible. A trend in the difference in vapour pressure deficit between grassland and plantation (ΔD) showed that the air above the grassland was always drier than that over the plantation. A moist surface within the plantation increased partitioning of turbulent flux through λE resulting in higher α than in the grassland. Diurnal α values for the plantation (0.8–3.6) and for the grassland (0.6 –2.6) were consistent with observations in several previous studies that found α to be positively correlated with soil-water supply, and ranging in value from <0.9 to >4.5 (Jury and Tanner, 1976; Flint and Childs, 1991; Li and Yu, 2007).

In the plantation, the correlations between α′ and both G and soil temperature was positive, but was negative with water availability (f_{wa}) and H (Figure 4) suggesting that a substantial fraction of the advected energy was generated locally, especially in this vegetation cover. No such correlations between α′ and either G or H were observed on the grassland where the topsoil, which contains more than 60% of the roots, was relatively dry for prolonged periods (Figure 2c). The drying soil in both vegetation covers heated the overlying air to generate H as a local source of advection consistent with a high correlation between α′ and air temperature in the two vegetation covers (Figure 5a).

3.3 Interrelationships between fluxes in the grassland and plantation

Several components of the energy dynamics over the grassland were correlated with λE over the plantation. For example, α′ for the two vegetation cover-types were highly correlated with each other, while λE over the plantation held a significant relationship with both G and H over the grassland (Figure 5). This suggested that heat transfer from the grassland to the plantation was driven by the warmer air over the former, especially under the northerly winds that crossed the grassland toward the plantation during this period (Figure 1). Kochendorfer and Paw U (2011) showed that horizontal advection is especially strong and enhanced λE by up to 15% over a tall and transpiring canopy when the prevailing wind crossed a low-lying and senescing canopy. Similarly, wind mediated enhancement of sensible heat advection from dry surrounding fields increased transpiration by nearly 70% over a tree belt (Hernandez-Santana *et al.*, 2011) and by 50% over irrigated wheat (Li and Yu, 2007).

3.4 Diurnal trends in energy fluxes during heatwaves

Figure 6 compares diurnal trends in heat fluxes during non-heat wave days in August with two heat wave days for the two vegetation cover-types. The R_n increased by more than a factor of 2.5 during the heat wave compared with non-heat wave days, and was mostly expended (62–70%) as H from the grassland; grassland H was three times as large as that that emitted from the plantation where λE accounted for 58–72% of incoming energy. On the grassland, λE was always smaller than, and lagged behind, R_n in the morning. In contrast, R_n and λE were in tandem in the early morning until 0900 h, after which λE declined rapidly and stopped almost entirely by 1400 h. This was likely a consequence of the low zenith angle of the sun (<36^o) that declined rapidly as the sun moved northwestwards, shading the southern half of the tree canopy and resulted in gradual stomatal closure of the canopy leaves. Furthermore, the northern half of the canopy would have experienced mutual shading and this feature was tested by approximating the shadow length (L) for the tree rows using the following (Shettigara and Sumerling, 1998):

$$L = \frac{h}{\tan \Theta} \quad (8)$$

in which h is row height and Θ is the angle between horizon and the sun. This equation yielded a shadow length of at least 10 m around midday, extending to 17 m by 1600 h, which was large enough to cast shadows onto the canopy rows located to the south.

The majority of the incident R_n from midday onwards was therefore emitted as H, even exceeding the magnitude attained by λE earlier in the day. This was despite the high f_{wa} and low

D at this time (Table 1). The impact of limited incident energy receipt by the canopy was less severe on the plantation compared with the low laying grass that was also dormant at this time so that 94% total turbulent flux (λE+H) was mainly H.

During the heat waves in summer the sun was close to its zenith and the day length was longer. Any stomatal restraint on λE was primarily associated with dryness of the air and not with f_{wa}, because the subsoil was quite moist on the two heat wave days (Figure 2d). A $\lambda E/(R_n$-G) of 0.66 on November 21 and 0.80 on January 13 (Figure 6) indicated a constraint on λE most likely due to a high D that was twice as large on November 21 as on January 13 (Table 1). Conversely the warming potential of the plantation ($H/(R_n$-G)) of 0.34 and 0.20 on the two heat wave days, was much smaller than 0.77 and 0.68 for the grassland and was reflected in the differences in air temperature above the two vegetation covers. Notwithstanding the adequate soil-water supply, a limitation in the hydraulic capacity of the plants likely triggered stomatal closure in the woody species of the plantation as a response to high D and temperature (Eamus *et al.*, 2008; Whitley et al, 2013; Yunusa *et al.*, 2010a). Thus transpiration has been observed to virtually cease in two common *Euclayptus* spp when temperatures >30 ^{o}C or D > 2.5 kPa (Yunusa *et al.*, 2010a). Despite this λE over the plantation was 65 and 85% of the turbulent flux compared to 33 and 35% over the grassland on the two heat wave days. It was also probable that the plantation accessed the groundwater during this study, unlike in the previous years when the root system was still shallow (Yunusa *et al.*, 2011).

