Ecohydrological controls of soil evaporation in deciduous drylands: How the hierarchical effects of litter, patch and vegetation mosaic cover interact with phenology and season

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ARTICLE INFO

ABSTRACT

Soil evaporation, a critical ecohydrological process in drylands, can exhibit substantial spatio-temporal variation. Spatially, ecohydrological controls of soil evaporation may generally depend on a hierarchical structure spanning from the presence or absence of litter, through canopy patches of woody plants and intercanopy patches separating them, up to the overall vegetation mosaic characterized by density of woody plant cover in the landscape, although assessment of these factors in concert is generally lacking. Temporally, ecohydrological controls can be further complicated by not only seasonal climate, but also phenology, particularly in seasonally deciduous drylands. We experimentally assessed the interactive controls on soil evaporation along a gradient of mesquite cover (Prosopis velutina) within the North American monsoon region, with respect to such hierarchical structure and seasonality/phenology. Our results indicate that presence of litter exerts a dominant control on soil evaporation, independent of seasonality; in absence of litter, both patch and mosaic attributes influence soil evaporation variably with season/phenology. Correlations from related measures of incoming energy suggest energy limits evaporation in many cases, although other factors such as wind may potentially influence hierarchical and seasonal/phenological combinations. Our results highlight the need to account for both hierarchical vegetation structure and seasonal/phenological variability to improve ecohydrological predictions of soil evaporation.

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1. Introduction

Evapotranspiration dominates water fluxes in semiarid ecosystems, often accounting for >95% of the annual water budget (Branson et al., 1981; Wilcox et al., 2003; Williams et al., 2004; Huxman et al., 2005). Although most research has focused on evapotranspiration as an aggregated process, more recently, emphasis is being placed on the importance of distinguishing between and quantifying the two major components of evapotranspiration (after accounting for evaporation of water intercepted by the canopy): evaporation from the soil and transpiration from plants (Dugas et al., 1996; Williams et al., 2004; Huxman et al., 2005; Lauenroth and Bradford, 2006; Yaseef et al., 2009). This distinction is one of the most fundamental ecohydrological challenges in drylands (Newman et al., 2006) and has important implications not only for the water budget, but also for understanding potential feedbacks between vegetation dynamics and water as well as other biogeochemical cycles (Raupach, 1998; Rodriguez-Iturbe, 2000; Eagleson, 2002; Newman et al., 2006; D'Odorico et al., 2007). In particular, determining the dynamics and drivers of soil evaporation in drylands is a fundamental step for improving estimates of the partitioning of evapotranspiration.

Soil evaporation is expected to exhibit substantial spatio-temporal variability. Spatially, the vegetation-associated controls

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of soil evaporation are expected to respond to a hierarchical structure spanning from the presence of a litter layer on the surface (Facelli and Pickett, 1991; Vetaas, 1992; Joffre, 1993), through the canopy patches of woody plants and the intercanopy patches separating them (Breshears et al., 1998; Martens et al., 2000; Loik et al., 2004), up to the overall vegetation mosaic characterized by the density of woody plant cover (Geiger, 1965; Schulze et al., 1995; Breshears et al., 1998; Roberts, 2000; Baldocchi and Xu, 2007; Villegas et al., 2009). Many ecosystems, particularly drylands, are dominated by woody plants that not only vary spatially in terms of amount of cover but also temporally because of seasonally dependent changes in leaf phenology. Such seasonal variations in plant cover associated with the deciduous nature of the dominant woody species significantly influence the dynamics of soil evaporation as well (Baldocchi et al., 1997; Wilson et al., 2000; Vivoni et al., 2008). However, previous studies of the effects of woody plants on soil evaporation and associated ecohydrological processes have largely focused on the effects of evergreen trees, where woody plant canopy cover and foliage density remain relatively constant throughout the year (Breshears et al., 1998; Martens et al., 2000; Adams, 2007; Lebron et al., 2007).

