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Litter is more effective than forest canopy reducing soil evaporation in Dry Chaco rangelands

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Abstract

Soil evaporation is a dominant water flux of flat dry ecosystems, reducing available water for plant transpiration. Vegetation plays a key role at controlling evaporation, especially by altering soil surface micro-meteorological conditions. Here, we explored the vegetation cover effect on soil evaporation, differentiating the effects of canopy cover (shadow) and of surface cover (litter) in forests and pastures of Dry Chaco rangelands (San Luis, Argentina). We measured daily soil evaporation using irrigated micro-lysimeters installed at regularly spaced (2 m) patches along transects in native dry forests (n = 54 patches) and pastures (n = 27 patches). In each forest patch, we established a pair of micro-lysimeters, one with litter (3 cm depth, representing high litter cover conditions of the site) and one with bare soil, but in pastures, only one micro-lysimeter with bare soil was installed at each patch (representing the typical no litter cover conditions of pastures of the study site). We found that, when soil water was not limiting, litter cover had the strongest effect in reducing evaporation rates, with a 4- and 6.4-fold reduction respect to bare soil micro-lysimeters in the forest and pasture, respectively. Evaporation decreased sharply with declining incident radiation fraction in bare soil micro-lysimeters from 5.6 mm/day (full radiation) to 3.5 mm/day (full canopy shadow; R^2 = 0.50). Litter-covered micro-lysimeters showed lower and more stable evaporation rates, decreasing only from 1.35 to 1.03 mm/day under the same radiation conditions (R^2 = 0.10). In accordance with J.T. Ritchie evaporation model, we identified a threshold of ~10.5 mm of cumulative evaporation at which evaporation switched from energy to water limitation in all situations, as revealed by declining evaporation rates and raising surface temperatures. Under typical wet–summer conditions, the pasture, the forest with bare soil, and the forest with litter would need on average a drying cycle of 1.5, 2.5, and 9.5 days, respectively, to reach that threshold. Simulations showed that, considering the distribution of rainfall events at our study site, litter would maintain evaporation in the energy-limited mode most of the time (68.8% of summer days), potentially favouring transpiration. The ecohydrological key role of soil litter controlling evaporation highlights the importance of an accurate assessment of management practices controlling the evaporation/transpiration partition in dry ecosystems.

KEYWORDS

Arid Chaco, clearing, ecohydrology, lysimeters, Ritchie's model, transpiration, water balance, woodlands

1 | INTRODUCTION

The productivity of dry rangelands depends on the effectiveness of rainfall inputs to be channelled through roots to sustain plant transpiration (Newman et al., 2006; Wilcox, Breshears, & Allen, 2003). The water balance in dry ecosystems, particularly those occupying flat sedimentary landscapes, can be summed up in that precipitation represents the unique input and evapotranspiration (ET) involves more than 95% of the output, with run-off and deep drainage being negligible (Wang, Good, & Caylor, 2014; Wei et al., 2017). The individual components of ET include soil evaporation (E), vegetation transpiration (T), and canopy interception (Kool et al., 2014; Villegas et al., 2015).

Interception often represents a minor fraction of ET (less than 7–12%), and E and T are the dominant fluxes (Méndez-Barroso et al., 2014; Raz-Yaseef, Yakir, Rotenberg, Schiller, & Cohen, 2010; Sutanto, Wenninger, Coenders-Gerrits, & Uhlenbrook, 2012). The function of E and T within ecosystems is distinctly different: T is strongly associated with plant growth (Monteith, 1988), whereas E does not directly contribute to primary production (Asbjornsen et al., 2011; Schlesinger & Jasechko, 2014). Clearly, in terms of increasing net primary production, it is desirable to maximize transpiration and to reduce evaporation.

For a given soil, evaporation depends on meteorological conditions (atmospheric demand) and soil moisture (Hillel, 1998; Philip, 1957). The combination of high atmospheric demand (high incident radiation, air temperature and wind speed, and low air humidity) and high soil moisture favours soil evaporation (Allen, Pereira, Raes, & Smith, 1998; Breshears, Nyhan, Heil, & Wilcox, 1998; Royer, Breshears, Zou, Cobb, & Kurc, 2010). After a large rainfall event, when soil reaches field capacity (where all pores that can store water are filled), evaporation process occurs in two distinct phases (Philip, 1957; Ritchie, 1972; Suleiman & Ritchie, 2003). The first one, commonly named "energy-limited," takes place when soil water content is high and evaporation rate depends exclusively on meteorological conditions, so evaporation matches the atmospheric demand (i.e., the potential evaporation rate). The second phase, commonly named "water-limited," takes place when evaporation is no longer limited by the atmospheric demand but by soil moisture and the capacity of the soil, given by its hydraulic properties, to transport water to the surface. In flat drylands without a water table close to the surface, evaporation is water-limited most of the time (Noy-Meir, 1973; Porporato, D'odorico, Laio, Ridolfi, & Rodriguez-Iturbe, 2002; Reynolds, Kemp, Ogle, & Fernández, 2004).