Majority of the H in the plantation emanated from the understorey of mixed pasture groundcover, which accounted for at least half the land area but a small fraction λE in the plantation. Assuming a similar constraint to evapotranspiration from the pasture groundcover in the plantation as in the grassland, the maximum λE contributed by the understorey groundcover (λE_{cov}) in the plantation can be approximated from the $\lambda E/R_n$ of the grassland and the R_n of the plantation ($R_{n,pl}$) as:

$$\lambda E_{cov} = \left(\frac{\lambda E_{gl} f_A R_{n,gl}}{R_{n,pl}} \right) \tag{9}$$

where f_A is the fractional land area covered by the understorey (taken to be 0.5) in the plantation, subscript *gl* represents grassland and *pl* plantation. This produced λE_{cov} values of 0.05, 1.28 and 1.77 MJ/m^2 on representative days in August, November and December (Figure 6) respectively.

Therefore the the trees that directly intercepted ≤50% of the incident R_n, contributed was 98% of λE in winter (August) and about 74% during the heat waves in summer. The additional energy for λE from the trees was supplied by advection mostly from the underlying pasture groundcover. Water needed to sustain enhanced transpiration by the trees was most probably extracted from the shallowest water table. Reductions in ambient temperatures arising from enhanced λE and negligible H over woody shrubs with access to a water table were reported by Kustas *et al.* (1989) for Owens Valley, USA (36° 48′N 118° 121′W). The λE_{cov} fraction was particularly low in summer when the grass component of the pasture was dormant. However, instead of the H emanating from the pasture groundcover being given to warm up the surrounding air it was used to contribute to λE from the trees in the plantation and thereby cooling the surrounding air mass.

Differences between the grassland and plantation presented here were unlike those found in similar comparisons between grassland and forest dominated by, or containing a considerable proportion of, conifers at high (northern) latitudes (Teuling *et al.*, 2010). In that study the lower

λE over grassland/crop compared with the forests was attributed to daytime stomatal restriction of transpiration in the woody species by the prevailing high *D*. A similar situation probably prevailed at Bremgarten (47° 54' N, 7° 37' E) in Germany, where λE was always larger, while *H* was smaller, from grassland than from a nearby pine forest (Rost and Mayer, 2006). Our site was at a lower latitude (33° 39' 41" S) and the plantation was dominated by broadleaved evergreen woody species that would generally have lower canopy resistance than conifers (Kelliher *et al.*, 1993; Wilson *et al.* 2002). At the high latitudes (>45^{o} N) limitations imposed by reduced energy supply (compared to our site) is likely to have a greater impact on the coniferous forests.

Conditions at our mid-latitude sub-temperate environment were closer to those of Mediterranean climate where β and surface resistance tend to be relatively small because of proximity to seas/oceans, and advection is common (Wilson *et al.*, 2002). In general, β tends to be higher for deciduous and coniferous forests and grasses than for evergreen woody vegetation (Wilson *et al.*, 2002). A small contribution of *H* to turbulent flux in the plantation thus minimized heat input into the surrounding air mass, which was cooler by as much 4 ^{o}C, and more humid, when compared with over the grassland during the days that experienced heat waves (Figure 7).

3.5 Diurnal patterns of advection

The pattern of advection to λE in both vegetation cover-types changed during the day (Figure 8). In winter advection generally suppressed λE both at night and during the day, except for a brief period around midday when there was an enhancement. As discussed above, it is likely that the stomates shut early in the day during winter as a consequence of low solar elevation and a shorter photoperiod. However, during both heat wave days in summer, advection enhanced λE and was more pronounced in the plantation, where it accounted for >50% of λE. Furthermore, β in the plantation declined, while that in the grassland increased, and were consistent with the higher $\lambda E/(R_n\text{-}G)$ for the plantation on the heat wave days as discussed above. Advection also enhanced λE in the grassland most of the time, but to a much lesser extent than in the plantation (Figure 8). Whatever energy advected to the grassland was emitted, along with that emitted from within, resulting in large *H*, thereby making the grassland more of a source than a sink for *H*. Percentage suppression/enhancement of λE by advection was within the -300 – +300 % reported for irrigated wheat by Li and Yu (2007) and comparable to -40 – +60 % in a tree-belt within a cropped landscape (Smith *et al.*, 1997).

3.6 Annual water budget

To estimate λE for the periods with missing data, α' was predicted from f_{wa} and air temperatures using polynomial equations for the two vegetation covers as follows:

Grassland: $\alpha' = -0.33 + 0.165 f_{wa} + 0.088\,airtemp$ $r^2 = 0.59$ (10a)

Plantation: $\alpha' = -0.082 - 0.254 f_{wa} + 0.132\,airtemp$ $r^2 = 0.89$ (10b)

We consider these schemes to be a logical approach since they rely on just two variables that are easily determined to predict α' and so were used in eqn 2 to obtain ET. Daily ET for the plantation was generally consistent with an average of 2–4 mm d^{-1} observed earlier in 2007–2008 (Yunusa *et al.*, 2011) despite the trees in the plantation being a year older and their contribution to the composite LAI would have also increased. As discussed above, λE dominated the turbulence flux (50 –80%) during this study in the mostly dry year compared with 30% two years previously when rainfall was almost 54% larger than in the year of the current study (Yunusa *et al.*, 2011). This is because the grass/legume pasture groundcover accounted for at least half of the land area under the plantation. Although ET from the grassland was almost 17% less than the total rainfall during the period (Table 2), it exceeded rainfall by 81% in the plantation that must have accessed shallow groundwater as discussed above. Drainage past the root zone from the grassland occurred predominantly in winter when the grasses were mostly dormant. Using as much of the antecedent soil-water as possible in the spring–summer seasons can increase the storage capacity for the storage of rainfall in winter when ET is low and risk of drainage is higher. This will be especially beneficial under vegetation types that experience seasonal dormancy. Such a system is desirable on landscapes containing buried waste materials that need to be hydrologically isolated and drainage eliminated (Gwenzi *et al.*, 2012; Schneider *et al.*, 2012).

