Hydrology and Earth System Sciences Discussions

The importance of plant water use on evapotranspiration covers in semi-arid Australia

A. Schneider, S. Arnold, D. Doley, D. R. Mulligan, and T. Baumgartl

The University of Queensland, Sustainable Minerals Institute, Centre for Mined Land Rehabilitation, Brisbane, Australia

Correspondence to: A. Schneider (a.schneider@cmlr.uq.edu.au)

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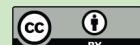
Abstract

We estimated the evapotranspiration (ET) for an area vegetated with characteristic semi-arid native Australian plant species on ET mine waste cover systems. These systems aim to minimise drainage into underlying hazardous wastes by maximising evaporation (E) from the soil surface and transpiration from vegetation. An open top chamber was used to measure diurnal and daily ET of two plant species – *Senna artemisioides* (silver cassia) and *Sclerolaena birchii* (galvanised burr) – after a simulated rainfall event, as well as E from bare soil. Both ET and E decreased with increasing time after initial watering. Different temporal patterns were observed for daily ET from the two plant species and E from bare soil, revealing *Senna artemisioides* as intensive and *Sclerolaena birchii* as extensive water exploiters. A strong positive linear relationship was identified between ET (and E), and the atmospheric water demand represented by the vapour pressure deficit. The relationship always was more pronounced in the morning than in the afternoon, indicating a diminishing water supply from the soil associated with a declining unsaturated hydraulic conductivity of the soil in the afternoon. The slopes of the regression lines were steepest for *Senna artemisioides*, reflecting its intensive water-exploiting characteristics. We used the derived estimates of ET and E to predict the effect of species composition on plot ET in relation to total vegetation coverage. Although both species proved suitable for an operational ET cover system, vegetation coverage should exceed at least 50 % in order to markedly influence plot ET, a value which is likely to be unsustainable in semi-arid climates.

1 Introduction

Evapotranspiration (ET) cover systems, also referred to as monolithic cover, alternative cover or phytocaps, are increasingly accepted for the closure of mining waste facilities, such as waste rock dumps and tailings storage facilities, as well as municipal landfills (Benson et al., 2002; Knoche et al., 2006; Madalinski et al., 2003; Rock, 2010;

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Waugh et al., 1994; Yunusa et al., 2010). The objective of those covers is to minimise drainage into the underlying hazardous wastes by maximising vegetation rainfall interception, soil water storage, and ET, the combination of direct evaporation from the soil surface and transpiration from vegetation, and thereby minimising surface runoff

5   and deep drainage (Salt et al., 2011). After rainfall ceases, the loss of stored soil water through ET increases the soil water storage capacity for future rainfall events (e.g. Hauser et al., 2001; Rock, 2010). Cover materials as well as cover designs vary greatly in their characteristics and complexity and may incorporate geotextile liners, multiple soil layers with selected hydrological properties, and compacted clay layers, depending

10   on local climate and material availability (Benson et al., 2002).

The rate of water loss from an ET cover system depends on available energy, atmospheric demand for water vapour, and soil water availability (Seneviratne et al., 2010). ET losses from cover systems are commonly assessed indirectly through lysimeter studies and the water balance (Barnswell and Dwyer, 2011; Knoche et al., 2006; Mel-

15   chior et al., 2010; Nyhan et al., 1997), through numerical modelling (Bohnhoff et al., 2009; Preston and McBride, 2004; Zornberg et al., 2003), or by direct on-site measurements of ET (Gwenzi, 2010; Yunusa et al., 2010; Lynch, 2007).

Most previous ET studies did not directly measure plant water usage and therefore did not consider partitioning between plant transpiration and evaporation from bare

20   soil. The plant contribution to ET from cover systems may vary from 44–93 % in temperate eastern Australia (Yunusa et al., 2010) to about 22 % in Mediterranean Western Australia (Gwenzi, 2010). Furthermore, plant community maturity and composition are likely to substantially affect the water usage by vegetation (Barnswell and Dwyer, 2011; Smesrud et al., 2012). In contrast, information about the effect of vegetation composi-

25   tion on ET losses from cover systems in semi-arid climate is limited, but it is necessary to identify plant species that can both reliably minimise drainage of water through cover systems and maintain robust vegetation cover during prolonged unfavourable weather conditions.

Therefore, the aim of this study was to investigate ET rates of two native shrub species on an ET cover design in semi-arid Australia to identify the main drivers of ET under semi-arid conditions, quantify water use characteristics of key plant species, and develop indicators of vegetation cover and species composition for the management of
5 ET cover systems.

2 Methods and materials

2.1 Study site

The study site was located near Cobar, western New South Wales, Australia (31°33′ S, 145°52′ E). The climate of this area is described as BSh (B = arid, S = steppe, h = hot)
10 in the Köppen and Geiger climate classification (Kottek et al., 2006), with a long term average annual rainfall of approximately 400 mm (Bureau of Meteorology, 2012). Rainfall distribution does not follow a seasonal pattern but tends to be uniformly distributed throughout the year. However, rainfall can be highly variable, especially in early spring and summer. Mean annual minimum and maximum temperatures are 12.8 °C and
15 25.2 °C, respectively (Bureau of Meteorology, 2012).

Evapotranspiration and evaporation was investigated at a 2.0 m thick test plot cover system (35 × 35 m plot area) constructed from benign (non-acid-forming) waste rock (O'Kane Consultants Inc., 2002), overlain by 150 mm loamy topsoil. A water retention curve was determined for the topsoil by core sampling and laboratory analysis. From
20 the water contents ranging between saturation (0.45 m^3 m^{-3}) and residual (0.0 m^3 m^{-3}), the van Genuchten parameters (van Genuchten, 1980) α and n were derived as 0.0468 and 1.22, respectively. Scattered shrub, herb and grass species had established on the cover in the three years between topsoil application and measurement. Vegetation cover was determined by a modified Braun-Blanquet method (Mueller-Dombois and El-
25 lenberg, 1974) and by foliage projective cover (FPC) (Specht, 1981). Up to 30 species provided average total vegetation coverage (FPC$_v$) of 26 %. Based on a vegetation

abundance survey, we selected two dominant species on the plot for the evapotranspiration measurements, namely *Senna artemisioides* (DC.) Randell (silver cassia) (Fig. 1a and b) and *Sclerolaena birchii* (F. Muell) (galvanised burr) (Fig. 1c and d). The two species differ markedly in shoot and leaf morphology. *Senna artemisioides* is an erect shrub with a pinnate arrangement of terete leaves resulting in a feathery appearance of the canopy. Therefore, shadows cast by individual plants are diffuse. In contrast, *Sclerolaena birchii* individuals are low-growing but develop a dense system of hairy shoots with small persistent elliptical leaves and spiny fruits that more completely shade a greater area of the soil surface than does *Senna artemisioides* (Fig. 1).

2.2 Experimental design

A field experiment was conducted over a period of 5 days in April 2011 to establish the relationships between atmospheric vapour pressure deficit (VPD), and the evapotranspiration of an individual plant (ET_i). The latter was used to predict the actual evapotranspiration of the test plot (ET_{plot}) in relation to various scenarios of coverage and potential evapotranspiration (pET). Two individuals of each species (*Senna artemisioides* (Sen) and *Sclerolaena birchii* (Scl)) were selected to estimate ET_i. Likewise, one spot with no vegetation was selected to estimate evaporation from bare soil (E_b), providing a total of five measurement locations on the test plot. Furthermore, a representative replicate of each *Senna artemisoides*, *Sclerolaena birchii* and the bare soil were selected for destructive soil moisture sampling in the upper 5 cm. Initially, all measurement locations and replicates were watered to simulate a 17 mm rainfall event, which was sufficient to raise the near-surface soil water content of each location markedly. ET_i measurements were conducted with an open top chamber (OTC, detailed below) over the course of a day from dawn (06:00 h) to dusk (18:30 h) and then integrated to estimate daily values of ET_i. The OTC was removed after 10 min of measurement to minimise micro-climatic disturbances. Evapotranspiration was assumed to be negligible at night although we are aware of studies that indicate the occurrence of nocturnal evapotranspiration for other vegetation types (Donovan et al., 1999). The

soil water content of the top soil layer (5 cm) was measured both in the morning and evening. A weather station at the experimental site provided meteorological information. The weather situation prior to the experiment was characterised by dry conditions with precipitation less than 33 mm over the previous 6 weeks and typical for the climate in this semi-arid region.

