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Rainfall intensity switches ecohydrological runoff/runon redistribution patterns in dryland vegetation patches

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Abstract. Effectively managing net primary productivity in drylands for grazing and other uses depends on understanding how limited rainfall input is redistributed by runoff and runon among vegetation patches, particularly for patches that contrast between lesser and greater amounts of vegetation cover. Due in part to data limitations, ecohydrologists generally have focused on rainfall event size to characterize water redistribution processes. Here we use soil moisture data from a semiarid woodland to highlight how, when event size is controlled and runoff and interception are negligible at the stand scale, rainfall intensity drives the relationship between water redistribution and canopy and soil patch attributes. Horizontal water redistribution variability increased with rainfall intensity and differed between patches with contrasting vegetation cover. Sparsely vegetated patches gained relatively more water during lower intensity events, whereas densely vegetated ones gained relatively more water during higher intensity events. Consequently, range managers need to account for the distribution of rainfall event intensity, as well as event size, to assess the consequences of climate variability and change on net primary productivity. More generally, our results suggest that rainfall intensity needs to be considered in addition to event size to understand vegetation patch dynamics in drylands.

Key words: canopy; Dry Chaco woodlands; forest; rainfall intensity; rangelands; spatial heterogeneity; water balance.

Introduction

The net amount of moisture that enters into the soil from rainfall and its spatial redistribution at the patch scale are key drivers of dryland biological processes such as net primary productivity (NPP; Huxman et al. 2004, Newman et al. 2006). Runoff, although usually representing a very small fraction of the water balance at the larger stand scale, can generate a significant small-scale horizontal water redistribution flux that influences plant-available water, as well as soil erosion losses, nutrient recycling, and evaporation/transpiration partitioning (Reid et al. 1999, Wilcox et al. 2003, Ludwig et al. 2005, Yu et al. 2008). The direction and intensity of water redistribution depend on a complex relation between vegetation attributes and soil properties, in combination with rainfall characteristics (e.g., event size or intensity; Cerdà 1997, Davenport et al. 1998, Puigdefabregas et al. 1999). Runoff/runon redistribution can enhance NPP by concentrating water in vegetated patches, potentially reducing direct evaporation and increasing water available for plant transpiration (Bhark and Small 2003, Ludwig et al. 2005, Urgeghe et al. 2010).

Understanding redistribution processes is particularly relevant in rangelands, where livestock production depends on an efficient allocation of rainfall to transpiration by forage plants and, in some cases, on runoff capture and storage for animal water supply. Extensive areas of rangeland are affected by runoff/runon redistribution processes, exemplified by the South American Dry Chaco, one of the largest and flattest semiarid rangelands globally (almost 1 million km^2; Adámoli et al. 1990, Jobbágy et al. 2008, Baldi and

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Jobbágy 2012). The primary land use of Dry Chaco is extensive cattle production, using forage in native woodlands (Baldi et al. 2013, Gasparri and Baldi 2013). Two main challenges that livestock production faces in the region are the lack of fresh surface or groundwater sources for drinking supply, and the low fraction of the NPP that is allocated to forage (as opposed to non-forage woody tissues) in the rangelands (Baldi and Jobbágy 2012). While the lack of fresh water is resolved by runoff harvesting in human-made impoundments (Magliano et al. 2015*b*), the availability of forage here as well as elsewhere depends on the redistribution of surface water via runoff/runon to vegetation patches (Ludwig et al. 2005, Urgeghe et al. 2010). Both issues are highly dependent on horizontal water redistribution at the patch to landscape scales (Breshears et al. 1997, Davenport et al. 1998), and can be affected intentionally or non-intentionally by the management of livestock grazing and associated trampling and soil compaction (George et al. 2004).

Recent research on water redistribution processes has focused on the effects of canopy architecture, spatial distribution of vegetation, ecosystem connectivity, and soil infiltration rate (Newman et al. 2010, Ravi et al. 2010, Villegas et al. 2010, Urgeghe and Bautista 2014, Okin et al. 2015). Notably, in these and other studies, rainfall has been typically characterized only by event size, largely due to the availability of historical daily aggregated data. Most previous studies on the ecohydrology of drylands have focused on large rainfall events, because of their disproportionately large contribution to total annual inputs (Sala and Lauenroth 1982, Reynolds et al. 2004, Magliano et al. 2015*a*). Large rainfall events generally generate more water redistribution than small ones (Reid et al. 1999, Wilcox et al. 2003). However, runoff can be influenced substantially by rainfall intensity (Hastings et al. 2005, Nicholson 2011), highlighting its possible key, but still poorly quantified, role in water redistribution process.