4.0 Conclusions

Advection exerted a significant influence on the partitioning of turbulent flux (λE and H) from the two vegetation cover-types investigated in this study. Fluctuating values of α showed strong seasonality that reflected the degree of canopy inactivity due to supply of either solar energy or soil-water. The generally low values (<1.26) for α in winter suggested suppression of λE by advection because the canopy was completely inactive in the dormant grassland and partially so in the plantation due to reduced illumination of the canopy throughout much of the photoperiod as a consequence of low solar elevation. Thus H dominated the turbulent flux accounting for 94% in the grassland and 66% in the plantation with this energy emitted as heat to the surrounding air during this cool season. As the daylight hours increased into spring and summer and a break in the dormancy of the grassland occurred, advection generally enhanced λE with α

>1.26, reaching as high as 2.4 in the grassland and 3.2 in the plantation. During the active growing season in spring–summer λE dominated turbulent flux, especially in the plantation where it accounted for 70%, compared with 34% in the grassland, during heat waves.

Thus the emission of H as warm air was larger from the grassland with the result that it's local air temperature was warmer by as much as 4 ^{o}C during the day compared with the local air temperature of the plantation. On balance, the plantation was primarily a sink, while the grassland was predominantly a source for advected energy. Contrary to the many examples with coniferous forests in high latitudes of the northern hemisphere, the plantation, which was dominated by broadleaved evergreen woody species, maintained a high rate of water-use that was probably relies in part on the shallow groundwater; consequently the plantation used 81% more water than rainfall during the one year study period.

Exceedance of rainfall by evapotranspiration (ET) in the plantation shows the difficulty of closing the soil-water balance on landscapes with a water table that is accessible to vegetation. It also provides strong evidence that drainage of water beneath the rooting depth can be reduced and perhaps eliminated by woody species within six year, and thus limiting the risk of contaminating water resources on landscapes with buried wastes and on mined sites.

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FIGURE LEGENDS

Figure 1. Site of study indicating locations of the Bowen Ration Energy Balance (BREB) monitoring towers at Castlereagh, Australia. The years in which the plantations were established are given in parenthesis.

Figure 2. Five-day running averages for (a) minimum and maximum temperatures, (b) rainfall for the site, (c) soil-water stored in the topsoil (0–0.3 m), (d) soil-water stored in the subsoil, (d) latent heat flux (λE) from grassland and plantation, and (e) Priestley-Taylor coefficient, observed between 2009 and 2010 at Castlereagh, Australia. The x in (c) and (f) indicates when the grass was mowed.

Figure 3. Five-day running averages for the differences (grassland-plantation) in (a) α or net radiation (R_n) and (b) air temperature or vapour pressure deficit (D), between 2009 and 2010 at Castlereagh, Australia. The two heat wave periods are indicated as *HW* in (b).

Figure 4. Regressions of Priestley-Taylor coefficient (α) on fraction of available water (f_{wa}) in the topsoil (0–0.3 m layer) (a, e), sensible heat flux (H) (b, f), soil-heat flux (G) (c, g), and soil temperature (e, h) observed between 2009 and 2010 at Castlereagh, Australia. The top panels are for grassland and bottom panels for the plantation.

Figure 5. Relationships between energy exchange variables over grassland and plantation between 2009 and 2010 at Castlereagh, Australia: (a) Priestley-Taylor coefficient (α) *versus* mean air temperature; (b) α for grass versus that for plantation; (c) relationships between latent heat flux (λE) from the plantation with either sensible heat (H) or with (d) ground heat flux (G) from the grassland. The two fitted lines in (a) have a common intercept.

Figure 6. Diurnal fluxes of net radiation (R_n, solid line), latent heat (λE, dotted line), sensible heat (H, dashed line) and ground heat (G, dashed-dotted line) observed on August 2 (a, b), November 21 (c, d) and January 13 (e, f) over grassland (a, c, e) and plantation (b, d, f) at Castlereagh, Australia. Daily totals ($MJ/m^2/d$) for the four fluxes are given for each date.

Figure 7. Diurnal trends in the differences (grassland-plantation) in (a) temperature, (b) net radiation (R_n) and (c) vapour pressure deficit observed on the three dates at Castlereagh, Australia. Also shown are the base (*zero*) lines.

Figure 8. Percentage contribution of advection to latent heat flux on grassland and plantation on (a) 2 August 2009, (b) 21 November 2009 and (c) 13 January 2010 at Castlereagh, Australia.

TABLE LEGENDS

Table 1. Daily averages for key meteorological variables over the whole study site or the respective vegetation covers on three selected days at Castlereagh, Australia

Table 2. Summary of water balance variables and leaf area index (LAI) for the grassland and plantation covers between July 2009 and June 2010.