2.2.1 Atmospheric variables

The hydrological boundary conditions of ecosystems, particularly with regard to the plant available soil water balance, are set by the atmospheric demand for water vapour, expressed through the vapour pressure deficit (VPD):

$$VPD = e_s - e_a, \tag{1}$$

where e_s and e_a denote the saturated and actual vapour pressures [kPa], respectively. The saturated vapour pressure was calculated according to Murray (1967) as:

$$e_s = 0.611 \exp \frac{17.27(T_a - 273.16)}{T_a - 35.86}, \tag{2}$$

where T_a is the actual air temperature [K]. The actual vapour pressure was calculated according to Monteith and Unsworth (1990) as:

$$e_a = \frac{e_s H_r}{100}, \tag{3}$$

where H_r denotes the relative humidity [%].

In addition to VPD we used the potential evapotranspiration (pET [mm d^{-1}]) to estimate the atmospheric water demand; pET was calculated with the FAO56 Penman-Monteith method (Allen et al., 1998):

$$pET = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T} u \, (VPD)}{\Delta + \gamma(1 + 0.34u)}, \tag{4}$$

where Δ denotes the slope of the vapour pressure curve [kPa $°C^{-1}$], R_n is the net radiation [MJ m^{-2} d^{-1}], G is the soil heat flux density [MJ m^{-2} d^{-1}] (assumed to be zero), γ is the psychrometric constant [kPa $°C^{-1}$], T is the mean daily air temperature at 2 m height [$°C$], VPD is the vapour pressure deficit [kPa], and u denotes the wind speed at 2 m height [$m\,s^{-1}$].

2.2.2 Evapotranspiration

Evapotranspiration measurements were conducted with an open top chamber (OTC), similar to the systems described by Hutley et al. (2000). The total volume of the chamber was 1.42 m^3 and ground area was 0.64 m^2. The metal frame was covered by a clear PVC foil of 0.2 mm thickness. Measurements of photosynthetic active radiation (PAR) showed that the attenuation due to the foil was 9 % under cloud-free skies and 20 % under cloudy conditions, which is in the range of attenuation reported by other studies (Garcia et al., 1990; Müller et al., 2009). Air was pumped into the chamber through a centrifugal fan at the base of the chamber. Air flow was measured at the chamber outlet through a vane thermo-anemometer (RS Components Ltd., Smithfield, NSW, Australia). Air temperature and relative humidity inside and outside the chamber were measured with a Vaisala HUMICAP$^{®}$ Humidity and Temperature Probe (HMP155, Vaisala, Inc., Helsinki, Finland), and PAR with a LI-190 quantum sensor (LI-COR, Lincoln, Nevada, USA).

The evaporation rate from bare soil (E_b [mm s^{-1}]) was calculated according to Hutley et al. (2000):

$$E_b = \frac{(V\,\Delta\rho)_b}{A_b},$$ (5)

where subscript "b" denotes measurements of bare ground, V is the volumetric air flow rate [$m^3\,s^{-1}$], $\Delta\rho$ is the difference in vapour densities outside and inside the chamber [g m^{-3}], A_b is the ground area [m^2] (Fig. 2).

The evapotranspiration rate from the area covered by an individual plant i ET_i [mm s^{-1}]) was then calculated as:

$$ET_i = \frac{(V\Delta\rho)_{OTC} - \left(\frac{A_b - A_v}{A_b}\right)(V\Delta\rho)_b}{A_v}, \tag{6}$$

where the subscripts "v" and OTC refer to vegetation and chamber measurement, re-
spectively. The chamber was tested under controlled conditions prior to the field experi-
ment by comparing the gravimetric water loss from a tray (E_g) to the evaporational water
loss measured by using the chamber (E_{OTC}). The OTC was tested for two different wind
speeds to account for a possible range of speeds of air flow during the experiment. For
both high (0.8 m s^{-1}) and low (0.4 m s^{-1}) values of air flow, highly significant positive
linear relationships were found (R^2 = 0.94 and R^2 = 0.97, respectively) between E_{OTC}
and E_g. This emphasises the reliability of evapotranspiration rates estimated using the
chamber. However, since E_{OTC} slightly underestimated E_g, the measured values of ET_i
and E_b during the field experiment were corrected accordingly.

We used the estimated values of ET_i to predict the actual evapotranspiration from
the test plot (ET_{plot} [mm d^{-1}]) under different scenarios of species composition as:

$$ET_{plot} = \frac{\left(FPC_v \left(\sum_{i=1}^{n} \omega_i ET_i\right) + FPC_b E_b\right)}{100}, \tag{7}$$

where FPC_v and FPC_b denote the projective cover of vegetation and bare soil [%],
respectively, ω_i denotes the fractional coverage within FPC_v, n is the total num-
ber of individual plants, and E_b is the daily evaporation rate of bare soil. To in-
vestigate the influence of each species on ET_{plot} we considered three scenarios of
species composition ($\omega_{Slc}/\omega_{Sen}$): (1) $\omega_{Slc}/\omega_{Sen}$ = 0.5/0.5, (2) $\omega_{Slc}/\omega_{Sen}$ = 0.7/0.3,
and (3) $\omega_{Slc}/\omega_{Sen}$ = 0.3/0.7.

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3   Results

Climatic conditions on all measurement days were similar with sunny mornings and slightly overcast, windy afternoons. Maximum VPD occurred around 14:00 h and varied between 4.4 kPa on 8 April and 3.9 kPa on 6 April. Air temperature fluctuated between 10–15 °C in the mornings and 30–36 °C in the afternoons. Soil moisture was markedly increased through watering and decreased rapidly thereafter. However, volumetric soil moisture seven days after watering exceeded moisture conditions prior to watering (Fig. 3).

Figure 4 illustrates the integrated daily values of ET for each individual plant and bare soil. Generally, for all OTC measurements, ET decreased over the period of observation. Daily ET was most elevated for *Senna artemisioides* and *Sclerolaena birchii*, and lowest for bare soil on all three days of measurement. However, three different temporal characteristics of daily ET/E were observed for the two plant species and bare soil. For *Senna artemisioides*, daily ET was highest (e.g. 4.8 mm d^{-1} for Sen1) three and five days after watering, but dropped to 3.1 mm d^{-1} at seven days, while for *Sclerolaena birchii* no such distinctive pattern of daily ET was detected (e.g., 2.6, 2.4, and 2.0 mm d^{-1} for Scl1). Contrary to both plant species, evaporation from bare soil (E_b) was elevated on the third day only (1.2 mm d^{-1}) and dropped substantially to 0.7 mm d^{-1} five and seven days after watering (Fig. 4).

ET$_i$, E_b, and VPD followed diurnal courses as shown in Fig. 5. For both *Senna artemisioides* and *Sclerolaena birchii*, ET$_i$ exceeded E_b as early as 07:00 h, indicating the role vegetation plays for water extraction. *Senna artemisioides* showed markedly higher values of diurnal ET three and five days after watering compared to *Sclerolaena birchii* (Fig. 5a, b). Seven days after watering, the differences between the two species were only apparent in the morning, while afternoon ET values were similar (Fig. 5c).