Variations in the amount and seasonality of effective surface cover associated with the phenology of woody plant cover can modify the relative importance of the physical processes that drive soil evaporation, particularly radiation availability, temperature, wind, soil and vegetation characteristics at the different levels of the vegetation structure hierarchy (Kondo et al., 1992; Baldocchi et al., 2000; Baldocchi et al., 2002; Kurc and Small, 2004). At the individual patch scale, woody plants influence the dynamics of soil evaporation by locally reducing the amounts of solar radiation reaching the ground (Breshears et al., 1998; Martens et al., 2000; Fu and Rich, 2002; Zou et al., 2007; Breshears and Ludwig, 2009) and by the addition of litter to the ground beneath the canopy (Facelli and Pickett, 1991; Lafleur, 1992; Kelliher et al., 1998; Wilson et al., 2000; Throop and Archer, 2007). At the overall vegetation mosaic scale, woody plant canopy cover can influence soil evaporation through the general attenuation of solar radiation (which differs from the localized effects of canopy patches), the modification of wind dynamics, and the alteration of soil microclimate (Geiger, 1965; Bonan, 2002; Warner, 2004; Breshears et al., 2009; Villegas et al., 2009). In addition, the interactive nature of these effects likely varies in response to associated seasonality, vegetation phenology and climate. Collectively, these issues highlight that lacking is a systematic evaluation of how the changes in surface cover imposed by the seasonal dynamics of deciduous vegetation, both at the scales of individual patches and of vegetation mosaics, influence the dynamics of soil evaporation. Such evaluation is needed to improve our understanding of the water budget in semiarid ecosystems and the potential feedbacks between the dynamics of vegetation and climate.

In this study we assess how the spatial and temporal variability in soil evaporation relates to the hierarchy of vegetation structure, specifically considering the effects of litter, patch, and vegetation mosaic scales and how these effects are influenced by the temporal dynamics associated with seasonal climate and leaf phenology. We approached this problem by performing a series of field experiments with microlysimeters. Based on our results, we discuss the mechanisms associated with these dynamics in the context of the environmental drivers of evaporation, and more generally, propose a conceptual framework to synthetically describe the mechanisms that drive soil evaporation and their interaction with vegetation patterns.

2. Materials and methods

We measured the dynamics of soil microclimate and soil evaporation along a gradient of vegetation cover located in the North American monsoon region, where soil evaporation rates and their seasonal variability can be particularly high. We assessed the seasonal dynamics of evaporation by conducting experiments during the main phenological seasons: fall intermediate senescence, winter leafless, spring intermediate green-up, and summer full leafout.

2.1. Study site

Experiments were conducted at the University of Arizona pasture cell at the Santa Rita Experimental Range (31.79° N, 110.84° W), about 50 km south of Tucson, Arizona, USA. The area is approximately 1200 m in elevation with a coarse textured, sandy-loam soil developed on Holocene-aged alluvium. Slopes range between 5% and 8%. Mean annual precipitation is 294 mm, with a bimodal distribution. Approximately 60% of the annual rain falls during the North American monsoon season, and the remaining precipitation mostly occurs during the winter (McClaran et al., 2002).

We established six 50-m transects that represent a gradient of canopy cover dominated by the seasonally deciduous velvet mesquite (*Prosopis velutina*). Canopy cover levels in this gradient included 2%, 16%, 26%, 37%, 56%, and 73%. Values of canopy cover were calculated during the full leafout season as the fraction of ground covered by the vertical projection of the canopies of all trees in the 50×20 m rectangular plot that was centered on the transect. Since cover was calculated as the area under drip line, it would only change with branch growth and death and not with. Transects were uniform with respect to edaphic, topographic and climatic conditions. In particular, soil texture, which is one of the most important variables defining soil hydraulic characteristics is not significantly different between transects (Villegas et al., 2009). On each transect, we randomly selected five canopy and five intercanopy locations, except for the 2% cover plot, where only intercanopy locations were selected. Canopy locations fell directly beneath a canopy structure whereas intercanopy locations did not have a canopy directly above them. At each one of these locations we deployed two microlysimeters: one containing bare soil and the other with a litter layer on top of the soil surface, yielding four treatments: (1) canopy locations with a litter layer, (2) canopy locations without a litter layer, (3) intercanopy locations with a litter layer, and (4) intercanopy locations without a litter layer. For each level of canopy cover, a total of 20 individual microlysimeters (except at the lowest level of canopy cover, where only 10 are measured due to the absence of canopy locations) were deployed at each experiment, resulting in a total of at least 5 replicates for each treatment at each level of canopy cover.