Vegetation influences evaporation in at least four different ways: (a) by surface run-off/ run-on redistribution processes that concentrate water in densely vegetated patches (Magliano, Breshears, Fernández, & Jobbágy, 2015; Urgeghe, Breshears, Martens, & Beeson, 2010; Wilcox et al., 2003), (b) by altering soil physics, for example, changing its hydraulic conductivity and/or its water holding capacity (Caldwell, Young, McDonald, & Zhu, 2012; Lebron et al., 2007; Magliano, Fernández, Florio, Murray, & Jobbágy, 2017), (c) by plant water uptake (transpiration), which decreases soil moisture (Newman et al., 2006; Rodriguez-Iturbe, 2000), and (d) by altering micro-meteorological conditions at the soil surface, thus reducing atmospheric demand (Haverd & Cuntz, 2010; Ritchie & Burnett, 1971). In the last two decades, much effort has been devoted to understand vegetation micro-meteorological effects on evaporation losses because they are highly sensitive to human transformations (Ferretti et al., 2003; Haverd & Cuntz, 2010; Köstner, 2001), such as wood plant encroachment caused by livestock intensification (Huxman et al., 2005; Wilcox & Huang, 2010), or agricultural practices on recently cleared lands (Ji & Unger, 2001; Van Donk et al., 2010). The analysis of how vegetation canopy cover and litter interact in the regulation of soil evaporation is crucial to understand the ecohydrology of dry ecosystems and to infer how different agricultural practices may affect this process.

Most previous evaporation research has been focused in contrasting patchy-vegetation ecosystems, dominated by fully vegetated and bare soil patches (Newman, Breshears, & Gard, 2010; Stannard & Weltz, 2006; Villegas, Breshears, Zou, & Law, 2010). However, a large fraction of drylands consist of intermediate vegetation situations where it is more difficult to define such contrasting phases, yet ecohydrological process are shown to respond to more gradual cover shifts (Bisigato, Villagra, Ares, & Rossi, 2009; Breshears & Ludwig, 2010; Magliano, Breshears et al., 2015). The South American Dry Chaco is an example of these ecosystems dominated by a vegetation cover gradient at the patch scale that presents two challenges for assessing evaporation dynamics in relation to vegetation changes: (a) the predominance of extensive livestock production systems that continuously transform spatial vegetation patterns (Magliano, Murray et al., 2015; Rueda, Baldi, Verón, & Jobbágy, 2013; Steinaker et al., 2016) and (b) the occurrence of regional land cover changes at high rates, in which native forests are replaced by planted pastures to intensify livestock production (Houspanossian, Giménez, Baldi, & Nosetto, 2016; Hoyos et al., 2013; Murray, Baldi, von Bernard, Viglizzo, & Jobbágy, 2016). Understanding how the spatial heterogeneity of vegetation patches can affect evaporation dynamics may represent an avenue to improve livestock production of Dry Chaco rangelands.

In this paper, we explored the vegetation cover effect on soil evaporation, differentiating the effects of canopy cover (shadow) and of surface cover (litter) in forests and pastures of Dry Chaco rangelands (San Luis, Argentina). We measured daily soil evaporation in micro-lysimeters installed at 2-m regularly spaced patches across transects in both vegetation types. Then, on the basis of these data and soil surface temperature, we determined the soil water threshold beyond which evaporation switches from energy to water limitation and its possible joint influence on annual evaporation rates.

2 | METHODS

This study was conducted in the southern edge of the Dry Chaco (Arid Chaco), in the province of San Luis in Argentina (33.5°S, 66.5°W; Baldi & Jobbágy, 2012; Morello & Adámoli, 1974). Mean annual rainfall is 430 mm, concentrated in the spring–summer season, and mean annual evapotranspiration is 1350 mm (Magliano, Fernández, Mercau, & Jobbágy, 2015). Soils are derived from Quaternary fine loess and, to a lesser extent, alluvial sediments (Pennington, Prado, & Pendry, 2000; Tripaldi et al., 2013). They are Typic Torriorthents with 53% sand, 15% clay, and 1.4% organic matter in the upper 10 cm of the profile (Peña Zubiate, Anderson, Demmi, Saenz, & D'Hiriart, 1998). Landscape slope is 1.5%. Native woody vegetation consists of 7-m high canopies dominated by *Prosopis flexuosa* and *Aspidosperma quebracho-blanco* trees and *Larrea divaricata* shrubs (Marchesini, 2011). A large fraction of native dry forests has been converted to pastures by traditional deforestation or roller-chopping over the past 30 years (Boletta, Ravelo, Planchuelo, & Grilli, 2006; Hoyos et al., 2013; Steinaker et al., 2016).

We worked on three stands covered by native dry forest and three stands of *Cenchrus ciliaris* pasture. Within each stand, we traced a randomly located transect where we performed a systematic sampling that included 2-m regularly spaced patches (Figure 1). We opted for this systematic sampling in order to objectively characterize the natural
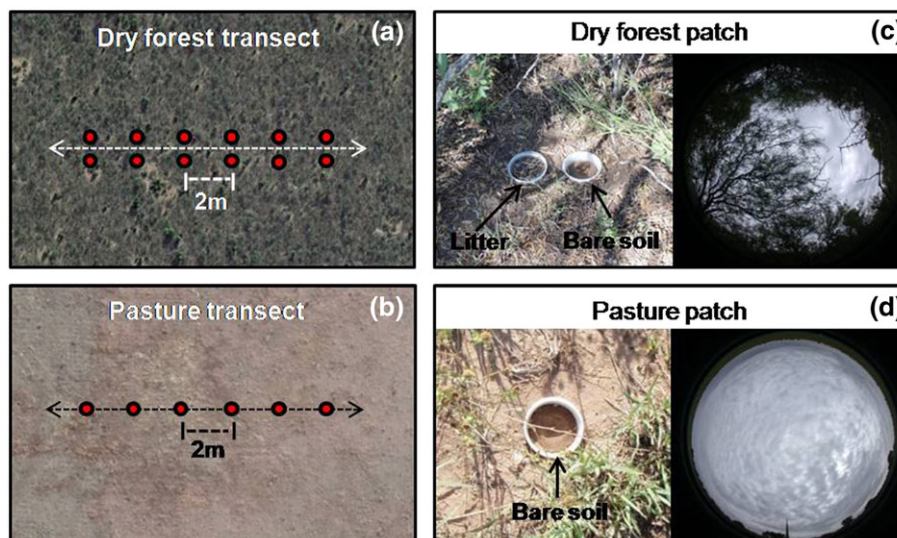
FIGURE 1 Portion of (a) dry forest and (b) pasture transect. Red points represent micro-lysimeters systematically distributed along 36 and 18 m in dry forest and pasture, respectively. Images were obtained from Google Earth. (c) Dry forest patch with two micro-lysimeters, one with bare soil and one with 3 cm of litter on surface (left photograph); right hemispherical photograph shows an example of typical close canopy cover. (d) Pasture patch with one micro-lysimeter with bare soil (left photograph); right hemispherical photograph shows an example of typical open canopy cover