The diurnal courses in Fig. 5 indicate the occurrence of different relationships between ET$_i$ or E_b and VPD for observations before and after midday. Therefore, we estimated the strength of the linear relationship [coefficient of correlation (R^2)] between

both metrics and their slope for observations in the morning and afternoon (Fig. 6). The distinction between morning and afternoon values was made based on the maximum value of ET_i or E_b for each day, which occurred between 13:00 and 14:00 h. In general, a strong positive linear relationship was identified between ET_i or E_b and

5 VPD with values of R^2 ranging between 0.87 and 0.76. For all measurements the relationship was stronger in the morning than in the afternoon. The slopes of the regression lines were most elevated for *Senna artemisioides* (Fig. 6b) with values of 5.2×10^{-5} mm s^{-1} kPa^{-1} and 7.5×10^{-5} mm s^{-1} kPa^{-1}, in the morning and afternoon, respectively. For *Sclerolaena birchii* the slopes were markedly lower (Fig. 6c) with val-

10 ues of 2.5×10^{-5} mm s^{-1} kPa^{-1} and 3.4×10^{-5} mm s^{-1} kPa^{-1}. The steeper slopes of the regressions for both species in the afternoon are associated with the cessation of ET at much greater VPD values near sunset than in the morning. The lowest values (9.3×10^{-6} mm s^{-1} kPa^{-1} and 8.5×10^{-6} mm s^{-1} kPa^{-1}) were derived for the slope of the regression line between E_b and VPD (Fig. 6c).

15 As both plant species show differences in their plant specific ET, we investigated whether the species composition, given the observed vegetation coverage of 26 %, is influencing ET on a plot scale. In Fig. 7 we plotted estimated time series of ET_{plot} for three scenarios of species composition, as well as pET. For all three scenarios, ET_{plot} was markedly below pET. Moreover, no pronounced difference was found for ET_{plot}

20 between the three scenarios.

In order to investigate the influence of vegetative coverage (FPC_v) on the results derived in Fig. 7, we compared the projections of ET_{plot} given the ET_i and E_b values observed five days after watering (Fig. 4) for the same scenarios of species composition in relation to FPC_v. For this theoretical projection it is assumed that ET would

25 not be affected by a possible depletion of soil water. The results in Fig. 8 indicate that below vegetation coverage of 50 % the influence of species composition on ET_{plot} was relatively small, whereas for values of FPC_v above 80 % species composition critically influenced ET_{plot}. In the scenario where *Senna artemisioides* was the dominant species and vegetation cover was 100 %, pET could be used as a predictor of ET_{plot}.

4 Discussion

4.1 Ecohydrology of vegetation on ET cover systems

For water-limited ecosystems, evapotranspirational losses constitute the most critical ecohydrological variable (Hultine and Bush, 2011; Rodriguez-Iturbe et al., 2001). The results of this field study confirm that both evapotranspiration from individual plants ET_i) and evaporation from bare soil (E_b) are increased substantially under wet soil conditions, i.e. shortly after initial watering (Fig. 4) which simulated a rainfall event of 17 mm. However, the maximum diurnal rates of water loss into the atmosphere are markedly higher for both plant species than from bare soil (Fig. 5), resulting in overall higher daily ET_i compared to E_b (Fig. 4). This emphasises the critical role of transpiration when partitioning evapotranspiration into evaporation from bare soil and plant transpiration (Cavanaugh et al., 2011; Raz-Yaseef et al., 2012; Xu et al., 2011; Zhang et al., 2011). Daily E_b from the soil surface is already stable five days after watering, indicating that E_b of a semi-arid environment quickly converges to its minimum (Paruelo et al., 1991; Wythers et al., 1999), when a minimum water content has been reached in a generally dry soil profile. The lack of a marked drop in ET_i from *Senna artemisioides* before the seventh day after watering (Fig. 4) indicates limited but continuing plant-available water in the root zone (Denmead and Shaw, 1962; Williams and Albertson, 2004).

Not only are daily patterns of ET_i and E_b influenced by soil water availability in combination with low soil hydraulic conductivity, but these factors may also be more important than atmospheric water demand (Liu et al., 2010; Pingintha et al., 2010; Stoy et al., 2006; van Heerwaarden et al., 2010; Wilske et al., 2010). For ecosystems with no soil water limitation evapotranspiration is mainly governed by the atmospheric water demand (Laio et al., 2001; Mackay et al., 2007; Rejskova et al., 2012; Takagi et al., 1998; Tang et al., 2006) and radiation (Mackay et al., 2007; Tang et al., 2006; Wolf et al., 2011). However, with decreasing soil water potential, i.e. drying of soil, evapotranspiration is more and more limited by plant-available soil water, associated with a declining unsaturated hydraulic conductivity of the soil (Seneviratne et al., 2010). The

distinctively different relationships between ET_i or E_b and VPD for the morning and afternoon, as well as for the two plant species and bare soil (Fig. 6), indicate that ET_i or E_b are not solely determined through atmospheric demand, but also by soil water flow characteristics. The similar responses of both species to increasing VPD in the morning of all three measurement days (Fig. 5) suggests that rehydration occurred throughout the plant on all nights during the observation period. However, the steeper slope of the regression line describing ET_i of *Senna artemisioides* (Fig. 6b) indicates faster water transport to the evaporation surfaces within leaves which could be due to a higher ratio of vascular conducting surface to leaf area surface, a closer connection between water storage and conducting tissues, or a higher leaf area conductance under optimum condition (Huber, 1956; Zimmermann and Brown, 1971). The distinctively different correlations between ET_i and VPD for morning and afternoon demonstrate that in the afternoon, transpiration is limited by factors that retard water re-supply to the transpiring interface and potentially lead to stomatal closure. The main limiting factor in the afternoon is likely to be perirhizal conductance, which is a function of low soil water availability and low hydraulic conductivity. While the slopes of the regression lines for bare soil evaporation are markedly lower, the relationships of bare soil evaporation to VPD are generally similar to those of the two plant species. This implies a replenishment of the soil surface overnight akin to the rewetting of vegetation. As opposed to vegetation with roots potentially tapping into deeper and moister layers, topsoil rewetting has to be based on 1-dimensional upward flow of water, the hydraulic conductivity of the soil, water vapour movement and potential dew formation. Similar daily patterns of water loss from bare soil and the plant species may be due to condensation of water vapour, transported from moister layers at depth, within the dry surface soil layer at times of lowest soil temperatures. This moisture is subsequently available to VPD driven evaporation in the following morning (Yamanaka and Yonetani, 1999). Stronger limitations for E_b compared to ET_i arise from the fact that the soil surface dries to much lower water potentials than the deeper root zone of the vegetation. This leads to a strongly reduced unsaturated hydraulic conductivity which is further pronounced

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through conditions at the soil to atmosphere interface while the 3-dimensional water flow to roots and water depletion in the soil space around roots is less strongly affecting the actual hydraulic properties.

In contrast to *Senna artemisioides,* the pattern of daily ET_i for *Sclerolaena birchii* was much more uniform (Fig. 4), indicating different water balance characteristics for the two plant species compared to evaporation from bare soil. Distinguishing between intensive and extensive water exploiters (Rodriguez-Iturbe et al., 2001), *Senna artemisioides* can be considered an intensive water exploiter, showing a strong increase of ET_i after a rain pulse, while the extensive exploiter *Sclerolaena birchii* mainly relies on deeper soil water and only shows a slight, delayed, or no reaction to rain events (Burgess, 2006; Rodriguez-Iturbe et al., 2001). Root excavations examined for the two plant species after the field campaign confirmed the hypothesis of a deeper root zone for *Sclerolaena birchii*. This species explores the cover system to a depth of 1.6 m although most of the root biomass was located between 0.1 and 1.0 m depth. Most of the *Senna artemisioides* root biomass was found to be in the upper 0.1 m of soil while no roots occurred below a depth of 1.1 m.