The microlysimeters were metal cylinders 12 cm high with a circular surface area of 254.5 cm^2. Each microlysimeter was insulated with two layers of commercially-available insulation material to avoid energy fluxes between the soil inside and outside of the lysimeter and to prevent potential temperature fluctuations associated with the manipulation of the microlysimeter during the experiments. Each microlysimeter was placed in the soil using a plastic liner that was preinstalled in the soil for ease of access. All microlysimeters were packed with a homogenized mixture of *in situ* soil to control for potential soil textural differences between them. The surface of each microlysimeter was leveled with the outside soil surface to minimize unnatural air flow at the near-ground boundary layer. Litter bags were built using the design of Throop and Archer (2007) and were 20×20 cm in size, made of

fine fiberglass window screen (∼0.9 mm openings, Phifer Wire Products, Tuscaloosa, Alabama, USA). The litter was collected on site and was 1.5 cm thick in the center of each bag, corresponding to the mean thickness of the litter layer under the canopies in the 73% canopy cover transect. Each microlysismeter had a temperature sensor installed at 5-cm depth (I-button DS1921G, Dallas Semiconductor). These sensors recorded soil temperature every 30 min throughout the duration of the soil evaporation experiments.

A soil evaporation experiment was conducted during each of the four main phenological seasons: Full leafout (June 21–June 29, 2007); leaf senescence (October 11–October 24, 2007); leafless (February 27–March 6, 2008), and leaf green-up (May 8–May 15, 2008). Soil evaporation experiments were initiated with the addition of a pulse of moisture equivalent to 20 mm to each microlysimeter (mean moisture added = 19.78 mm; 95% C.I. = 19.38–20.18). This amount of water would bring the local soil to field capacity to a depth of 10 cm (where most of the evaporation activity is expected to occur—Newman et al., 1997). Experiments were started when no rainfall events had occurred at the site for at least three weeks; this condition, along with soil moisture measurements at the nearby weather station, allowed us to assume that soils were dry at the beginning of each experiment. The pulse of moisture was simulated by the addition of commercially available ice, which was applied to the microlysimeters the night before the start of evaporation measurements and covered with plastic to minimize moisture losses via sublimation or direct evaporation from the soil surface. The use of ice (e.g. Breshears et al., 1997) improves horizontal uniformity in the application of the pulse, slows infiltration rates, creates a more uniform wetting front in the soil profile, and lowers rates of direct evaporation from the surface. Soil evaporation measurements began with the removal of the plastic cover approximately 16 h after the application of moisture, when the ice was completely melted, and all moisture had infiltrated. This time was sufficient for soil temperature to equilibrate with the environmental temperature (data not shown), thereby avoiding the potential effects of soil temperature change on soil evaporation due to ice.

Soil evaporation from the microlysimeters was calculated as the change in weight measured with portable, battery-operated, electronic scales (H-11, American Weigh Scales, Charleston, South Carolina) with 0.5 g precision, capable of accurately measuring a 0.05% change in gravimetric soil moisture content. Weight measurements were taken every 2 h during the first 24 h of the experiment, every 3 h for the following 12 h, and subsequently every 24 h up to the point when mean change in moisture content was not greater than 0.1% (gravimetric soil moisture content), which marked the end of the experiment. Sampling intervals were selected according to previous observations of soil moisture depletion for a 20 mm pulse of precipitation at the site, for which the greater evaporative activity occurs during the first 12–15 h, but continues through a period of more than 50 h (data not shown). For every measurement, the electronic scale was taken to all locations where microlysimeters were weighed and returned immediately to the soil. Previous literature has described soil evaporation as a two stage function of time, controlled by atmospheric demand and soil supply, that can be described by a linear function of time during the atmosphere-limited phase and subsequently by a non-linear function during the soil-limited phase (Menziani et al., 1999). For further analysis we calculated mean soil evaporation rates (expressed as percent change in gravimetric soil moisture content per hour) for the first 48 h of the experiments, which corresponded to the period of largest variation in soil moisture content and associated with the atmosphere-controlled period of evaporation.

Solar radiation indices at each location and season were quantified using hemispherical photography. Photographs were taken at 1.0 m above the ground—to capture only the influence of the mesquite-dominated canopy, avoiding any effect of undergrowth—using a horizontally leveled digital camera (CoolPix, 5400, Nikon, Tokyo, Japan), equiped with a fish-eye lens (FC-E9, Nikon, Tokyo, Japan), with a 180° field of view. Photographs were taken during uniform sky conditions at dawn, ensuring correct contrast between canopy and sky (Rich et al., 1999; Quilchano et al., 2008). Images were analyzed using Hemiview canopy analysis software version 2.1 (1999 Delta-T Devices, Ltd., Cambridge, UK—Rich et al., 1999). We calculated the Direct Site Factor (DSF), which is the proportion of direct solar radiation reaching a given location over a year, relative to that in the same location with no sky obstructions, under clear sky conditions. This approach accounts for obstructions imposed by plant canopies and surrounding topographic features, if present, over an entire course of a year, or for a particular month of the year, assuming clear sky conditions. In our analysis we used monthly values of DSF, which incorporate the variation in solar radiation input associated with the seasons.