heterogeneity of the system. So, $n = 54$ in forests (18 patches × 3 transects) and $n = 27$ in pastures (9 patches × 3 transects). More observations were considered necessary in forest than in pasture because of the higher heterogeneity of the former in our study site (Magliano et al., 2016; Magliano et al., 2017; Marchesini, Fernández, & Jobbágy, 2013; Marchesini, Fernández, Reynolds, Sobrino, & Di Bella, 2015). Soil evaporation was measured using micro-lysimeters installed on patches (Boast & Robertson, 1982; Kool et al., 2014). Two micro-lysimeters were installed in each forest patch, one with bare soil and one covered with 3 cm depth litter (~3 kg/m^2), which represents the 95th percentile of soil litter found in the study site (Magliano, Breshears et al., 2015). Only one micro-lysimeter with bare soil was installed in each pasture patch because litter was rarely found in this vegetation cover (Figure 1). So, three treatments were considered: forest with bare soil ($n = 54$ micro-lysimeters), forest with litter ($n = 54$ micro-lysimeters), and pasture ($n = 27$ micro-lysimeters).

Micro-lysimeters consisted of plastic cylinders (diameter: 10.6 cm; height: 18.0 cm) were installed in soil holes coated with PVC tubes to facilitate daily manipulation (diameter: 11.0 cm; height: 18.0 cm), so that the top of micro-lysimeters were at the soil surface level. Micro-lysimeters were filled with 1 kg of homogenized and sieved soil from the study site, and 28 mm of water were added to reach field capacity, according to laboratory determinations based on the Colman method (Colman, 1947; Hillel, 1998). Micro-lysimeters were weighted daily at 9 a.m. (all micro-lysimeters weighted within 60 min) during 5 rainless days from 2/9/2012 to 2/13/2012, with an electronic precision balance (0.1 g, Traveler, Ohaus). In this case, the short duration of the experiment (4 days) is compensated by the high spatial variability explored. *Actual evaporation* (E$_{ac}$, mm/day) was calculated as the micro-lysimeter weight difference between 1 day and the following one (4 consecutive observations in each micro-lysimeter) divided by the micro-lysimeter area. In order to characterize the declining evaporation rates as water becomes limiting, we computed the ratio between *actual evaporation* (E$_{ac}$) and *non-water-limited* or *potential*

evaporation (E$_p$). Because micro-meteorological conditions differed among micro-lysimeters, E$_p$ was computed for each micro-lysimeter assuming that evaporation on the first day of the experiment (E$_1$) was not water limited (Ritchie, 1972); this is confirmed in Figure 4 (see below). By relating E$_1$ to the *reference evapotranspiration* (ET$_0$) of that day, we obtained the correction factor (k$_E$) to compute E$_p$ from ET$_0$ for the following days (Equation 1), so k$_E$ was calculated for each micro-lysimeter at each day. As k$_E$ was 1 for some micro-lysimeters in the pasture, we confirmed that unsaturated hydraulic conductivity for the soil contained into the micro-lysimeters was not limiting. ET$_0$ above the canopy was computed from meteorological variables measured at the study site, according to the Penman–Monteith method developed by FAO (Allen et al., 1998).

$$E_p = E_1 \quad \text{(for the first day of the experiment)}$$
$$E_p = ET_0{}^*k_E \quad \text{(for the following days, where} \quad \tfrac{1}{2}$$
$$k_E = E_1/ET_0, \text{ with ET}_0 \text{ of the first day)} \tag{1}$$

where E$_p$ is the potential evaporation of each micro-lysimeter, E$_1$ is the actual evaporation of the first day, ET$_0$ is the reference evapotranspiration above the canopy and k$_E$ a correction factor to compute E$_p$ from ET$_0$.

Incident radiation at 25 cm height from the soil surface was estimated from hemispherical photographs obtained at each patch with a Nikon Coolpix 5400 camera fit with a FC-E9 Fisheye lens (Nikon, Tokyo, Japan). Hemispherical photographs capture the full range of surrounding geometry associated with canopy architecture, thereby enabling a robust assessment of site microclimate (Breshears & Ludwig, 2010; Rich, 1989). Hemispherical digital photos were analyzed using Delta-T HemiView software (HemiView 2.1, Delta-T Devices, Cambridge, UK; Breshears & Ludwig, 2010; Rich, 1989; Rich, Wood, Vieglais, Burek, & Webb, 1999) to compute the incident radiation fraction. Soil surface temperature of each micro-lysimeter was measured daily at 9 a.m. (all micro-lysimeters were measured within 60 min)

during 5 days from 2/9/2012 to 2/13/2012 with an infrared thermometer (62 Mini, Fluke devices). So, one value of incident radiation was obtained at each patch the first day of the experiment, and one value of surface temperature was obtained at each micro-lysimeter at each day of the experiment.