Given the critical role plant transpiration imposes for ET of areas covered with vegetation, it is reasonable to question the relevance of this result for plot evapotranspiration under conditions of low vegetation coverage. Many studies have concluded that in arid and semi-arid ecosystems evaporation from bare soil is a much more important contributor to plot ET than plant transpiration (e.g. Lauenroth and Bradford, 2006; Paruelo et al., 1991; Stannard and Weltz, 2006). Indeed, the projections of three scenarios of species composition plotted in Fig. 7 suggest that for a vegetation cover percentage as low as 26 % (as estimated at the study site), vegetation composition is irrelevant for daily plot evapotranspiration. Furthermore, for all scenarios, the actual plot evapotranspiration remains markedly below the potential evapotranspiration, indicating that the latter is a rather weak predictor for plot evapotranspiration under conditions of low vegetation coverage.

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However, the opposite is the case as vegetation coverage approaches 100 % and species with high transpiration rates such as *Senna artemisioides,* dominate the plant community (Fig. 8). In general, vegetation composition plays a critical role in water loss from a cover system if vegetation coverage exceeds 50 %. Nevertheless, it should be noted that for the sustainable establishment of plant communities, vegetation density has to be in equilibrium with soil moisture availability (Specht and Specht, 1999; Josa et al., 2012). In semi-arid Australia, vegetation coverage on rehabilitated waste rock material is generally below that of natural sites and rarely exceeds 50 % (Morrison et al., 2005; Vickers et al., 2012). In addition, vegetation on rehabilitated areas shows a higher sensitivity to environmental fluctuations (Vickers et al., 2012) and may therefore be more susceptible to death during prolonged periods of drought.

4.2 Implications for evapotranspiration cover design

All the above findings have critical implications for the design of any ET cover system (be it waste rock covers in the mining industry or municipal landfill covers), particularly with regard to species selection and composition of plant communities in the context of climatic conditions. Keeping in mind the fundamental objective of ET cover systems, which is to minimise drainage by, for example, maximising evapotranspiration (Salt et al., 2011), it becomes apparent that site-specific conditions, such as the climate regime, are crucial. Both plant species considered here seem to be well adapted to the climatic conditions of the site although they exhibit different water usage characteristics. The intensive water exploiter *Senna artemisioides* facilitates higher water loss through ET shortly after rainfall events and should therefore be more suitable for areas with rainfall occurring predominantly in frequent and low intensity events, eventually resulting in high soil infiltration rates. If the climate is characterised by prolonged drought periods and if rainfall events occur as high intensity storms, a more extensive water user with deeper roots and hence extended long-term water use may be preferable, such as *Sclerolaena birchii*. It is clear that, under the current climate of western New South Wales, both intensive and extensive water users can survive. However,

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the initial re-establishment of those ecosystems might be challenging since intensive water users with elevated initial biomass production may out-compete extensive water users if both species show similar drought adaptations (Smesrud et al., 2012; Zea-Cabrera et al., 2006). Nevertheless, the coexistence of species with those contrast-
5 ing water use strategies is favoured by a spatial segregation of soil moisture (Zea-Cabrera et al., 2006), which is likely to occur on reconstructed ecosystems due to the high likelihood of spatial heterogeneity of soil physical properties (Gwenzi et al., 2011; Krümmelbein et al., 2010; Mazur et al., 2011; Schneider et al., 2010).

Regardless of the water use characteristics of individual species, the plant commu-
10 nity tends to converge towards a stable equilibrium with long-term availability of soil water (Specht and Specht, 1999). It is therefore questionable if water-limited ecosys-tems in arid and semi-arid regions are able to sustain vegetation coverage of above 50 %. This value, however, is critical to employ plant transpiration as the main driver of water loss from soil rather than evaporation (Fig. 8). Therefore, the application and
15 management of ET cover systems in water-limited environments remains a challenging task for both industry and science.

Analysing the soil-vegetation-atmosphere continuum in the context of ET cover sys-tems denotes an important future research task (Arora, 2002), which requires (a) fur-ther on-site measurements with regard to vertical soil water dynamics, (b) controlled
20 manipulative experiments with regard to ET characteristics of plants under limited soil water conditions, and (c) modelling frameworks aiming to establish an optimal soil-vegetation design with regard to soil texture and thickness, and climatically well-adapted plant communities and their species composition. Built on those premises, this study denotes the starting point of further investigations to identify optimal ET cover de-
25 signs that are robust and reliable under given climatic conditions.

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5 Conclusions

This study has exemplified that a well-considered selection of plant species can make the difference between success and failure of operational ET cover systems. The dynamic interplay between climate, plant community and soil water denotes the crucial foundation of designing robust and reliable ET cover systems in the face of extreme weather events of semi-arid and arid areas such as prolonged drought periods and intense rainfall events. Built on this premise, the distinct ET characteristics of plant species can be utilised to design an optimal barrier that maximises ET and thereby minimises drainage into the underlying hazardous wastes. However, considering the minor role vegetation ET plays under conditions of low vegetation coverage, we stress the need for thorough evaluation of the trade-offs between total plant-available water in dryland ecosystems and the relatively large vegetation coverage that is required to make plant community composition a critical determinant of water loss through evapotranspiration.

References

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop evapotranspiration: guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper, 56, 1–328, 1998.

Arora, V.: Modeling vegetation as a dynamic component in soil-vegetation-atmosphere transfer schemes and hydrological models, Rev. Geophys., 40, 1006, doi:10.1029/2001rg000103, 2002.

Barnswell, K. D. and Dwyer, D. F.: Assessing the Performance of Evapotranspiration Covers for Municipal Solid Waste Landfills in Northwestern Ohio, J. Environ. Engineering-Asce, 137, 301–305, doi:10.1061/(asce)ee.1943-7870.0000326, 2011.

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Benson, C. H., Albright, W. H., and Roesler, A. C.: Evaluation of final cover performance: field datafrom the Alternative Cover Assesment Program (ACAP), Proc. Waste Management 02, Tuscon, AZ, 2002.

Bohnhoff, G. L., Ogorzalek, A. S., Benson, C. H., Shackelford, C. D., and Apiwantragoon, P.: Field data and water-balance predictions for a monolithic cover in a semiarid climate, J. Geotech. Geoenviron., 135, 333–348, doi:10.1061/(asce)1090-0241(2009)135:3(333), 2009.

Burgess, S. S. O.: Measuring transpiration responses to summer precipitation in a Mediterranean climate: a simple screening tool for identifying plant water-use strategies, Physiol. Plantarum, 127, 404–412, doi:10.1111/j.1399-3054.2006.00669.x, 2006.

Cavanaugh, M. L., Kurc, S. A., and Scott, R. L.: Evapotranspiration partitioning in semiarid shrubland ecosystems: a two-site evaluation of soil moisture control on transpiration, Ecohydrology, 4, 671–681, doi:10.1002/eco.157, 2011.

Climate of Cobar: http://www.bom.gov.au/weather/nsw/cobar/climate.shtml (last access: 1 March 2012), 2012.

Denmead, O. T. and Shaw, R. H.: Availability of soil water to plants as affected by soil moisture content and meteorological conditions, Agron. J., 54, 385–390, 1962.

Donovan, L. A., Grise, D. J., West, J. B., Pappert, R. A., Alder, N. N., and Richards, J. H.: Predawn disequilibrium between plant and soil water potentials in two cold-desert shrubs, Oecologia, 120, 209–217, doi:10.1007/s004420050850, 1999.