Mean hourly meteorological data was recorded for each experiment using a standard weather station located close to the 2% canopy cover plot, approximately 200 m from the farthest cover plot (73% canopy cover). We obtained hourly averages of air temperature and humidity (CS500-L, Campbell Scientific, Logan, USA); wind speed, measured at 3 m above the ground (034B wind sensor, Met One instruments, Inc., Grants Pass, OR, USA); and total incoming solar radiation (LI200X-L Li-Cor Inc., Lincoln, USA). Vapor pressure deficit (VPD) was calculated from temperature and relative humidity measurements.

2.2. Data analysis

To generally characterize the climate seasonality at the site, non-parametric Friedman's rank tests were performed for meteorological variables (air temperature, wind speed, vapor pressure deficit and incoming solar radiation) recorded at the nearby weather station. This test identifies differences in the mean values of the variables through pairwise comparisons of their values throughout the duration of the experiments.

We calculated soil drying curves as a function of time during the atmosphere-controlled period of evaporation for each patch type at each season (representing cumulative soil evaporation through time). Both linear and non-linear models for cumulative soil evaporation during the first 100 h of soil drydown were fitted, with

Table 1
Results from Friedman's rank test analysis, used to characterize the variation in mean meteorological conditions at the site during the experimental periods. Shaded cells indicate significant differences between seasons at an alpha level of 0.05.

	Leaf senescence	Leafless	Leaf green-up
Air temperature			
Leafout	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$
Leaf senescence		$p < 0.0001$	$0.05 < p < 0.10$
Leafless			$p < 0.0001$
Wind speed			
Leafout	$p < 0.0001$	$p < 0.0001$	$0.0001 < p < 0.0005$
Leaf senescence		$p > 0.20$	$p > 0.20$
Leafless			$p > 0.20$
VPD			
Leafout	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$
Leaf senescence		$p < 0.0001$	$0.05 < p < 0.10$
Leafless			$p < 0.0001$
Solar radiation			
Leafout	$0.005 < p < 0.01$	$0.025 < p < 0.05$	$p > 0.20$
Leaf senescence		$p > 0.20$	$0.025 < p < 0.05$
Leafless			$0.10 < p < 0.20$

the most significant fit always occurring with 2nd order poly-nomials. The resulting functions were all of the form: *Cumulative Soil Evaporation (mm)* $= at + bt^2$, where t represents the hours of drying time.

To define the factors that influenced soil evaporation at each season, we performed stepwise multiple linear regression analyses with soil evaporation rate—expressed as the mean rate for the first 48 h of the experiment—as the dependent variable and canopy cover, DSF, soil temperature, presence of a litter layer and patch type (canopy or intercanopy) as the independent variables. For each season we performed individual correlation analyses between canopy cover, DSF, temperature and soil evaporation rate for each treatment type. These analyses allowed us to evaluate the significance of specific relationships between variables that drive soil evaporation dynamics at all phenological stages. All correlations reported were significant at the $p = 0.05$ level. All the analyses were performed using SPSS v. 11.0 and Matlab v.7.7.0.471.

3. Results

Air temperature and vapor pressure deficit varied significantly among experimental periods, except between leaf green-up and leaf senescence when they were similar (Friedman's rank test). Wind speed was significantly lower during the full leafout experimental period but had higher instantaneous values during the leaf senescence experiment. Solar radiation varied as expected through that experiments, although during leaf senescence, radiation was lower, likely due to cloudy conditions during the experimental period, making it not significantly different than incoming solar radiation during the leafless period (Table 1).