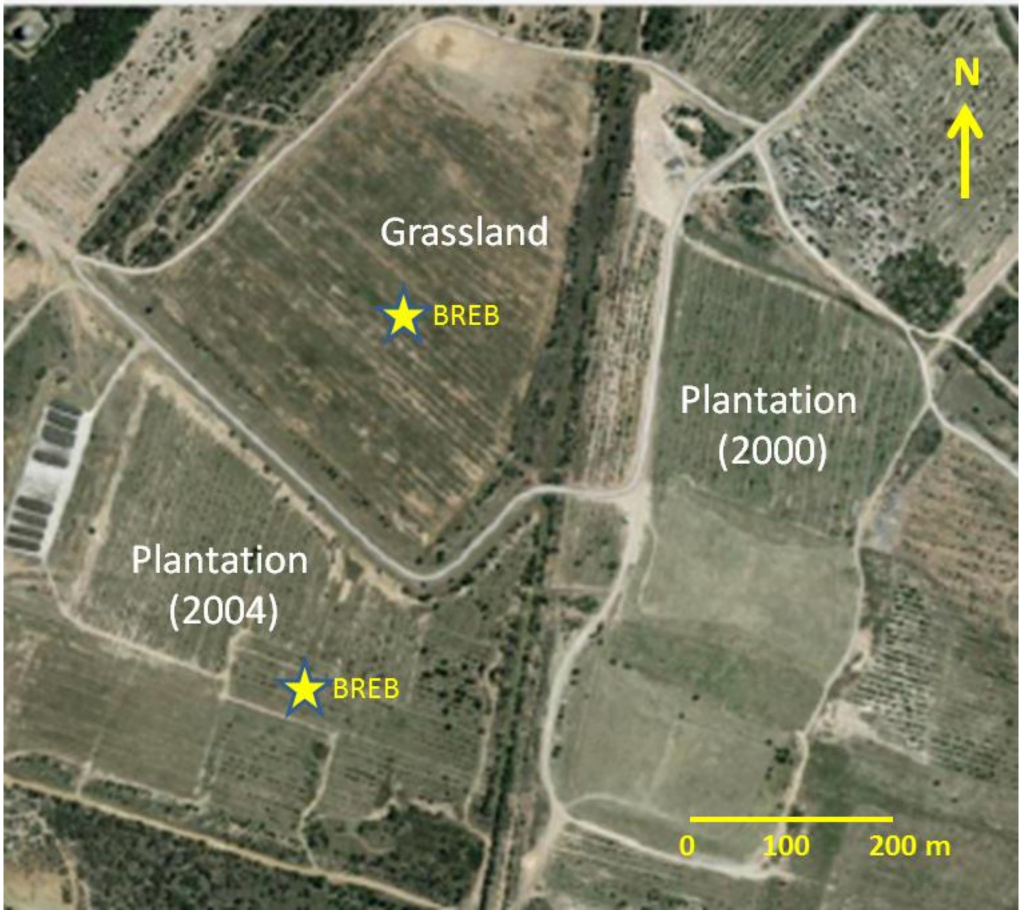
Table 1. Daily averages for key meteorological variables over the whole study site or the respective vegetation covers on three selected days at Castlereagh, Australia

Variables	Vegetation	2 Aug	21 Nov	13 Jan
Wind speed (m s^{-1})	Site	0.51	1.71	1.83
Mean wind direction (deg)	Site	198	212	174
%Adv (%)	Grassland	-79.1	24.6	45.0
	Plantation	-62.4	74.2	44.0
Mean θ	Grassland	0.28	0.14	0.15
	Plantation	0.39	0.24	0.24
Calculated PT coefficient (α')	Grassland	0.71	1.76	2.01
	Plantation	0.80	3.98	3.65
Mean β	Grassland	0.05	0.46	0.79
	Plantation	1.66	0.10	-0.26
Mean vapour pressure deficit (D, kPa)	Grassland	0.45	2.26	1.19
	Plantation	0.43	2.15	1.07
Mean air temp (^{o}C)	Grassland	8.2	29.2	27.0
	Plantation	8.5	27.6	26.2
Mean soil temp (^{o}C)	Grassland	9.9	31.0	33.3
	Plantation	8.4	28.8	31.8

Table 2. Summary of water balance variables and leaf area index (LAI) for the grassland and plantation covers between July 2009 and June 2010.

Variables	Vegetation covers	Feb–Jun '09 (Autumn)	Jun–Sep '09 (Winter)	Sep–Dec '09 (Spring)	Dec 09–Apr '10 (Summer)	Total or (average)
Rainfall (mm)	Site	271	49	109	34	463
E_o (mm)	Site	257	159	362	440	1218
Mean Leaf area index	Grassland	1.5	1.8	2.2	1.8	(1.8)
(LAI)	Plantation	2.9	3.1	3.3	2.8	(3.0)
Change in soil-water	Grassland	39	-69	-6	-20	52
storage (mm)	Plantation	29	-21	10	-87	-31
Evapotranspiration	Grassland	128	40	112	108	38**4**
(mm)	Plantation	195	94	267	282	838
Putative drainage	Grassland	104	78	3	-50	185
(mm)[1]	Plantation	47	-24	-168	-161	47

[1]negative values effectively represent zero drainage and are additional water sourced from the groundwater