Garcia, R. L., Norman, J. M., and McDermitt, D. K.: Measurements of canopy gas exchange using an open chamber system, Remote Sensing Reviews, 5, 141–162, 1990.

Gwenzi, W.: Vegetation and soil controls on water redistribution on recently constructed ecosystems in water-limited environments, PhD, Faculty of Natrural and Agricultural Sciences, The University of Western Australia, Perth, 2010.

Gwenzi, W., Hinz, C., Holmes, K., Philip, I. R., and Mullins, I. J.: Field-scale spatial variability of saturated conductivity on a recently constructed artifical ecosystem, Geoderma, 166, 43–56, 2011.

Hauser, V. L., Weand, B. L., and Gill, M. D.: Natural covers for landfills and buried waste, J. Environ. Engineering-Asce, 127, 768–775, 2001.

Huber, B.: Die Gefäßleitung, in: Handbuch der Pflanzenphysiologie, edited by: Ruhland, W., Ashby, E., Bonner, J., Geiger-Huber, M., James, W. O., Lang, A., Müller, D., and Stälfelt, M. G., Springer-Verlag, Berlin, 541–582, 1956.

The importance of plant water use on evapotranspiration covers

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Interactive Discussion

Hultine, K. R. and Bush, S. E.: Ecohydrological consequences of non-native riparian vegetation in the southwestern United States: A review from an ecophysiological perspective, Water Resour. Res., 47, W07542, doi:10.1029/2010wr010317, 2011.

Hutley, L. B., O'Grady, A. P., and Eamus, D.: Evapotranspiration from eucalypt open-forest savanna of northern Australia, Funct. Ecol., 14, 183–194, 2000.

Josa, R., Jorba, M., and Ramon Vallejo, V.: Opencast mine restoration in a Mediterranean semi-arid environment: Failure of some common practices, Ecol. Eng., 42, 183–191, doi:10.1016/j.ecoleng.2012.02.020, 2012.

Knoche, D., Schramm, A., and Marski, R.: Hydrological properties of a double-layer soil cover system for uranium mining dumps in Eastern Germany, Arch Acker Pfl Boden, 52, 37–43, doi:10.1080/03650340500421281, 2006.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., and Rubel, F.: World Map of the Koeppen-Geiger climate classification updated, Meterologische Zeitschrift, 15, 259–263, 2006.

Krümmelbein, J., Horn, R., Raab, T., Bens, O., and Huettl, R. F.: Soil physical parameters of a recently established agricultural recultivation site after brown coal mining in Eastern Germany, Soil & Tillage Research, 111, 19–25, doi:10.1016/j.still.2010.08.006, 2010.

Laio, F., Porporato, A., Ridolfi, L., and Rodriguez-Iturbe, I.: Plants in water-controlled ecosystems: active role in hydrologic processes and response to water stress – II. Probabilistic soil moisture dynamics, Adv. Water Resour., 24, 707–723, doi:10.1016/s0309-1708(01)00005-7, 2001.

Lauenroth, W. K. and Bradford, J. B.: Ecohydrology and the partitioning AET between transpiration and evaporation in a semiarid steppe, Ecosystems, 9, 756–767, 2006.

Liu, S., Li, S. G., Yu, G. R., Asanuma, J., Sugita, M., Zhang, L. M., Hu, Z. M., and Wei, Y. F.: Seasonal and interannual variations in water vapor exchange and surface water balance over a grazed steppe in central Mongolia, Agr. Water Manage., 97, 857–864, doi:10.1016/j.agwat.2010.01.016, 2010.

Lynch, K. M.: Seasonal soil and plant water relations of rehabilitated sites in Gove, Northern Australia, PhD, Centre for Mined Land Rehabilitation, The University of Queensland, Brisbane, 2007.

Mackay, D. S., Ewers, B. E., Cook, B. D., and Davis, K. J.: Environmental drivers of evapotranspiration in a shrub wetland and an upland forest in northern Wisconsin, Water Resour. Res., 43, W03442, doi:10.1029/2006wr005149, 2007.

Madalinski, K. L., Gratton, D. N., and Weisman, R. J.: Evapotranspiration covers: An innovative approach to remediate and close contaminated sites, Remediation Journal, 14, 55–67, 2003.

Mazur, K., Schoenheinz, D., Biemelt, D., Schaaf, W., and Grunewald, U.: Observation of hydrological processes and structures in the artificial Chicken Creek catchment, Phys. Chem. Earth, 36, 74–86, doi:10.1016/j.pce.2010.10.001, 2011.

Melchior, S., Sokollek, V., Berger, K., Vielhaber, B., and Steinert, B.: Results from 18 Years of In Situ Performance Testing of Landfill Cover Systems in Germany, J. Environ. Engineering-Asce, 136, 815–823, doi:10.1061/(ASCE)EE.1943-7870.0000200, 2010.

Monteith, J. L. and Unsworth, M. H.: Principles of environmental physics, 2nd ed., Edward Arnold, London, 1990.

Morrison, B., Lamb, D., and Hundloe, T.: Assessing the likelihood of mine site revegetation success: a Queensland case study, Australasian Journal of Environmental Management, 12, 165–182, 2005.

Mueller-Dombois, D. and Ellenberg, H.: Aims and methods of vegetation ecology, John Wiley & Sons, New York, 1974.

Müller, J., Eschenroder, A., and Diepenbrock, W.: Through-flow chamber CO_2/H_2O canopy gas exchange system-Construction, microclimate, errors, and measurements in a barley (Hordeum vulgare L.) field, Agr For. Meteorol., 149, 214–229, doi:10.1016/j.agrformet.2008.08.007, 2009.

Murray, F. W.: On the computation of vapor pressure, J. Appl. Meteorol., 6, 203–204, 1967.

Nyhan, J. W., Schofield, T. G., and Starmer, R. H.: A water balance study of four landfill cover designs varying in slope for semiarid regions, J. Environ. Qual., 26, 1385–1392, 1997.

O'Kane Consultants Inc.: As-built report for the Peak Gold Mine tailings dam cover system field trials, Saskatoon, Canada, 2002.

Paruelo, J. M., Aguiar, M. R., and Golluscio, R. A.: Evaporation estimates in arid environments – An evaluation of some methods for the Patagonian steppe, Agr For. Meteorol., 55, 127–132, 1991.

Pingintha, N., Leclerc, M. Y., Beasley Jr., J. P., Durden, D., Zhang, G., Senthong, C., and Rowland, D.: Hysteresis response of daytime net ecosystem exchange during drought, Biogeosciences, 7, 1159–1170, doi:10.5194/bg-7-1159-2010, 2010.

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Preston, G. M. and McBride, R. A.: Assessing the use of poplar tree systems as a landfill evapotranspiration barrier with the SHAW model, Waste Manage. Res., 22, 291–305, doi:10.1177/0734242x04045429, 2004.

Raz-Yaseef, N., Yakir, D., Schiller, G., and Cohen, S.: Dynamics of evapotranspiration partitioning in a semi-arid forest as affected by temporal rainfall patterns, Agr. For. Meteorol., 157, 77–85, doi:10.1016/j.agrformet.2012.01.015, 2012.

Rejskova, A., Cizkova, H., Brom, J., and Pokorny, J.: Transpiration, evapotranspiration and energy fluxes in a temperate wetland dominated by Phalaris arundinacea under hot summer conditions, Ecohydrology, 5, 19–27, doi:10.1002/eco.184, 2012.

Rock, S. A.: Evapotranspiration covers for landfills, in: Application of Phytotechnologies for Cleanup of Industrial, Agricultural, and Wastewater Contamination, edited by: Kulakow, P. A., and Pidlisnyuk, V. V., NATO Science for Peace and Security Series C – Environmental Security, 189–198, 2010.