In this paper, we use soil moisture data from a semiarid woodland in a flat sedimentary landscape to highlight how, when event size is controlled for and runoff and interception are negligible at the stand scale, rainfall intensity drives the relationship between water redistribution and associated canopy and soil patch attributes. More specifically, we explored the effect of rainfall intensity on surface water redistribution and its local controls in a woodland stand of the Dry Chaco, Argentina. We measured water capture (infiltrated water 24 hours after a rainfall event) from large rainfall events in 54 patches along transects (four rainfall events), which were supplemented with three years of hourly time domain reflectometry (TDR) moisture measurements (16 rainfall events) in contrasting vegetation patches (densely and sparsely vegetated). In addition, we evaluated redistribution responses as related to fourteen canopy and soil attributes.

METHODS

The study site is located on the southern edge of the Dry Chaco woodlands (Argentina; 33.5° S, 66.5° W) on a 2000-ha ranch covered by ~7 m high woody canopies dominated by trees *Prosopis flexuosa* and *Aspidosperma quebracho-blanco* and the shrub *Larrea divaricata* (Appendix A). Landscape slope is ~1% and soils are Entic Haplustols with 53% sand and 1.4% organic matter, developed on sedimentary material. Mean annual rainfall is 430 mm, concentrated in the spring–summer season and distributed on an average of 43 events per year (2009–2014 data). Although 60% of events are small (<10 mm), they represent 12% of total inputs; while large events (>20 mm) account for only 10% of the number of events, but represent 70% of total inputs. This paper focuses on these large events (>20 mm).

In a semiarid woodland stand, we measured water capture, defined as the infiltrated water 24 hours after a rainfall event, together with 14 biophysical attributes in 50 × 50 cm patches. Over a three-year period (2011–2014), we combined two sampling approaches: randomly distributed transects (intense spatial sampling) and selected contrasting vegetation (densely and sparsely vegetated) patches (intense temporal sampling). Rainfall was measured at 20-minute intervals with a tipping-bucket rain gauge (TR-525; Campbell Scientific, Logan, Utah, USA). Rainfall event size was determined as the sum of all 20-minute rainy intervals that were not separated from the next by more than 24 hours. Rainfall intensity was calculated as the volume-weighted average intensity of all the 20-minute intervals of the event. Soil volumetric water content (VWC) was measured using time domain reflectometry (TDR).

Intense spatial sampling involved three randomly located transects in a large woodland stand. We first determined the transect origin by random selection of latitude–longitude coordinates within the stand, avoiding distances >300 m or <600 m. Next, for each site we randomly assigned a different orientation (west–east, southwest–northeast, and south–north) to avoid any directional landscape topographic bias. Within each transect we performed a systematic sampling using regularly spaced points. We opted for this systematic sampling in order to objectively characterize the natural heterogeneity of the system. On each transect, we measured water capture after four similarly large events (from 35.6 mm to 50.8 mm) but with contrasting intensity (from 8.7 mm/h to 33.6 mm/h). These events were preceded by a period of >15 days without rainfall that warranted dry soil conditions prior to their onset (and also confirmed by the temporal approach described in the next paragraph). Soil moisture on the day after each rainfall event was determined at each patch by measuring VWC at intervals of 10 cm of depth with a handheld TDR sensor (Theta Probe; Delta-T Devices, Cambridge, UK) across the whole wetting front, at each patch. Dry soil conditions were described by an additional sampling down to one meter of depth performed at the same patches during the dry season of 2013. Water capture was calculated as follows:

$$\text{Water capture (\%)} = [(\text{VWC}_{\text{post-event}} - \text{VWC}_{\text{pre-event}})/\text{rainfall event size}] \times 100 \qquad (1)$$

where $\text{VWC}_{\text{post-event}}$ is volumetric water content of the soil 24 hours after the rainfall event and $\text{VWC}_{\text{pre-event}}$ is volumetric water content of dry soil.