One-way analysis of variance were performed to detect differences in measured variables among treatments and unpaired t-test for more specific comparisons (e.g., percentile comparison between two treatments). Linear regressions ($Y = a + bX$) were performed to analyze the relation between first-day evaporation (E_1) and incident radiation fraction. The non-linear model "Plateau followed by one phase decay" (Equation 2) was used to determine the threshold from which the evaporation process switches from energy to water limitation, according to Ritchie's model (Hillel, 1998).

$$
\begin{aligned}
Y &= Y_0 & \text{(for } X < X_0) \\
Y &= Plateau + (Y_0 - Plateau) * \exp(-K * (X - X_0)) & \text{(for } X > X_0)
\end{aligned}, \quad (2)
$$

where Y is the ratio of cumulative actual to potential evaporation (E_{ac}/E_p) for each micro-lysimeter and day; Y_0 is the E_{ac}/E_p ratio during the non-water-limited evaporation phase ($Y_0 \approx 1$); X is the cumulative potential evaporation (E_p) of each micro-lysimeter (mm); and X_0 is the cumulative evaporation threshold (mm) that separates energy-limited ($X < X_0$) from water-limited ($X > X_0$) evaporation phases. K is the rate constant (1/mm) and Plateau is the Y value at infinite times (Plateau ≈ 0). Y_0 and Plateau were forced to 1 and 0, respectively.

"Segmental linear regressions" were performed to describe the relationship between the surface–air temperature differential ($\Delta T = T_{surface} - T_{air}$) and micro-lysimeter moisture loss (initial moisture–actual moisture; mm) at each day (Equation 3). Air temperature was obtained from a nearby meteorological station (one value at each day). ΔT has been widely used to assess the moisture condition of vegetation and soils (Deardorff, 1978; Sandholt, Rasmussen, & Andersen, 2002); in this case, we used it as an indicator of the evaporation phase change. When evaporation is not water-limited, available energy is mostly dissipated as latent heat (i.e., evaporation), which tends to cool the soil surface. As moisture declines, latent heat fluxes decline as well and, given the low roughness of the soil surface, the sensible heat flux is not able to compensate and consequently the soil surface temperature increases. So in this sense, the higher the ΔT, the more water-restricted the evaporation would be. Segmental linear regressions were then used to find the micro-lysimeter moisture loss threshold from which evaporation becomes increasingly limited by water.

$$
\begin{aligned}
Y &= a_1 + b_1 * X & \text{(for } X < X_0) \\
Y &= a_2 + b_2 * (X - X_0) & \text{(for } X > X_0)
\end{aligned}, \quad (3)
$$

where Y is the surface–air temperature differential (ΔT, °C) measured in each micro-lysimeter each day; X is the micro-lysimeter moisture (mm); X_0 is the moisture threshold that separates energy-limited (I) and water-limited (II) phases of the evaporation process; and a1, a2 and b1, b2 are the Y-intercept and the slope of the linear models for evaporation phases I and II, respectively.

The potential evaporation of each micro-lysimeter (E_p; mm/d; obtained from Equation 1) and the cumulative evaporation threshold that separates energy-limited from water-limited evaporation phases (X_0; mm; obtained from Equation 2) were used to estimate the time needed to reach the evaporation phase change (t, days) in each vegetation cover, after a rainfall event sufficient to raise micro-lysimeter soil moisture to field capacity (Equation 4).

$$
t = X_0/E_p, \quad (4)
$$

where t (days) is the time needed to reach the evaporation phase change in each micro-lysimeter, X_0 is the E threshold from which evaporation process switches from energy to water limitation (mm), and E_p is the mean potential evaporation (non-water-limited; mm/day) value of each micro-lysimeter.

3 | RESULTS

First-day evaporation (E_1, non-water-limited) differed significantly among treatments ($p < .0001$) with values of 7.0 ± 0.9, 4.4 ± 0.9, and 1.1 ± 0.3 mm/day (mean ± SD), for pasture, forest with bare soil, and forest with litter, respectively (Figure 2a). Pasture and forest with bare soil showed high variability but with opposite skewed patterns. Pasture had few micro-lysimeters with low evaporation respect to its mean value, whereas forest with bare soil had few ones with high evaporation. Noticeably, the percentile 10 of pasture evaporation did not differ significantly from the percentile 90 of forest with bare soil ($p = .56$); however the percentile 10 of forest with bare soil was significantly different from the percentile 90 of forest with litter ($p < .0001$).

First-day evaporation (E_1) was significantly related to incident radiation in dry forest micro-lysimeters with bare soil and litter ($p < .0001$ and $p < .05$, respectively), but not for pasture micro-lysimeters which were mostly exposed to full radiation ($p = .50$; Figure 2b). Incident radiation explained 50% of E_1 variability in forest with bare soil and 10% in forest with litter. The sensitivity of these relationships (ratio between the slopes of the two linear models) resulted in that forest with bare soil presented 7 times higher sensitivity to radiation than forest with litter, which highlights that litter makes the ecosystem evaporation less sensitive to the atmospheric demand. Interestingly, even considering forest patches with incident radiation close to 0% (full canopy cover), bare soil had more than three times higher E_1 than litter cover mean value (3.48 mm vs. 1.1 mm for bare soil and litter, respectively). On the other extreme, it is noticeable that pasture patches without canopy cover (incident radiation ~1) presented higher E_1 than bare soil forest patches under the same light conditions; this suggests that the forest canopy generates other type of effects that reduce the potential evaporation, such as reducing wind speed.