Rodriguez-Iturbe, I., Porporato, A., Laio, F., and Ridolfi, L.: Plants in water-controlled ecosystems: active role in hydrologic processes and response to water stress – I. Scope and general outline, Adv. Water Res., 24, 695–705, doi:10.1016/s0309-1708(01)00004-5, 2001.

Salt, M., Lightbody, P., Stuart, R., Albright, W. H., and Yeates, R.: Guidelines for the assessment, design, construction and maintenance of phytocaps as final covers for landfills, Waste Management Association of Australia, 90, 2011.

Schneider, A., Baumgartl, T., Doley, D., and Mulligan, D.: Evaluation of the Heterogeneity of Constructed Landforms for Rehabilitation Using Lysimeters, Vadose Zone J., 9, 898–909, doi:10.2136/vzj2009.0172, 2010.

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., and Teuling, A. J.: Investigating soil moisture-climate interactions in a changing climate: A review, Earth-Sci. Rev., 99, 125–161, doi:10.1016/j.earscirev.2010.02.004, 2010.

Smesrud, J. K., Benson, C. H., Albright, W. H., Richards, J. H., Wright, S., Israel, T., and Goodrich, K.: Using pilot test data to refine an alternative cover design in northern California, Int. J. Phytoremediat., 14, 76–93, doi:10.1080/15226514.2011.607871, 2012.

Specht, R. L.: Foliage projective cover and standing biomass, in: Vegetation classification in Australia: Proceedings of a workshop sponsored by CSIRO Division of Land Use Research, Canberra, October 1978, edited by: Gillison, A. N. and Anderson, D. J., CSIRO and Australian National university Press, Canberra, 10–21, 1981.

The importance of plant water use on evapotranspiration covers

A. Schneider et al.

Specht, R. L. and Specht, A.: Australian plant communities: Dynamics of structure, growth and biodiversity, Oxford University Press, New York, 1999.

Stannard, D. I. and Weltz, M. A.: Partitioning evapotranspiration in sparsely vegetated rangeland using a portable chamber, Water Resour. Res., 42, W02413, doi:10.1029/2005wr004251, 2006.

Stoy, P. C., Katul, G. G., Siqueira, M. B. S., Juang, J.-Y., Novick, K. A., McCarthy, H. R., Oishi, A. C., Uebelherr, J. M., Kim, H.-S., and Oren, R.: Separating the effects of climate and vegetation on evapotranspiration along a successional chronosequence in the southeastern US, Glob Change Biol., 12, 2115–2135, doi:10.1111/j.1365-2486.2006.01244.x, 2006.

Takagi, K., Tsuboya, T., and Takahashi, H.: Diurnal hystereses of stomatal and bulk surface conductances in relation to vapor pressure deficit in a cool-temperate wetland, Agr. For. Meteorol., 91, 177–191, doi:10.1016/s0168-1923(98)00078-1, 1998.

Tang, J., Bolstad, P. V., Ewers, B. E., Desai, A. R., Davis, K. J., and Carey, E. V.: Sap flux-upscaled canopy transpiration, stomatal conductance, and water use efficiency in an old growth forest in the Great Lakes region of the United States, J. Geophys. Res.-Biogeo., 111, G02009, doi:10.1029/2005jg000083, 2006.

van Genuchten, M. T.: A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, Soil Soc. Sci. Am. J., 44, 892–898, 1980.

van Heerwaarden, C. C., de Arellano, J. V. G., Gounou, A., Guichard, F., and Couvreux, F.: Understanding the daily cycle of evapotranspiration: A method to quantify the influence of forcings and feedbacks, J. Hydrometeorol., 11, 1405–1422, doi:10.1175/2010jhm1272.1, 2010.

Vickers, H., Gillespie, M., and Gravina, A.: Assessing the development of rehabilitated grasslands on post-mined landforms in north west Queensland, Australia, Agriculture, Ecosystems, Environment, doi:10.1016/j.agee.2012.05.024, in press, 2012.

Waugh, W. J., Thiede, M. E., Bates, D. J., Cadwell, L. L., Gee, G. W., and Kemp, C. J.: Plant cover and water-balance in gravel admixtures at an arid waste-burial site, J. Environ. Qual., 23, 676–685, 1994.

Williams, C. A. and Albertson, J. D.: Soil moisture controls on canopy-scale water and carbon fluxes in an African savanna, Water Resour. Res., 40, W09302, doi:10.1029/2004wr003208, 2004.

Wilske, B., Kwon, H., Wei, L., Chen, S. P., Lu, N., Lin, G. H., Xie, J., Guan, W. B., Pendall, E., Ewers, B. E., and Chen, J. Q.: Evapotranspiration (ET) and regulating mechanisms in two

The importance of plant water use on evapotranspiration covers

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semiarid Artemisia-dominated shrub steppes at opposite sides of the globe, J. Arid Environ., 74, 1461–1470, doi:10.1016/j.jaridenv.2010.05.013, 2010.

Wolf, S., Eugster, W., Majorek, S., and Buchmann, N.: Afforestation of tropical pasture only marginally affects ecosystem-scale evapotranspiration, Ecosystems, 14, 1264–1275, doi:10.1007/s10021-011-9478-y, 2011.

Wythers, K. R., Lauenroth, W. K., and Paruelo, J. M.: Bare-soil evaporation under semiarid field conditions, Soil Sci. Soc. Am. J., 63, 1341–1349, 1999.

Xu, S. G., Ma, T., and Wang, H.: Partitioning of vertical water loss in reed swamp wetlands: theory, research and application, Sci. China-Technol. Sci., 54, 2896–2903, doi:10.1007/s11431-011-4556-0, 2011.

Yamanaka, T. and Yonetani, T.: Dynamics of the evaporation zone in dry sandy soils, J. Hydrol., 217, 135–148, doi:10.1016/s0022-1694(99)00021-9, 1999.

Yunusa, I. A. M., Zeppel, M. J. B., Fuentes, S., Macinnis-Ng, C. M. O., Palmer, A. R., and Eamus, D.: An assessment of the water budget for contrasting vegetation covers associated with waste management, Hydrol. Process., 24, 1149–1158, doi:10.1002/hyp.7570, 2010.

Zea-Cabrera, E., Iwasa, Y., Levin, S., and Rodriguez-Iturbe, I.: Tragedy of the commons in plant water use, Water Resour. Res., 42, W06d02, doi:10.1029/2005wr004514, 2006.

Zhang, Y. C., Shen, Y. J., Sun, H. Y., and Gates, J. B.: Evapotranspiration and its partitioning in an irrigated winter wheat field: A combined isotopic and micrometeorologic approach, J. Hydrol., 408, 203–211, doi:10.1016/j.jhydrol.2011.07.036, 2011.

Zimmermann, H. and Brown, C. L.: Trees – Structure and function, Springer-Verlag, New York, 1971.

Zornberg, J. G., LaFountain, L., and Caldwell, J. A.: Analysis and design of evapotranspirative cover for hazardous waste landfill, J. Geotech. Geoenviron., 129, 427–438, 2003.