The intense temporal sampling consisted of continuous measurements made for two contrasting cover conditions: patches that were either densely vegetated (>90% ground cover from trees, shrubs, grasses, and litter) or sparsely vegetated (<10% ground cover low and sparse canopy of shrubs and bare soil). These levels of cover corresponded to the 5th and 95th percentiles of cover amounts on the transects. Each pair of contrasting vegetation patches was equipped with fixed VWC sensors (HS-10 and EC-5 probes; Decagon Devices, Pullman, Washington, USA) connected to dataloggers (CR10X, Campbell Scientific Instruments). For each patch, we averaged measurements from pairs of sensors installed at six depths (2, 10, 20, 30, 40, and 50 cm). We recorded 15 and 11 large rainfall events (of a total of 16 rainfall events occurred in 2011–2014) in densely and sparsely vegetated patches, respectively. Water capture was calculated as in Eq. 1 based on the VWC readings before and after each rainfall event.

We characterized all studied patches considering 14 canopy and soil attributes (detailed in Appendix B). We estimated leaf area index above 25 cm and 150 cm height and incident radiation (direct site factor; Rich 1989, Rich et al. 1999) at the corresponding positions (25 cm and 150 cm) using hemispherical photographs obtained with a Nikon Coolpix 5400 camera fit with a FC-E9 Fisheye lens (Nikon, Tokyo, Japan; Breshears and Ludwig 2010). Digital photos were analyzed using Delta-T HemiView software (HemiView 2.1, Delta-T Devices, Cambridge, UK; Rich et al. 1999). Distance to tree was measured from each patch towards the nearest tree with a diameter at breast height >10 cm. Throughfall was measured by installing manual rain gauges (cylinders of 11 cm internal diameter and 18 cm height) at each patch for 11 rainfall events during 2012–2013 (Llorens and Domingo 2007). Throughfall fraction was estimated as the ratio of the amount of water collected at each patch relative to the amount of rainfall (registered by the tipping-bucket gauge). Interception was calculated as the difference between rainfall and average throughfall ($n = 11$ rainfall events). Soil litter cover was determined by visual interpretation of photographs of an area of 1 m^2 of the surface soil (0.85 × 1.20 m) centered on each patch, using four classes: 0–25.0%, 25.1–50.0%, 50.1–75.0%, and 75.1–100.0%. Soil litter depth was determined by measuring and averaging the thickness of the litter layer from the mineral soil surface to the top, at eight random points within patches. Water repellency was determined by the water drop penetration time test (WDPT; Lewis et al. 2006), after soil litter removal at four random points per patch and averaged. The microtopography of each patch (pixel per side 0.5 m) was determined using a Ziplevel Pro-2000 (Technidea, Escondido, California, USA). We calculated the relative elevation of each patch, with regard to its eight neighboring patches. Then we classified them into eight possible situations from 0 (lower than all neighbors) to 8 (higher than all neighbors); for example, 3 corresponds to a patch that is higher than 3 of its 8 neighbors, but lower than 5 of its 8 neighbors. Penetration resistance was measured and averaged at five randomly located points within each patch using an analog pocket penetrometer (Eijkelkamp, Gelderland, Netherlands). Infiltration rate was determined by the double ring method, using the basic infiltration rate data (Wilson and Luxmoore 1988). Field capacity 0–10 cm depth and 10–20 cm depth was determined as the VWC 24 hours after a rainfall event measured discretely with a portable TDR sensor. We used simple and multiple regressions to determine the association between one or more attributes and water capture.

RESULTS

At the stand scale, four rainfall events of similar size (Fig. 1A) but with very different intensities (Fig. 1B) yielded contrasting water redistribution patterns (Fig. 1C). Water redistribution (i.e., spatial variability of water capture across patches) increased with rainfall intensity, while total water capture (i.e., average water capture across patches) remained largely constant (Fig. 1C). The limited variation in event size had no relation to either water redistribution or total water capture ($P = 0.78$ and $P = 65$, respectively). Total water capture represented 92.5–97.5% of rainfall inputs for all events, so a minor fraction (2.5–7.5%) was lost by interception and/or runoff. We estimated interception losses to be 1.4 ± 0.2 mm/event (mean ± CV), which (even assuming no stemflow) would produce a net runoff of just 0.1–3% of rainfall inputs, even for the most intense event (event d, which was within the upper 5% of the intensity distribution for 2009–2014).