Evaporation differences among treatments decreased with time (Figure 3). Pasture micro-lysimeters presented higher cumulative actual evaporation (E_{ac}) than forest ones with bare soil for the first 3 days after the wetting event ($p < .01$, for days 1, 2, and 3), but no significant differences were found by the fourth day of the experiment when cumulative actual evaporation in bare-soil forest micro-lysimeters reached the pasture values ($p = .46$). When compared to the reference evapotranspiration (ET_0), pasture evaporation practically matched the atmospheric demand of the first day, but progressively diverged from it, as differences between pasture E_{ac} and ET_0 became increasingly higher. E_{ac} in forest bare soil micro-lysimeters was always lower than ET_0, being on average 52% lower in the first 2 days with increasing differences in the following days. As for forest micro-lysimeters with litter,
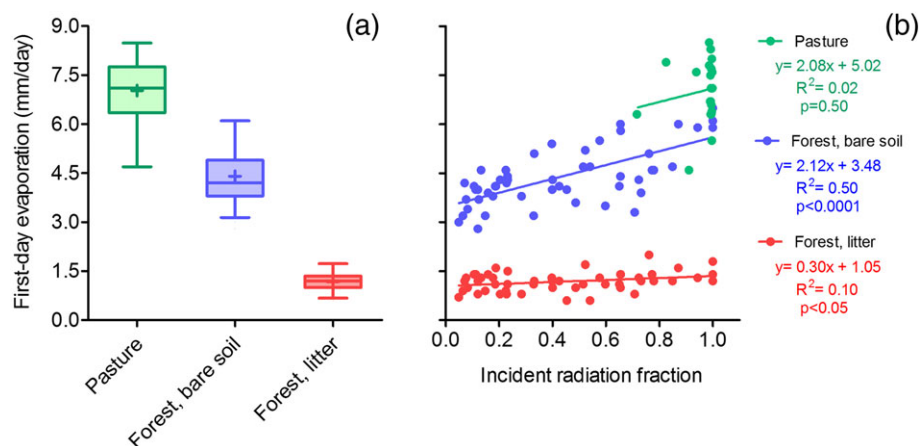
FIGURE 2 (a) First-day evaporation rates after watering (E1; mm/day). Micro-lysimeters under pasture (green; $n = 27$), forest with bare soil (blue; $n = 54$) and forest with litter (red; $n = 54$) are shown. Whisker plots show percentile 95, first quartile, median, third quartile, and percentile 5 values for 27 patches in pasture and 54 patches in forest with bare soil and forest with litter; positive signs show the mean value. (b) First-day evaporation as a function of the fraction of incident radiation measured for pasture ($n = 27$; green), forest with bare soil ($n = 54$; blue), and forest with litter ($n = 54$; red) micro-lysimeters. Each circular marker represents one micro-lysimeter
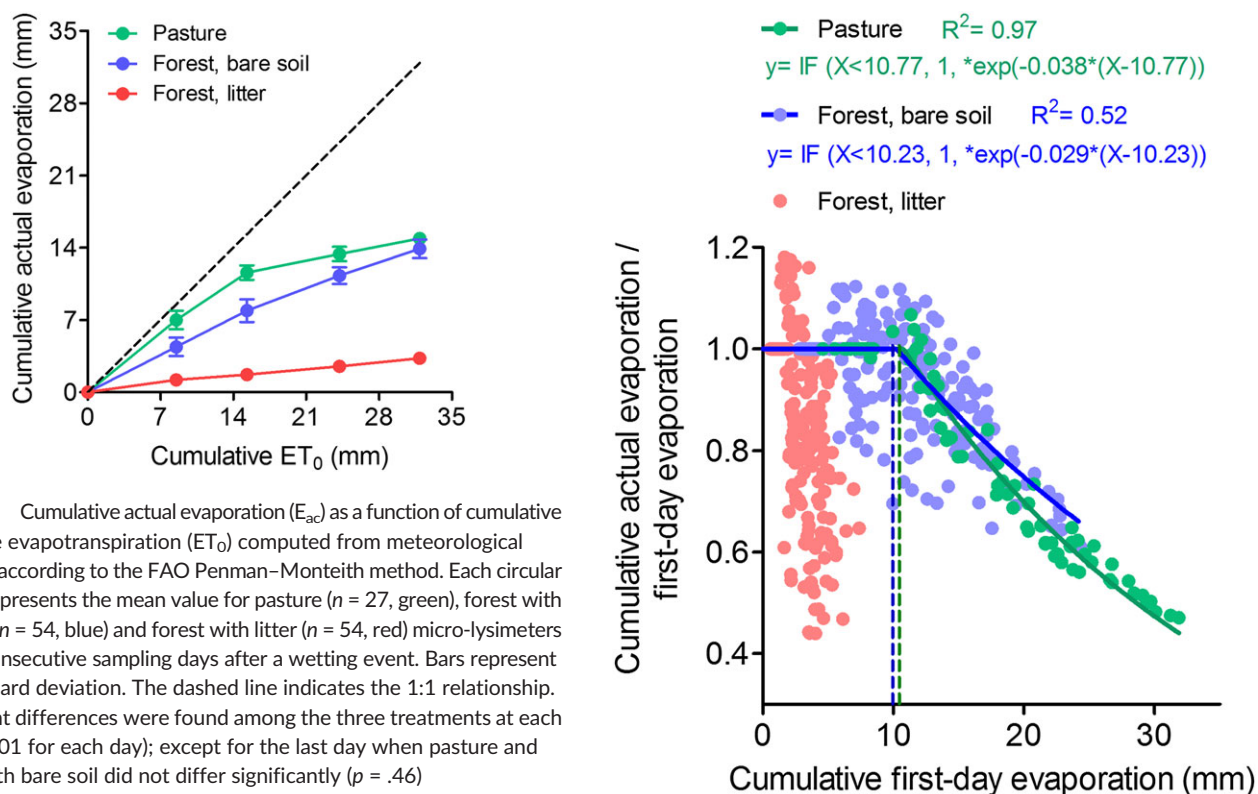