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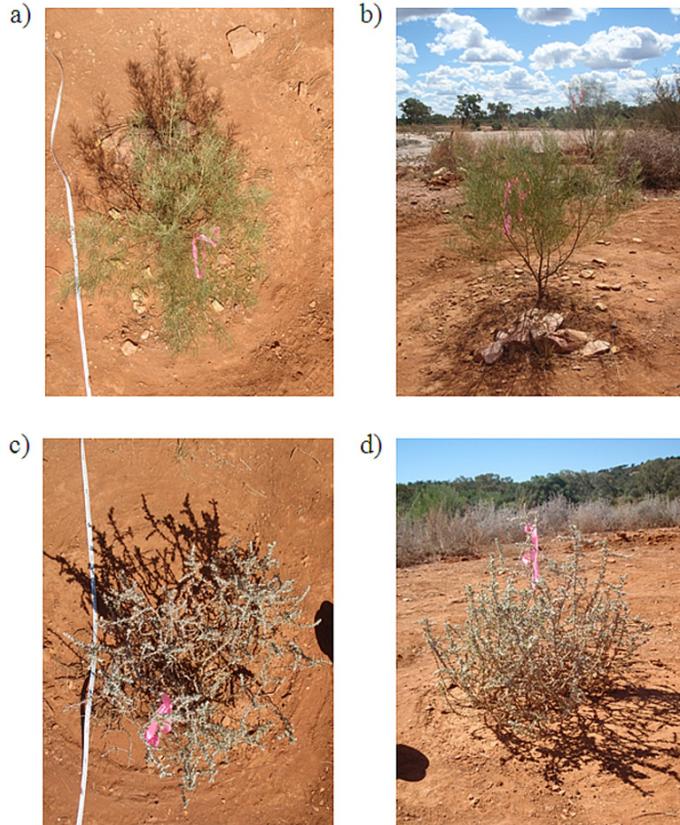
Fig. 1. Top and lateral views of *Senna artemisioides* **(a)** and **(b)** and *Sclerolaena birchii* **(c)** and **(d)**

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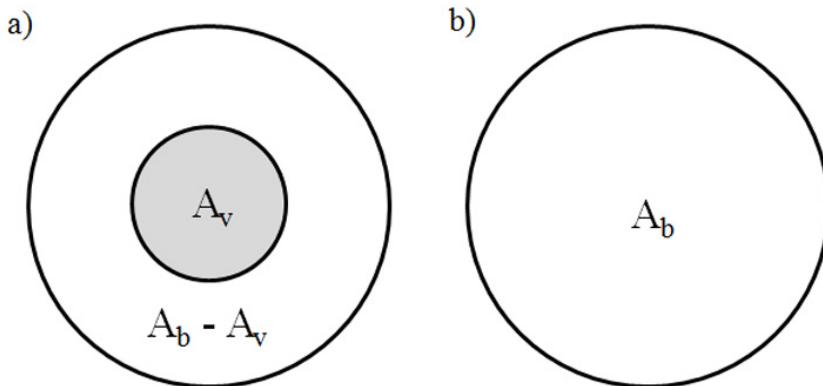
Fig. 2. Sketch of areas covered by the open top chamber for **(a)** vegetation coverage (A_v), and **(b)** bare soil (A_b), see Eqs. (5) and (6).