Monthly DSF values varied with season, in response to the seasonal variation of solar radiation, as well as to the phenological dynamics of *Prosopis*. The highest values of DSF occurred in the full leadout and decreased systematically with decreasing available energy (Fig. 1A). Within each season, DSF values were consistently higher at intercanopy locations. The difference between canopy and
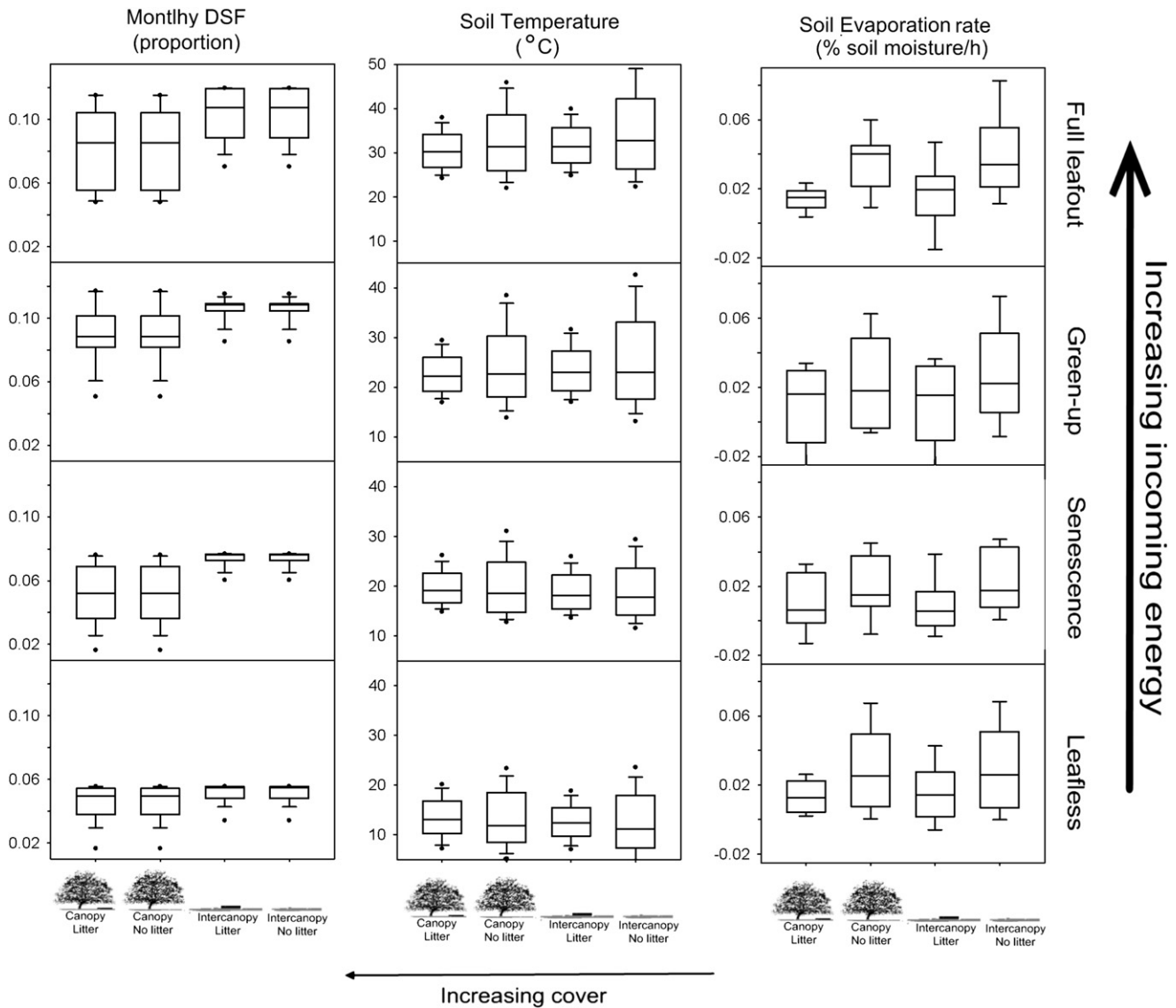