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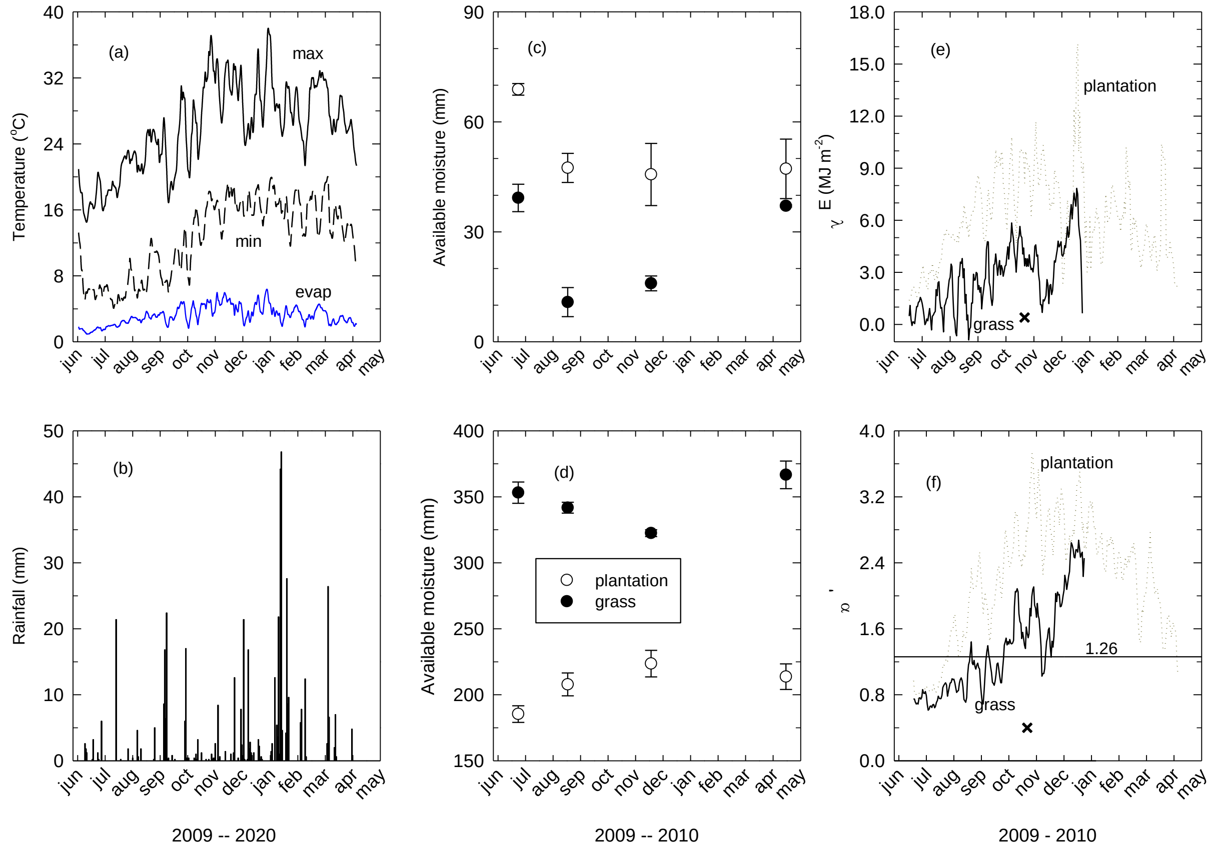

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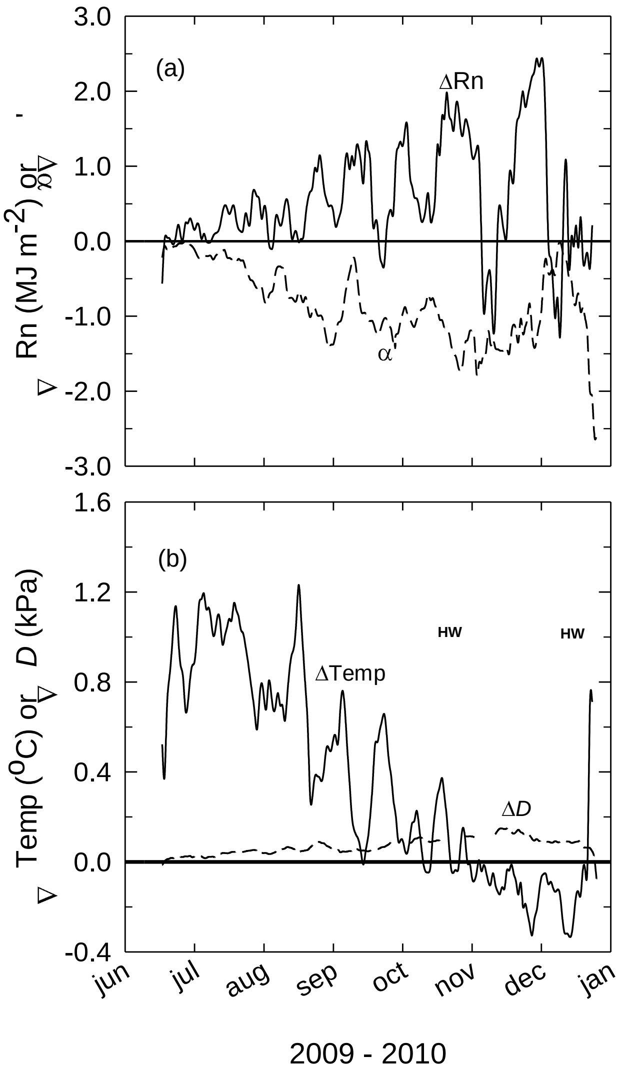