Fig. 3. Volumetric soil moisture in the upper 5 cm beneath the replicates of *Sclerolaena birchii* (Scl, black), *Senna artemisioides* (Sen, grey) and for the bare soil (bare, white) before and after application of 17 mm water.
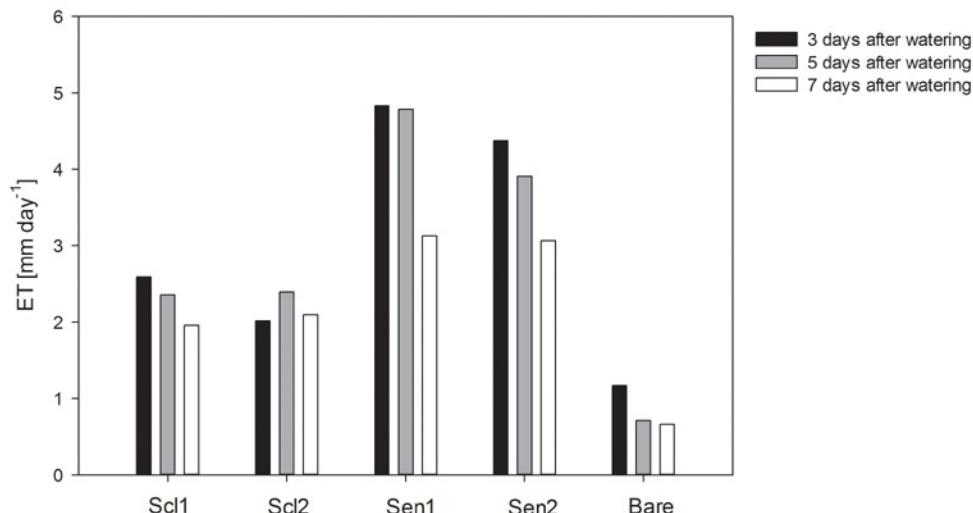
Fig. 4. Daily evapotranspiration for individual plants (ET$_i$) of *Sclerolaena birchii* (Scl), *Senna artemisioides* (Sen) and bare soil evaporation (Bare) on the third (black), fifth (grey) and seventh (white) day after watering.
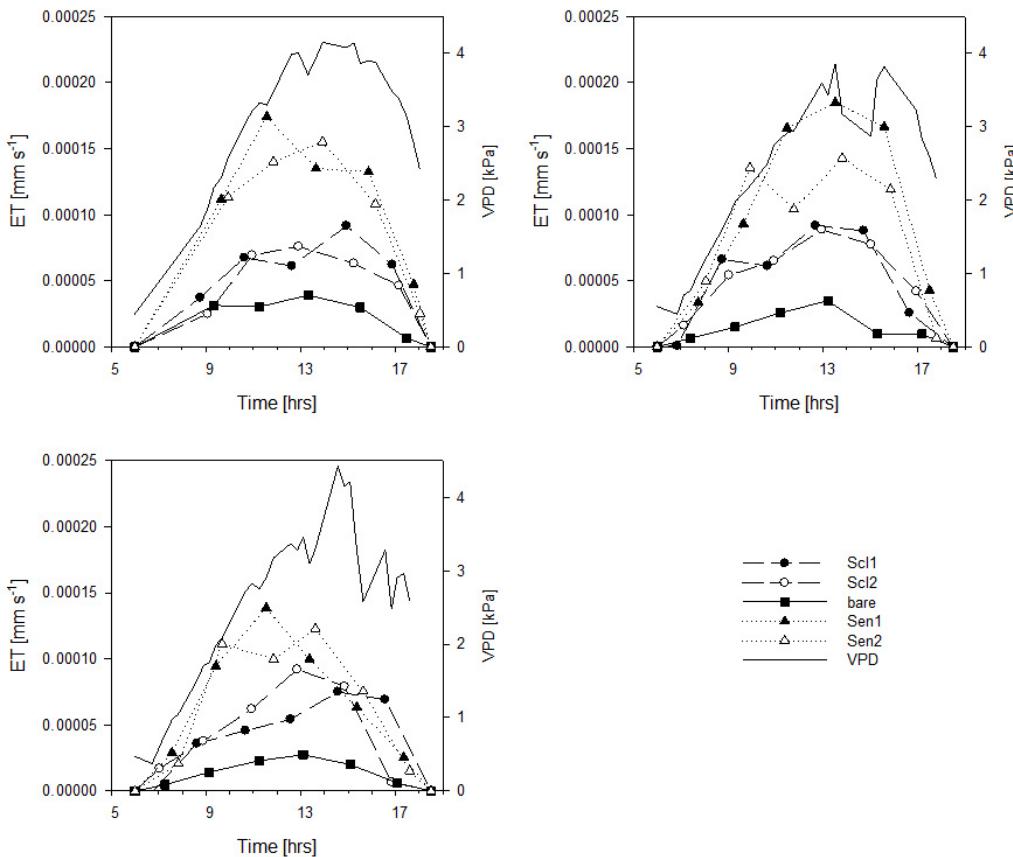
Fig. 5. Diurnal course of ET and VPD (solid line) from 06:00 h to 18:30 h for *Sclerolaena birchii* (Scl, circles), *Senna artemisioides* (Sen, triangles) and bare soil (square) **(a)** three days, **(b)** five days, and **(c)** seven days after watering.
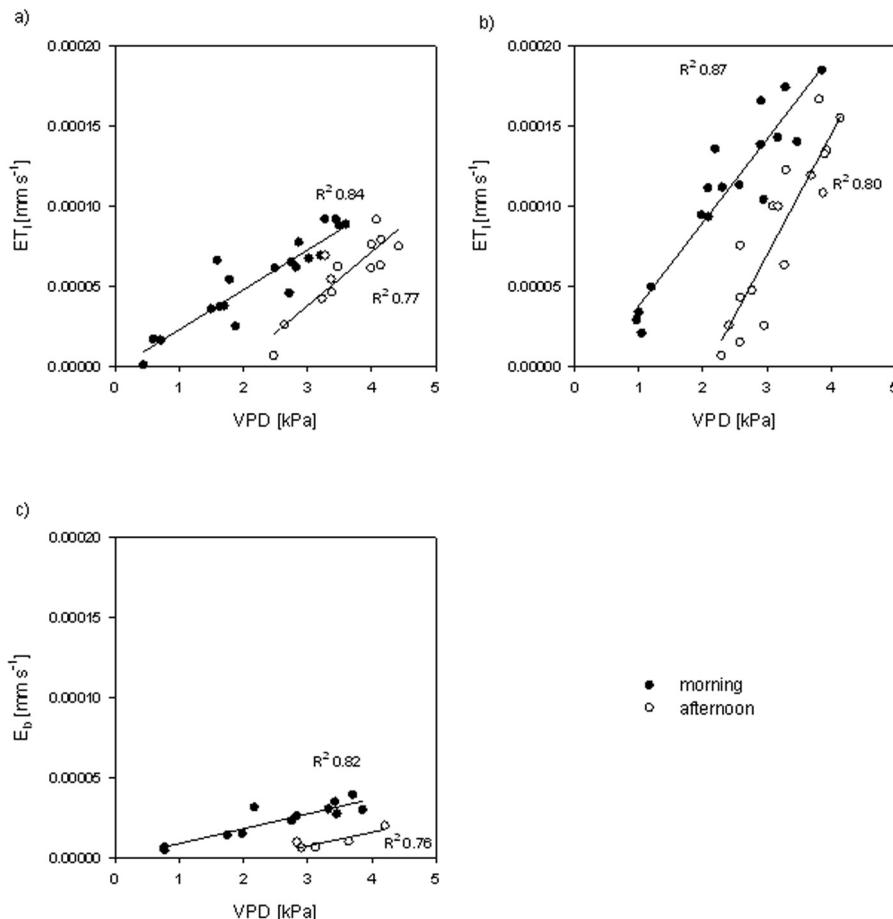
Fig. 6. Relationships between evapotranspiration (ET$_i$) and vapour pressure deficit (VPD) for **(a)** *Sclerolaena birchii*, **(b)** *Senna artemisioides*, and **(c)** evaporation from bare soil (E_b) in the morning (solid circles) and afternoon (open circles), respectively.
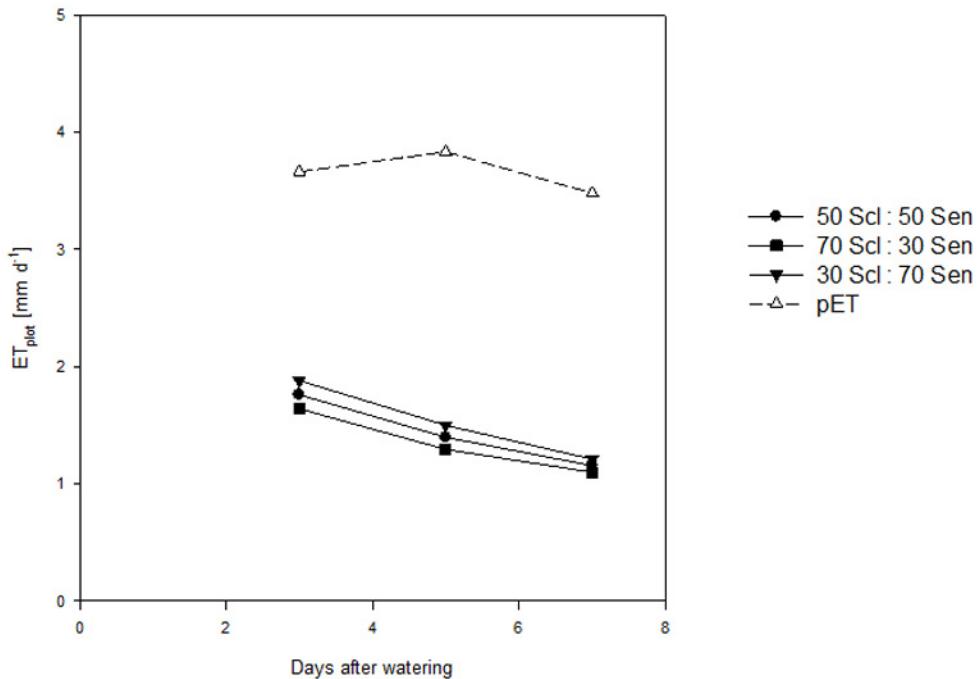
Fig. 7. Plot evapotranspiration ET$_{plot}$) (given the observed total vegetation coverage of 26 %) calculated as (1) no weighting between plants (circles), (2) weighting of 70 % *Sclerolaena birchii* (Scl) to 30 % *Senna artemisioides* (Sen) ratio (squares) and (3) weighting of 30 % *Sclerolaena birchii* to 70 % *Senna artemisioides* ratio (triangles). Open diamonds indicate average daily potential evapotranspiration pET) (Eq. 4).
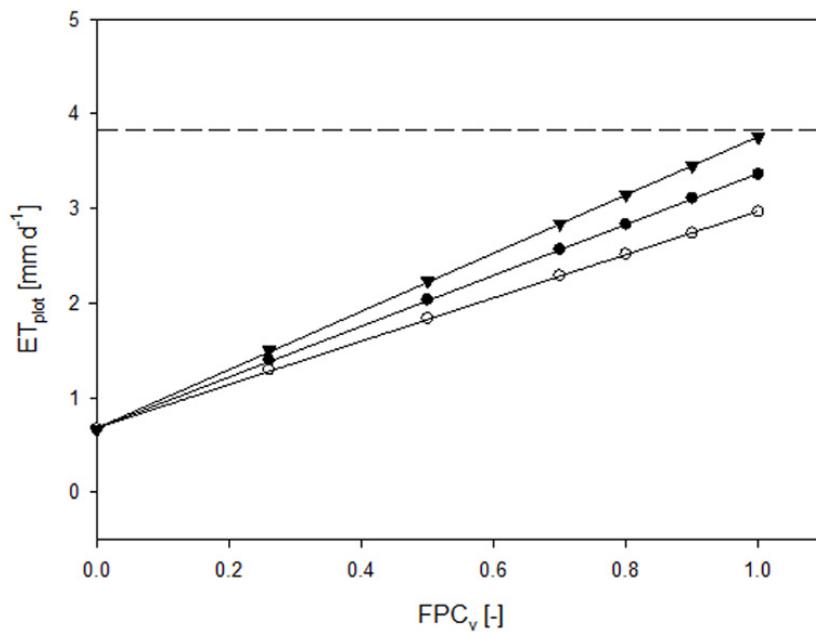
Fig. 8. Relationships between ET_{plot} and foliage projective cover (FPC_v) five days after watering for: no weighing of plant component between plant species (solid circles), 70 % of plant component formed by *Sclerolaena birchii* (open circles), and 70 % of plant component formed by *Senna artemisioides* (solid triangles). The dashed line indicates potential evapotranspiration (Eq. 4).