FIGURE 3 Cumulative actual evaporation (E_{ac}) as a function of cumulative reference evapotranspiration (ET_0) computed from meteorological variables according to the FAO Penman–Monteith method. Each circular marker represents the mean value for pasture ($n = 27$, green), forest with bare soil ($n = 54$, blue) and forest with litter ($n = 54$, red) micro-lysimeters in four consecutive sampling days after a wetting event. Bars represent the standard deviation. The dashed line indicates the 1:1 relationship. Significant differences were found among the three treatments at each day ($p < .01$ for each day); except for the last day when pasture and forest with bare soil did not differ significantly ($p = .46$)

FIGURE 4 Relative evaporation rate as a function of cumulative first-day evaporation for pasture (green), forest with bare soil (blue) and forest with litter (red). Relative evaporation is calculated as the ratio of cumulative actual evaporation and cumulative first-day (non-water-limited) evaporation of each micro-lysimeter. Each circular marker represents one measurement for one micro-lysimeter ($n = 4$ measurements × 27 micro-lysimeters in pasture; $n = 4$ measurements × 54 micro-lysimeters in forest with bare soil and forest with litter). Full lines represent the "plateau followed by one phase decay models" adjusted for pasture and forest with bare soil. Broken lines show the threshold from which evaporation process switched from energy to water limitation according to Ritchie's model (Hillel, 1998)

E_{ac} was significantly lower than the other two treatments along the analyzed period ($p < .0001$), representing only 13% of the atmospheric demand without signs of divergence from this general relation to ET_0.

The data presented in Figure 3 suggest that, for each treatment, E_{ac} was a relative constant fraction of ET_0 up to a point (between 7 and 11 mm of cumulative E_{ac}) from which E_{ac} becomes more restricted by other factors that increasingly uncouple E_{ac} from ET_0. Working from individual micro-lysimeter data, we could identify a cumulative evaporation threshold of ~10.5 mm (10.23 for forest with bare soil and 10.77 for pasture patches) from which the evaporation process switched from energy to water limitation (Figure 4). Below this threshold, actual

evaporation (E_{ac}) matched potential evaporation (E_p) resulting from the micrometeorological conditions of each patch, and beyond it, relative evaporation (i.e., the E_{ac}/E_p ratio) decreased exponentially, consistent with Ritchie's model. As pasture E_p was higher, almost all micro-lysimeters had surpassed the evaporation threshold by the second day of the experiment and most of the forest micro-lysimeters with bare soil did it on the third or the fourth day. All forest micro-lysimeters with litter had scattered cumulative E_{ac} values, all well below the evaporation threshold by the end of the experiment. The low E_p values registered in this treatment (E_p 1.1 ± 0.3, mean and SD) were close to the expected experimental error and might have been the cause of the scatter in relative evaporation found in this cover. However, as the magnitude of the threshold to switch from energy to water limitation depends exclusively on soil physical variables (Hillel, 1998), it is expected that it would be next to ~10.5 mm.

The evaporation threshold of ~10 mm from which the process switched from energy to water limitation was confirmed by temperature observations on micro-lysimeters surface (Figure 5). Micro-lysimeters of both pasture and forest with bare soil maintained a relative constant surface–air temperature differential (ΔT, °C) until
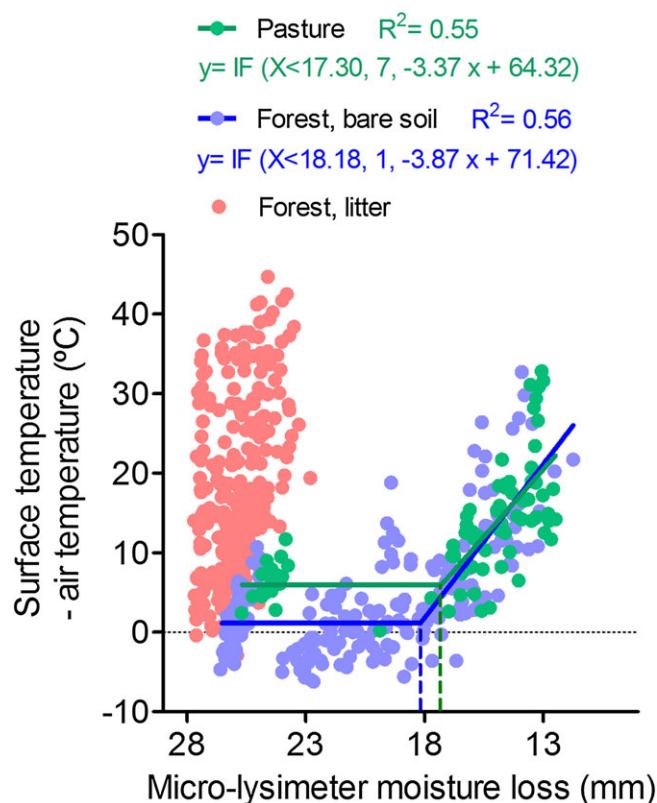
reaching a moisture loss threshold of 10.7 and 9.8 mm, respectively, beyond which further moisture losses increased significantly the surface–air temperature difference (~3.5°C per additional mm lost). The difference in surface temperature between both covers when water was not limiting (below the threshold) could be partly explained by differences in the incident radiation among patches, suggested by the significant correlation between incident radiation fraction and ΔT in forest with bare soil (R^2 = 0.27; p < .01; data not shown). A large variability in surface temperature measurements was found in forest with litter micro-lysimeters, with extreme values of >40°C of ΔT. These temperature values seem to correspond to dry litter readings rather than those of the wet soil below, indicating that part of the incident radiation of those patches is used in the heating of litter instead of on the evaporation process.