Fig. 1. Distribution of (A) mean monthly values of direct site factor (DSF), (B) soil temperature (°C), and (C) soil evaporation rates (% gravimetric/h – for the first 48 h of drydown), for each patch type during soil evaporation experiments performed at the full leafout, green-up, leaf senescence and leafless phenological seasons. Units for all panels within a given column are presented above the corresponding column.
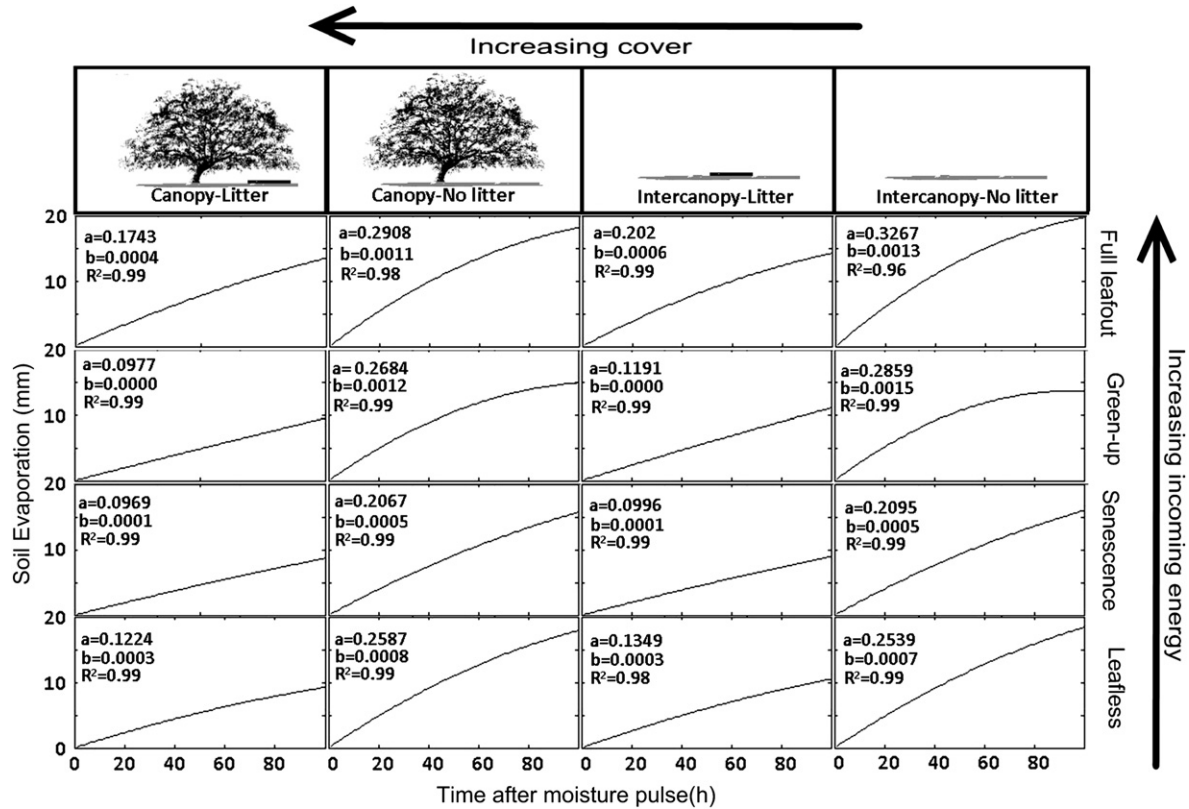
Fig. 2. Soil evaporation (mm) curves as a function of time (h) for all patch types and seasons. Equations are of the form *Soil Evaporation (mm)* $= at + bt^2$, Values of *a* and *b* parameters and r^2 for each condition are presented above the curve. All regression models are significant at $p = 0.001$ level.

intercanopy locations was more pronounced during the full leafout season, when foliage was at its maximum. Soil temperature also varied systematically with season. However, there were no significant differences between treatments within season (Fig. 1B). Soil evaporation rates for a given patch type were consistently higher during the full leafout experiment at locations where litter was absent compared to when litter was present; similar significant differences for other seasons were not detectable (Fig. 1C).

We fitted soil drying curves for the initial 100 h of drydown, corresponding mostly to the atmosphere-limited period of evaporation, for each treatment at each season. Regression models were significant at the p value $= 0.001$ level, with r^2 values greater than 0.96 in all cases. Regression analyses show that soil evaporation dynamics varied for each patch type and season, but most importantly, between locations with a litter layer and those without one. Soil evaporation rates generally decreased with decreasing seasonal energy availability, with the highest rates of evaporation occurring during the full leafout season at *intercanopy–no litter* locations and the lowest rates at *canopy–litter* locations in leaf senescence and leafless seasons (Fig. 2). It is worth noting that the best fit was obtained from a second order polynomial. However, the second order coefficients are very low, which concurs with previous theoretical descriptions of a linear decrease in soil moisture during the atmosphere-limited period of the soil drying curve (Menziani et al., 1999).

The results from our stepwise multiple linear regressions show that soil evaporation varied systematically with canopy cover, DSF, soil temperature, surface cover, the presence of a litter layer on the soil and patch type (canopy/intercanopy locations) throughout the seasons (Table 2). Notably, for all seasons, the presence of a litter layer on the soil was the most important factor influencing soil evaporation. In particular, during the summer full leafout period,

when no energy limitation is expected, only litter controls soil evaporation. In contrast, during the leafless season (the coldest and more energy limited season), an additional energy-associated limitation (temperature) follows the presence of a litter layer controlling soil evaporation. Finally, during the intermediate seasons (green-up and leaf senescence), other energy-related variables are also instrumental on controlling soil evaporation, specifically canopy cover and soil temperature for the green-up season and temperature and patch type for the leaf senescence season (Table 2).