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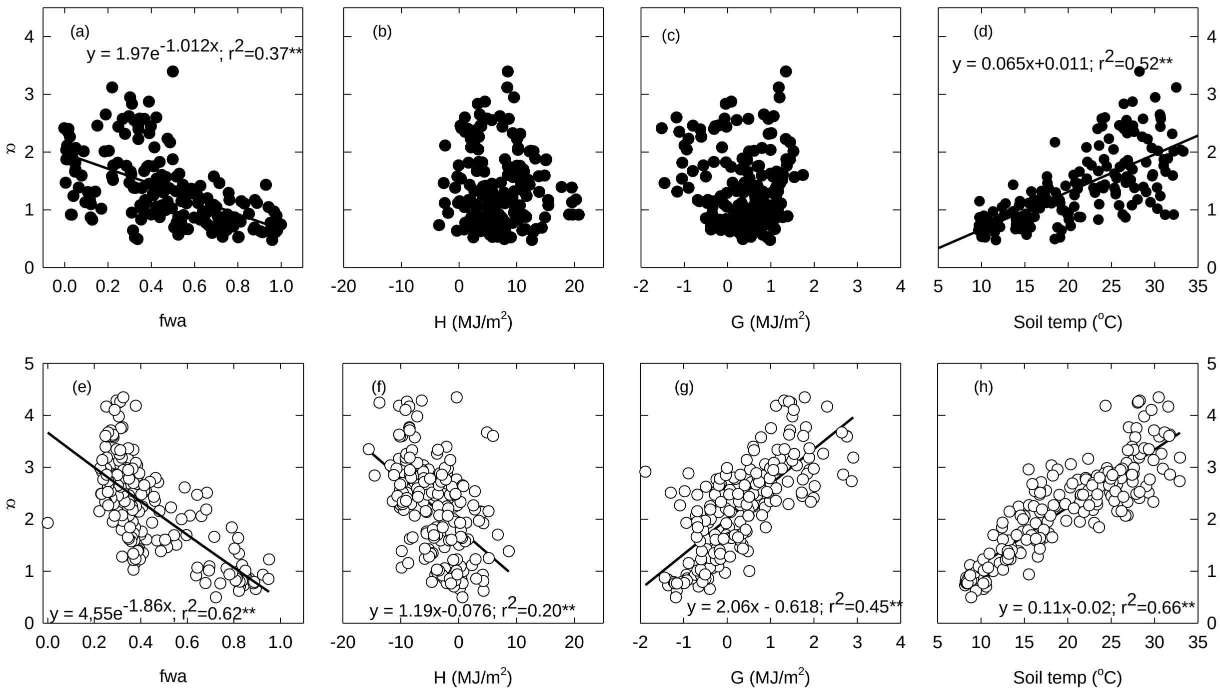

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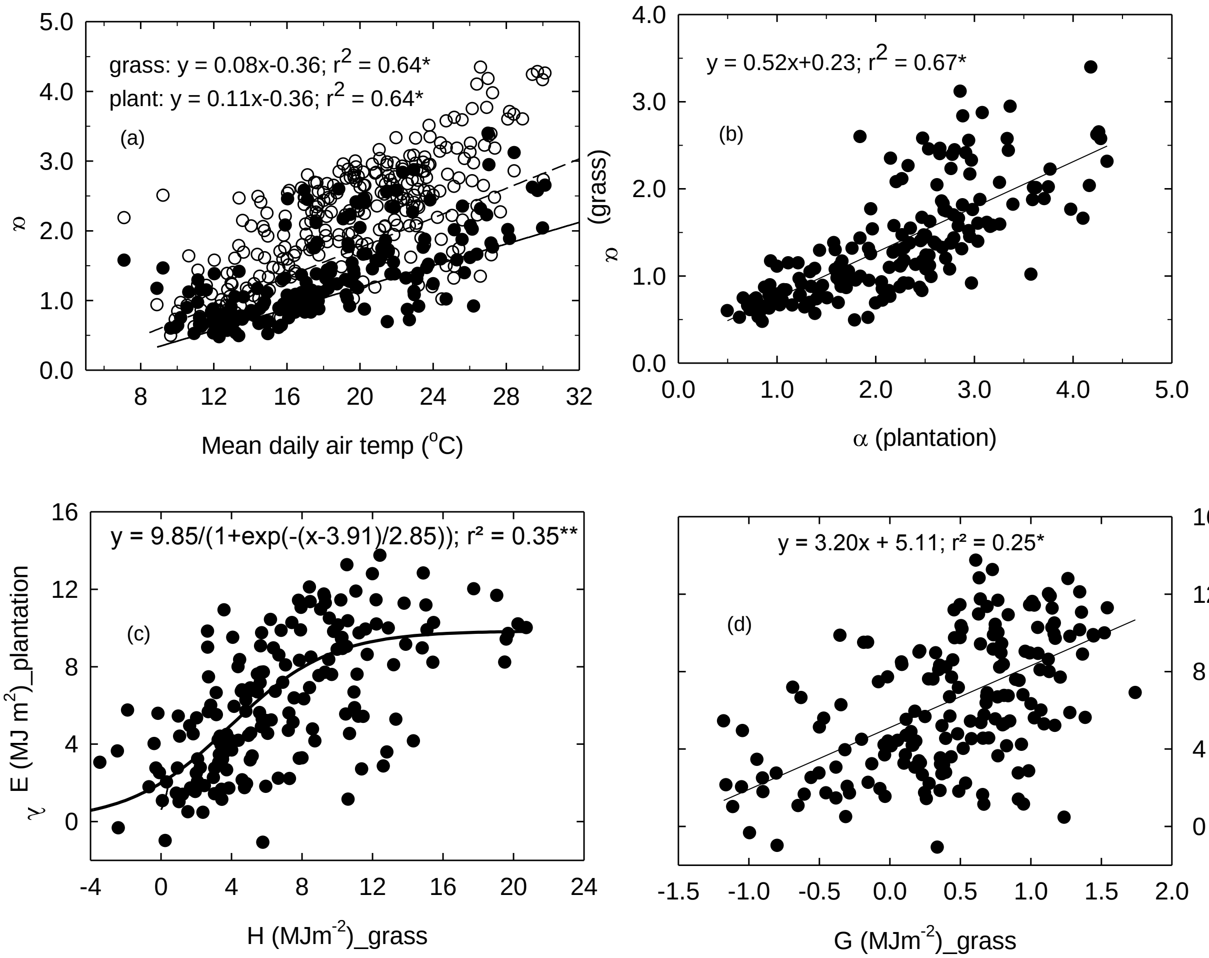