Micrometeorological contrasts between analyzed situations translated into different time spans required to switch from energy to water limitation in the evaporation process. Combining the potential evaporation of each micro-lysimeter (Figure 2) and the threshold of ~10.5 mm (Figure 4), we estimated that pasture, forest with bare soil, and forest with litter would need on average 1.5, 2.5, and 9.5 days of typical summer meteorological conditions (after a wetting event) to switch from the energy- to the water-limited phase of Ritchie's evaporation model (Figure 6). This time did not differ significantly for pasture and forest with bare soil (p > .05), and forest with litter was significantly higher than the other two ones (p < .0001) and also showed higher variability, with micro-lysimeters that required more than 16 days to reach the threshold (percentile 95). It is important to note that only evaporation flux is considered here, if transpiration would be also considered the differences between treatments to switch from the energy to the water-limited phase would be smaller.
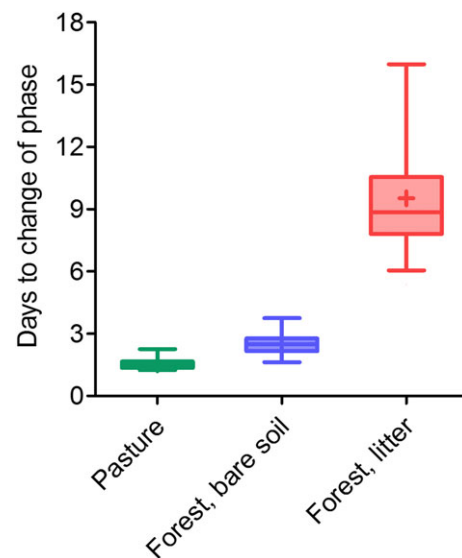

FIGURE 5 Difference between surface and air temperature (°C) as a function of micro-lysimeters moisture loss (mm) for pasture (green), forest with bare soil (blue), and forest with litter (red). Each circular marker represents one measurement for one micro-lysimeter (n = 4 measurements × 27 micro-lysimeters in pasture; n = 4 measurements × 54 micro-lysimeters in forest with bare soil and forest with litter). Full lines represent the "segmental linear regression models" adjusted for pasture and forest with bare soil. Broken lines show the threshold from which the difference between surface and air temperature switched from a constant value to increase linearly. Dotted line shows y = 0

FIGURE 6 Days required to switch from the energy to the water-limited phase of Ritchie's evaporation model for pasture (green), forest with bare soil (blue), and forest with litter (red), after a large rainfall event, when soil reaches field capacity. Whisker plots show percentile 95, first quartile, median, third quartile, and percentile 5 values for 27 micro-lysimeters in pasture and 54 in forest with bare soil and forest with litter; positive signs show the mean value

4 | DISCUSSION

Soil evaporation is a dominant water loss in dry ecosystems, and vegetation, by altering soil surface micro-meteorological conditions, plays a key role at controlling it. In this paper, we explored the separate effects of the tree canopy cover and litter on evaporation losses in pastures and forests of Dry Chaco rangelands. Although tree canopy cover had a minor effect in reducing non-water-limited evaporation rates (i.e., E_1 in bare-soil forest micro-lysimeters at full canopy cover was 38% lower than at full exposure to radiation), litter cover had a stronger effect with evaporation reductions in the order of 6.4 and 4 times those of bare soil pasture and forest micro-lysimeters, respectively. Under typical meteorological conditions of the wet summer season in our study site, pasture, forest with bare soil, and forest with litter would demand on average 1.5, 2.5, and 9.5 days to reach the cumulative evaporation threshold to switch from the energy-limited to the water-limited evaporation.

Litter effects on soil evaporation interact with canopy cover and with rainfall characteristics (event size and frequency) to determine the ecohydrology of dry ecosystems (Nicholson, 2011). By reducing evaporation losses, soil water content under litter-covered patches increases, favouring deep percolation of small (usually highly frequent) rainfall events, which under the typical micro-meteorological conditions of bare soil patches would be easily evaporated (Breshears, Myers, & Barnes, 2009; Cavanaugh, Kurc, & Scott, 2011; Ji & Unger, 2001). However, some studies suggested that if evaporation is prolonged in time, litter might have little or no effect and water from some small precipitation events might not be saved (Philip, 1957; Van Donk et al., 2010). In other words, when evaporation operates for a sufficiently long time without rains rewetting the surface, cumulative evaporation from bare and litter-covered soils would be identical (Hillel, 1998).

To explore and discuss the effect of days between rainfall events on evaporation, we developed a simple model, on the basis of the equations and parameters obtained in this study, and we run it with 11 years of meteorological data (2003–2014) from our study site. Basically, the daily water balance of a surface soil layer with the characteristics of the micro-lysimeters (18 cm depth, 28 mm of water retention at field capacity) was simulated. The simulation started with the first registered rainfall event big enough to raise soil moisture level to field capacity (≥28 mm), so that the initial condition was set at this moisture state, and proceeded the following days by adding daily rainfall inputs and subtracting daily evaporation losses. Evaporation losses were computed as the product of daily ET_0 and the corresponding K_E for each vegetation cover (0.83, 0.54, and 0.14, corresponding to mean values for pasture, forest with bare soil, and forest with litter, respectively; see Equation 1) when evaporation was energy limited (soil moisture >19.5 mm); and by affecting E_p with an exponential function derived from Equation 2 when evaporation was water-limited (soil moisture <19.5 mm). Water in excess (daily water balance >28 mm) was considered to percolate deeper in the soil profile. Figure 7 illustrates the model output for a typical year.