Patch water capture was significantly explained by more than one of the biophysical attributes (Fig. 2; Appendix C). Note, however, that the sign of the relationship switched from the lowest to the highest intensity rainfall events for some attributes (both endpoints were significant for leaf area index, incident radiation, and soil litter depth; Fig. 2). Sparsely vegetated patches favored water capture during the low-intensity event, whereas densely vegetated ones favored water capture during the high-intensity event. Therefore, water redistribution followed opposite patterns under low vs. high-intensity events (Fig. 3). For intermediate-intensity events water capture was predominantly explained by microtopography (Fig. 2; greater capture in low patches, $P < 0.1$). Multiple regression models offered little explanatory improvement for the least and most intense events (a and d, respectively), given the high internal correlation among the driving independent variables (Appendix B). However, for the intermediate-intensity events (b and c), where microtopography was more important, multiple regression models increase their explanatory power after including either incident radiation above 150 cm height in the case of event b (R^2 from 14% to 23%; $P < 0.01$) or throughfall in the case of event c (R^2 from 15% to 23%; $P < 0.01$).

Consistent with our findings along the transects, continuous TDR measurements on contrasting vegetation patches showed that increasing rainfall intensity produced progressively divergent water capture patterns (Fig. 4).Water capture was linearly related to rainfall intensity in both densely and sparsely vegetated patches, but in opposite directions (Fig. 4A; $P < 0.0001$, $n = 15$, and $P < 0.0001$, $n = 11$, respectively). Notably, no association was found with event size ($P = 0.93$ and $P = 0.55$, respectively). With higher rainfall intensity water capture increased under densely vegetated conditions, while decreasing under sparsely conditions, with the response (regression slope) being ~1.5 times steeper under sparsely vegetated conditions. The difference between densely and sparsely vegetated patches showed a strong positive linear relationship, with a threshold at a rainfall intensity of ~4 mm/h (Fig. 4B; $P < 0.0001$, $n = 9$). Below this threshold, water capture was greater in sparsely vegetated conditions; beyond the threshold it became greater under densely vegetated conditions, growing linearly to exceed 100% capture with intensities >~20 mm/h.

DISCUSSION

Our observations under natural field conditions indicate that the intensity of rainfall inputs has a critical ecohydrological relevance that is not well characterized by the more commonly used single metric of event size. Sparsely vegetated patches captured relatively more water than densely vegetated patches for lower intensity events, whereas more densely vegetated ones captured relatively more water than sparsely vegetated ones for higher intensity events. This could result from a switch in the dominant transport mechanism, shifting from interception losses during low-intensity events to runoff/runon redistribution during high-intensity events.

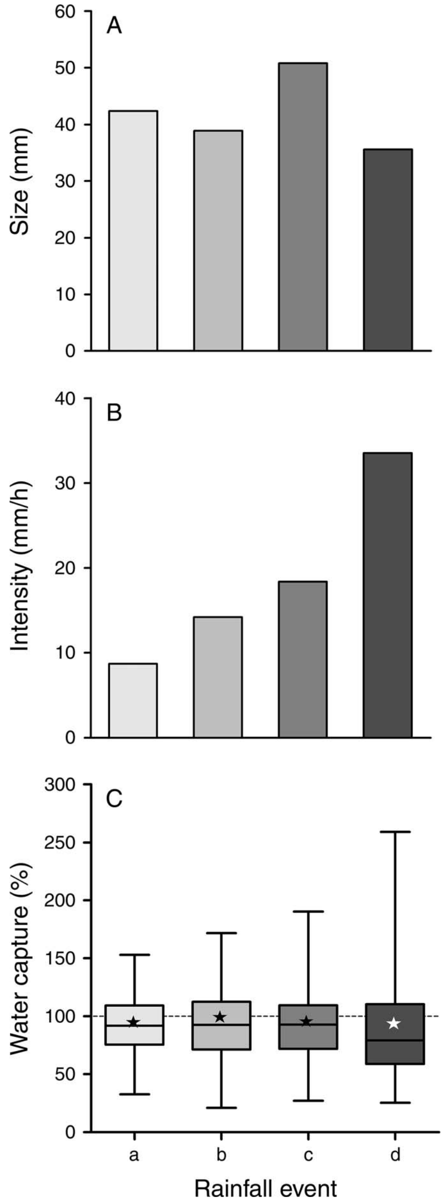

FIG. 1. (A) Event size, (B) event intensity, and (C) water capture on transects for each rainfall event, ordered from lowest to highest intensity (a, b, c, and d). In panel (C), whisker plots show maximum, first quartile, median, third quartile, and minimum values for 54 patches; stars show the mean value for 54 patches; and dashed line represents 100% of water capture. No significant differences in water capture were found across events ($P = 0.22$, $n = 4$).