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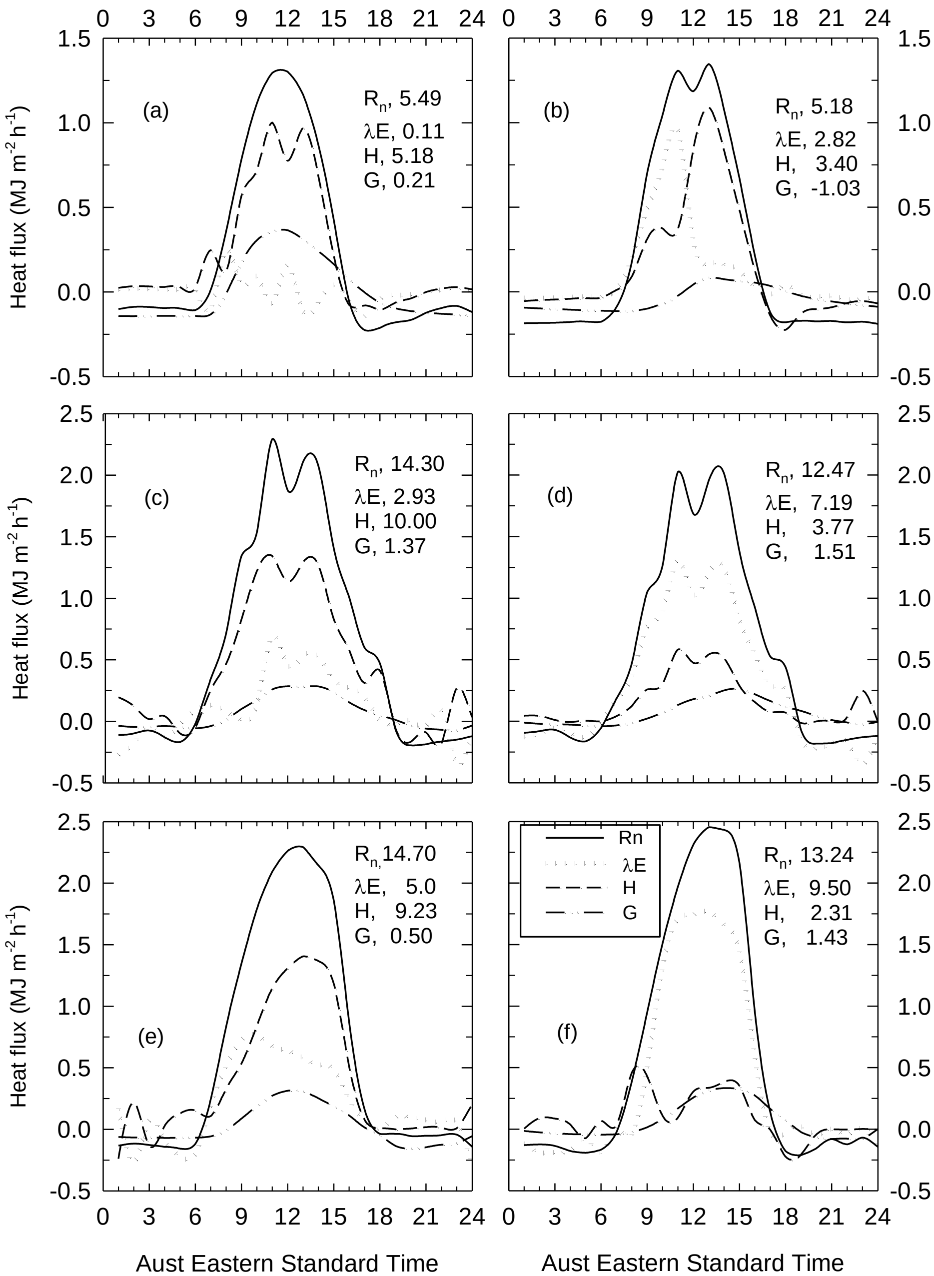