Results of 11 year modelling show that litter maintained evaporation in the energy-limited mode significantly longer ($p < .01$) than in bare soil conditions of both forest and pasture (which did not differ significantly between them; $p > .05$). During the summer wet season, the three treatments (pasture, forest with bare soil, and forest with litter) stay more time energy-limited than in the winter one, especially the forest with litter that presented a 68.8% of summer days energy-limited, on average, and a maximum of 95% (corresponding to the wetter year, with 60% higher rainfall inputs respect to the average of our study site). On the contrary, in winter, the low rainfall inputs make that the three treatments stay most of the time water-limited, even for forest with litter; this confirms that the effectiveness of litter to reduce evaporation depends also on rainfall characteristics (event size, frequency, and seasonality). A not-modelled but potentially critical aspect, which could be very important in terms of the magnitude of water losses of dry ecosystems, is vegetation canopy interception. Although canopy interception often represents a minor fraction of annual evapotranspiration losses in dry environments (Raz-Yaseef et al., 2010; Sutanto et al., 2012), for drier years with low frequent and small size rainfall events, litter interception can strongly reduce soil rainfall inputs (Carlyle-Moses, 2004; Domingo, Sánchez, Moro, Brenner, & Puigdefábregas, 1998; Martinez-Meza & Whitford, 1996).

The reduction in evaporation losses found in this study, on the one hand, increases the opportunity for plant roots to uptake water and, on the other, favours the percolation of rainfall water deeper in the soil profile where they are less subject to evaporation losses (Ji & Unger, 2001; Klocke, Currie, & Aiken, 2009). These two mechanisms positively interact with rainfall events enhancing plant transpiration when vegetation spatial distribution and soil physical properties are considered (Ludwig, Wilcox, Breshears, Tongway, & Imeson, 2005; Yu, Gao, Epstein, & Zhang, 2008). Surface run-off/run-on redistribution concentrate water in high-density vegetated patches (with close canopies and litter on surface), which, in turn, frequently present high infiltration rates, resulting in a greater amount of water capture (o percolation) of these patches respect to a no-redistribution situation (Caldwell, Young, Zhu, & McDonald, 2008; Wilcox et al., 2003). This water concentration can overcome the higher interception losses of densely vegetated patches respect to sparsely vegetated ones (Ludwig et al., 2005; Nouwakpo et al., 2016). In addition, vegetated patches often present lower water holding capacity, which facilitates the water storage deeper in the soil profile (Caldwell et al., 2012; Lebron et al., 2007; Magliano et al., 2017). In a possible climate-change scenario, characterized by less frequent but larger and more intense rainfall events (IPCC, 2014; Trenberth, Dai, Rasmussen, & Parsons, 2003), water concentration in densely vegetated patches would be enhanced, generating a positive feedback on plant transpiration and carbon uptake.

From a land-management perspective, litter would be critical to improve primary production in dry regions. Under practical conditions, reference evapotranspiration, rainfall inputs, and soil type are not controllable factors, but the amount, distribution, and persistence of litter (or crop residues in agricultural systems) are amenable to be controlled by management practices (Klocke et al., 2009; Steiner, 1989; Van Donk et al., 2010). For example, no-till and the effective management of crop residues have made possible the development of rainfed agriculture in semiarid regions (ca. 500–600 mm/year) such as the southern great plains in United States or the northeast plain in China (Ji & Unger, 2001). Although rainfed agriculture is not usually profitable in our study site, there is room for improving forage production
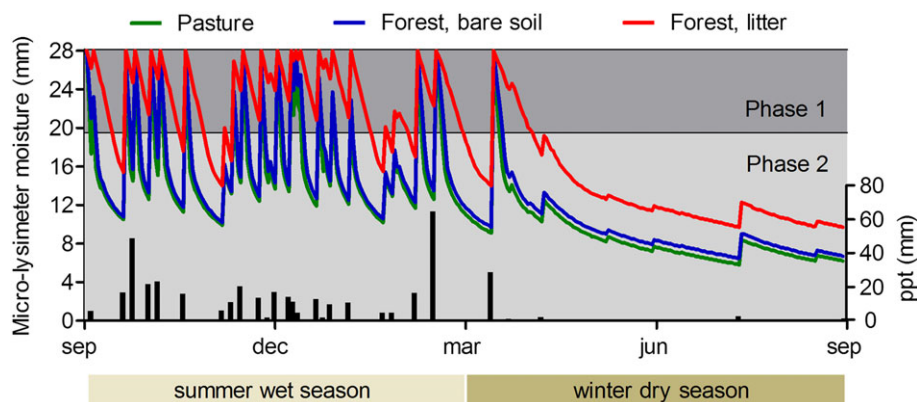
FIGURE 7 Modelled soil moisture (0–18 cm) for pasture (green line), forest with bare soil (blue line), and forest with litter (red line) for a typical (2006) year of our study site (Dry Chaco rangelands). Black vertical bars represent rainfall events. Dark grey represents phase 1 (energy-limited) and light grey represents phase 2 (water-limited)

for extensive cattle raising. Our results, and some experiences from local farmers, highlight the underlying litter effects that would potentially explain the effectiveness of the roller chopping practice based on favouring those key species that produce a large quantity (amount) of litter, such as *Prosopis flexuosa* trees (Blanco et al., 2005; Marchesini et al., 2015; Steinaker et al., 2016). This study suggests that the conditions generated by the roller-chopping practice (open canopies and large amount of palatable grasses) in combination with the ecohydrological effect of high amounts of litter on surface are the key to improve extensive livestock production in Dry Chaco rangelands.

5 | CONCLUSIONS

The partition of rainfall inputs into transpiration and evaporation is a key driver of ecosystem functioning and vegetation productivity in dry environments. By analyzing the structural heterogeneity of a dry forest and a contiguous pasture and by manipulating soil litter cover, we found that litter exerts a much more effective control of direct soil evaporation than the canopy shadow. At our study system, the reduction of evaporation by litter extended the energy-limited phase of this process to such an extent that it may be rarely limited by water availability in spite of a highly negative water balance (PPT/ET0 < 0.4) and would very likely increase plant transpiration. Our findings highlight the key ecohydrological role of soil litter on the water balance of these ecosystems.

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