The positive relationship between event size and water redistribution has been previously highlighted, both in theoretical and empirical studies (Noy-Meier 1973, Reid et al. 1999, Bhark and Small 2003, Loik et al. 2004). Our results build on that point to highlight that within an event size range, it is rainfall intensity that determines the nature and magnitude of water redistribution. This could imply that the relationship between event size and water redistribution is actually caused by intensity and not by size in itself. As event size and intensity are correlated, the first one could "mask" the second one. For example in our study site, both variables were significantly correlated (Appendix D; $R^2 = 0.45$, $P < 0.0001$, $n = 81$ events). Consistent with this, independently of event size, frontal storms (predominant in the cold season at our site) have been documented to

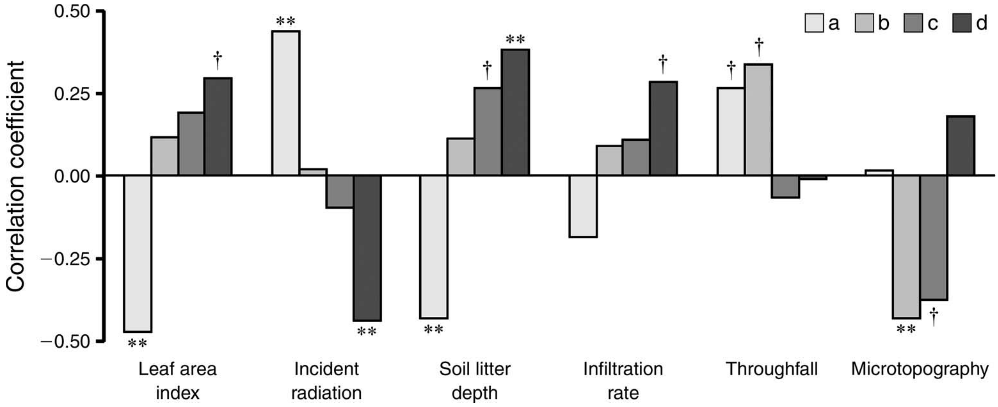

FIG. 2. Correlation coefficients for patch water capture and biophysical attributes for four rainfall events of increasing intensity. Each group of four bars corresponds to a single patch attribute and each bar corresponds to single rainfall event, ordered from lowest to highest intensity (a, b, c, and d). Asterisks indicate significant correlations († $P < 0.1$, ** $P < 0.01$). Correlations for all attributes, including other eight attributes are shown in Appendix C.

generate less runoff than convective storms (predominant in the warm season at our site; Reid et al. 1999, Wilcox et al. 2003, Nicholson 2011). In addition, large but low-intensity events, which do not generate horizontal water redistribution, could result in densely vegetated patches receiving less water than sparsely vegetated patches because of the relatively larger interception losses of the former (Reynolds et al. 1999,