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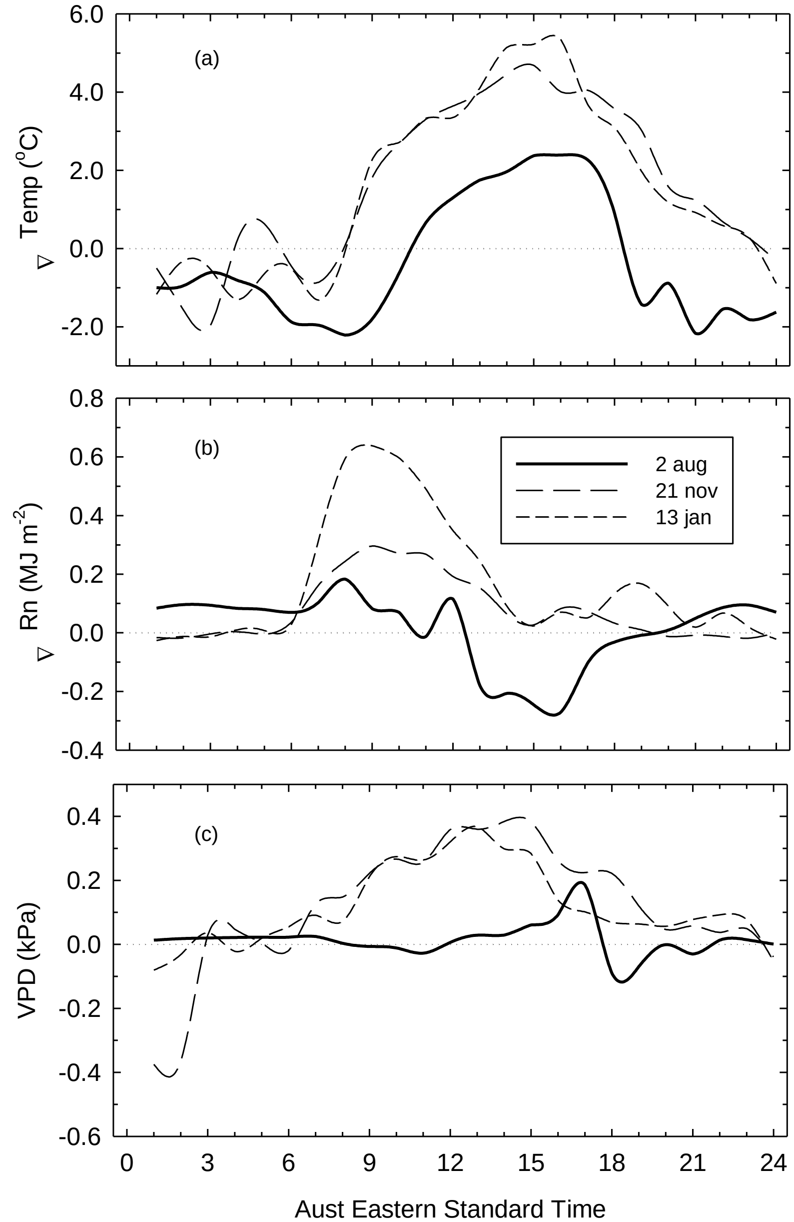

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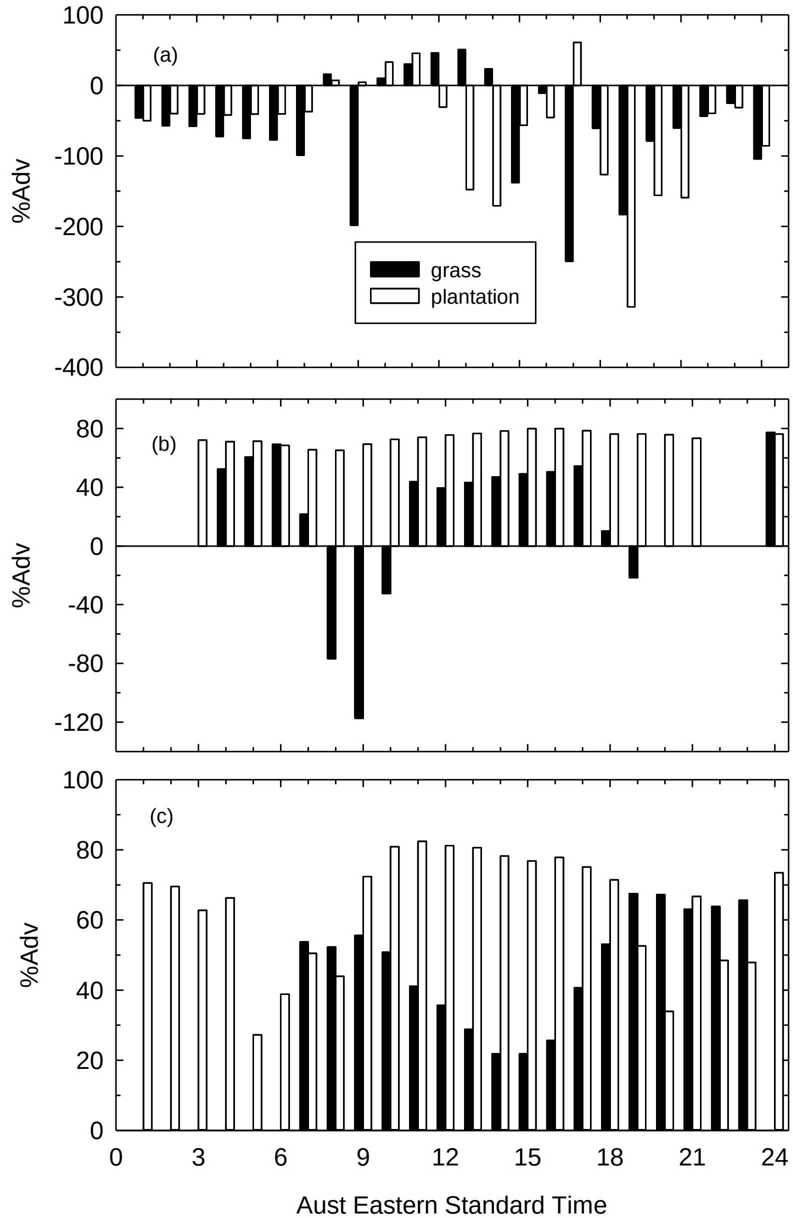

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