Our correlation analyses between individual variables associated with key drivers of soil evaporation suggest that the controls on soil evaporation vary among seasons and among levels of canopy cover (Appendix Fig. A1). For the full leafout period, soil evaporation was positively correlated with DSF and temperature for the *canopy–litter* treatment and there is suggestive evidence of a significant correlation with overall canopy cover for *intercanopy–litter*. During the green-up period, soil evaporation was negatively correlated with overall canopy cover for the

Table 2
Results from stepwise regression analyses indicating the main environmental drivers of soil evaporation for each season. Shaded cells indicate variables that were significant in explaining the variation of soil evaporation, using a stepwise regression model. Numbers indicate the relative importance of each variable on explaining the behavior of soil evaporation. Larger numbers indicate more explanatory power.

	Vegetation mosaic	Patch type	DSF	Temperature	Litter layer	R^2	p-value
Leafout					1	0.43	0.0001
Leaf senescence		3		2	1	0.48	0.0001
Leafless				2	1	0.62	0.0001
Leaf green-up	2			3	1	0.61	0.0001

intercanopy–no litter treatment and negatively correlated with temperature at the *intercanopy–litter* and *intercanopy–no litter* treatments. During the leaf senescence period, soil evaporation was negatively correlated with overall canopy cover at the *canopy–litter* treatment and positively correlated with temperature at the *intercanopy–no litter* treatment, where overall canopy cover was also negatively correlated with DSF, which in turn was positively correlated with temperature. Finally, during the leafless period, soil evaporation was positively correlated with temperature at all intercanopy locations, and negatively correlated with overall canopy cover at the *intercanopy–no litter* locations (Appendix Fig. A1).

4. Discussion

Our design allowed us to experimentally assess interactive controls on soil evaporation with respect to a hierarchical structure spanning from the presence or absence of litter, through the canopy patches of woody plants and the intercanopy patches separating them, up to the overall vegetation mosaic characterized by density of woody plant cover, as well as with respect to seasonality/phenology. Notably, we found that litter exerts a dominant control on soil evaporation—a result that was robust across seasons but amplified during the main precipitation seasons at the site (full leafout and leafless seasons; Table 2). The presence of a litter layer on the ground controls soil evaporation via two basic mechanisms: through the attenuation of radiation flux into and from the ground (Baldocchi et al., 2000; Wilson et al., 2000) and by increasing the resistance to water flux from the ground (Sakaguchi and Zeng, 2009). The combined effect of these two mechanisms produced by litter cover apparently provides such a strong control on soil evaporation that other components of hierarchical structure (patch and mosaic scales) are essentially overwhelmed, and seasonality and phenology only modify the magnitude of this effect. However, in the absence of litter, both patch and mosaic attributes can influence soil evaporation when climate is moderate, and when phenology is at an intermediate stage (e.g., patch effect during leaf senescence and mosaic effect during green-up; Table 2); in these cases the degree of control appears to be moderate and the causes are perhaps more complex, varying with season/phenology. Collectively, our results highlight that both hierarchical vegetation structure and seasonal/phenological variability can influence soil evaporation.

Our analysis of correlations from related measures of incoming energy (DSF and soil temperature), as well as patch type and vegetation mosaic, suggests that energy availability limits evaporation in many cases. This insight is indicated by correlations between soil temperature and evaporation rates (e.g., *intercanopy/no litter* during leaf senescence and leafless seasons; *intercanopy/litter* during leafless season, and *canopy/litter* during full leafout; Appendix Fig. A1). The seasonal/phenological variability in these responses as a function of patch type are consistent with expected trends—when it is hottest, the effect of soil temperature is apparent only in the most covered locations (*canopy/litter*), while when it is cooler, the effect is apparent at the intercanopy locations. Under specific conditions (*intercanopy/no litter* during the leaf senescence season), a progression of correlations (canopy cover–DSF, DSF–temperature, temperature–evaporation) indicate that the effect of the vegetation mosaic (reflected in amount of canopy cover) on energy can also limit soil evaporation (Appendix Fig. A1). In the absence of litter during the hottest season, lack of correlations with energy metrics may be indicative of a lack of energy limitation on evaporation (*canopy/no litter* and *intercanopy/no litter* during full leafout); conversely, lack of correlation with energy metrics during the coolest season may be indicative of dominant energy limitation (*canopy/litter* and *canopy/ no litter* during leafless season). Although we focused in this study on the potential influence of energy on soil evaporation, using incoming near-ground solar radiation and soil temperature as proxies, in several cases energy alone was insufficient to explain variation in soil evaporation. In several such cases, however, canopy cover is correlated directly with soil evaporation, yet other correlations that would indicate that this relationship was associated with limitations on energy availability (DSF–temperature and temperature–evaporation) are lacking (*intercanopy/litter during green-up, intercanopy/no litter during green-up, canopy/no litter during leaf senescence, and intercanopy/no litter during leafless*), thereby requiring consideration of alternative hypotheses about controlling mechanisms. Although we lack data to resolve this uncertainty, we speculate that this could be due to the other fundamental driver of evaporation besides energy—turbulence due to wind (McNaughton, 1986; Kurc and Small, 2004; Baldocchi and Xu, 2007); this speculation requires testing with additional research. Collectively, our results did not indicate a simple set of energy limitations, but rather, when considered in concert with recognition of both energy and wind as drivers of evaporation (McNaughton, 1986; Kurc and Small, 2004; Baldocchi and Xu, 2007), suggest a framework of hypotheses for further testing the relative controls on soil evaporation as related to hierarchical vegetation structure and season/phenology (Fig. 3).

Regardless of the specific mechanisms and their relative roles in driving soil evaporation with respect to hierarchical vegetation structure and season/phenology, the spatiotemporal differences that we quantified potentially have important ecohydydrological
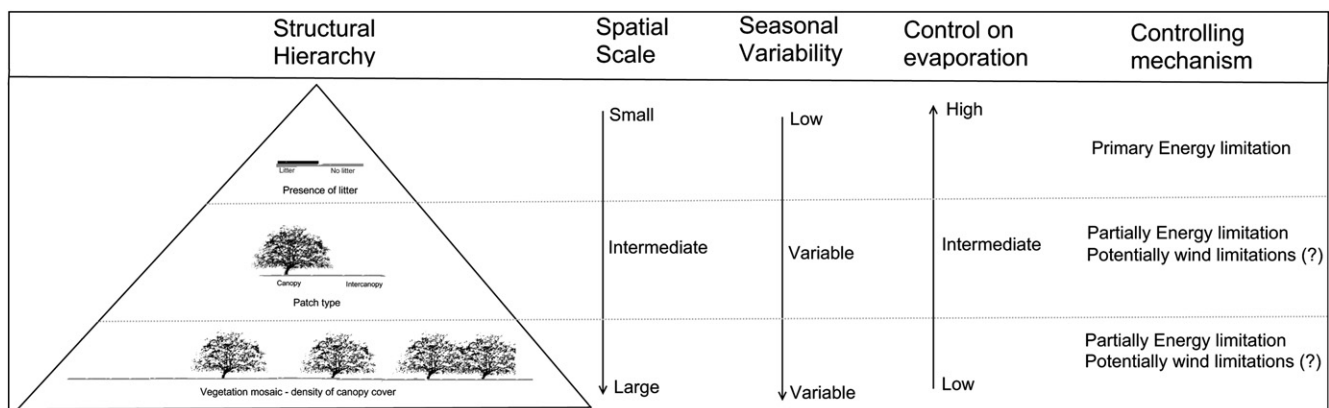

Fig. 3. Controls and hypothesized controlling mechanisms of soil evaporation at the hierarchical structure of vegetation cover (including litter, patch and vegetation mosaic scales) in response to seasonal/phenological dynamics of seasonally deciduous drylands.

implications. Notably, in drylands, the presence of a litter layer in the soil, not only affects processes such as evapotranspiration and land surface–atmosphere interactions, but also has important implications for other critical ecosystem dynamics associated with biogeochemical processes involving carbon and nitrogen in the soil. Notably, the enhanced moisture retention in the litter, associated with lower evaporation rates and increased water holding capacity can potentially favor soil respiration and decomposition, often limited by moisture in this type of ecosystems (Mazzarino et al., 1991; Conant et al., 2004; Riaesi and Asadi, 2006; Scott et al., 2006; Throop and Archer, 2008; McIntyre et al., 2009). In conclusion, our results that discuss vegetation-imposed limitations on soil evaporation at multiple temporal and spatial scales highlight the need to account for both hierarchical vegetation structure and seasonal/phenological variability to improve ecohydrological predictions of soil evaporation.

Acknowledgments

Appendix. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.jaridenv.2009.09.028.

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