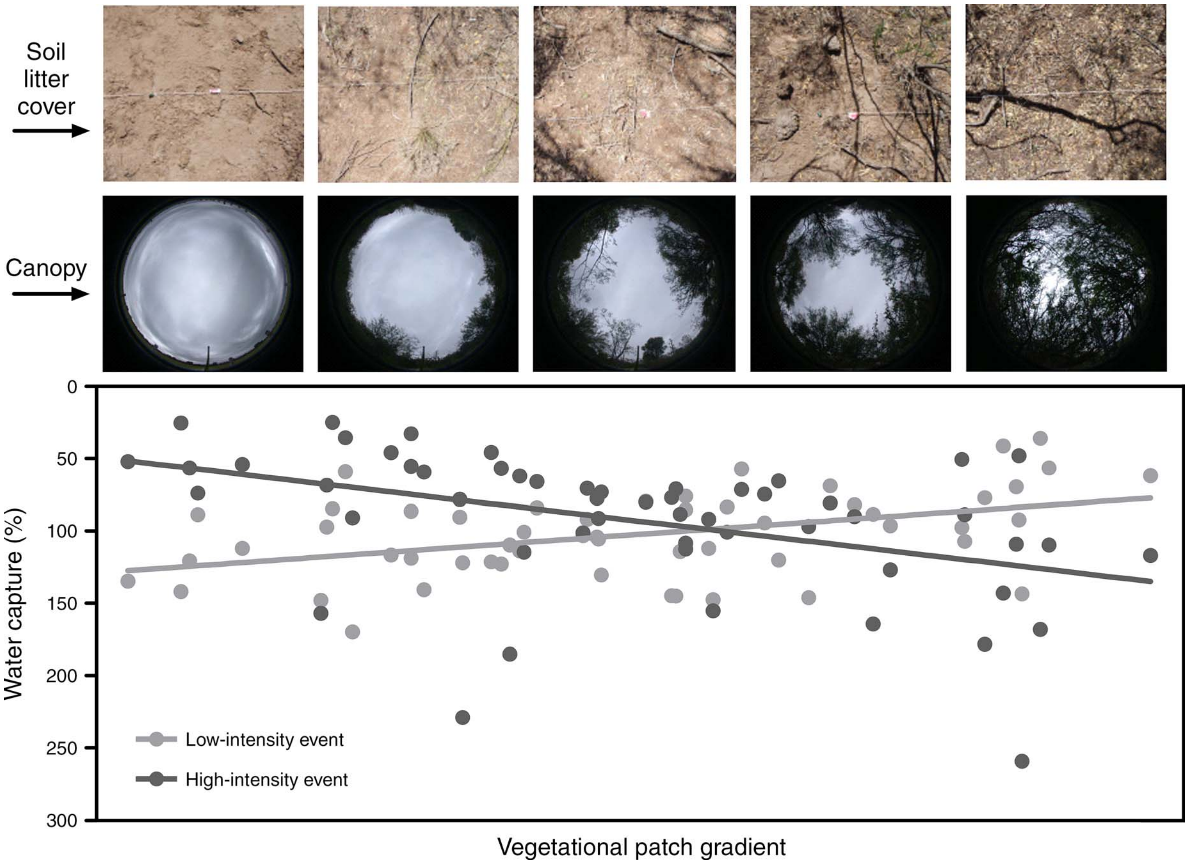

FIG. 3. Water capture values from the study transects along a vegetation patch gradient, sorted by canopy openness, for rainfall events with the lowest intensity (water capture [%] = −42.50 × [leaf area index above 150 cm height] + 127.40; $R^2 = 0.22$; $P < 0.0001$) and the highest intensity (water capture [%] = 44.13 × [leaf area index above 150 cm height] + 67.26; $R^2 = 0.18$; $P < 0.05$) (Fig. 1; events a and d, respectively). Representative photographs were selected to show the vegetation gradient in terms of canopy cover (hemispherical photos directly above graph) and associated changes in soil litter cover (top).

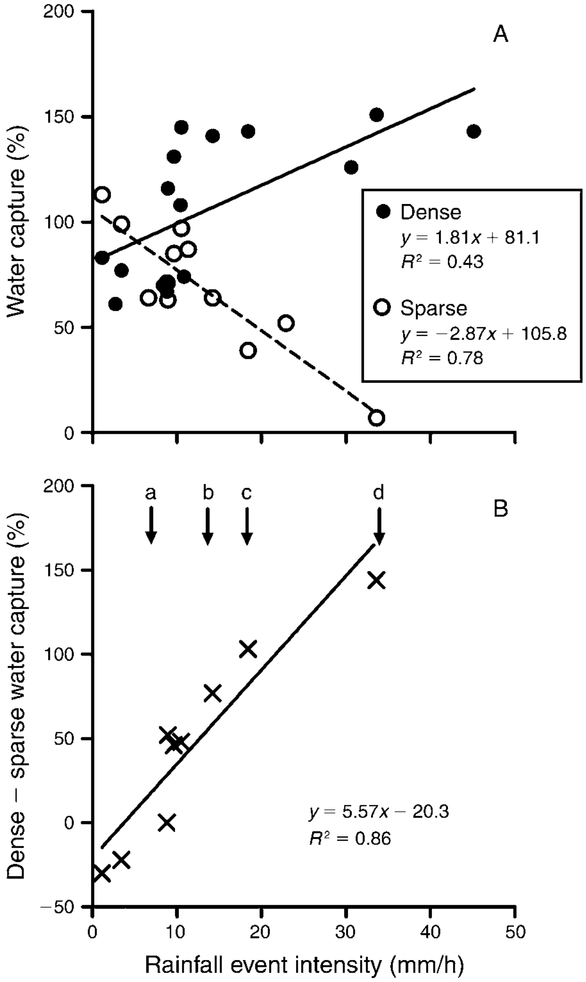

FIG. 4. (A) Water capture for contrasting vegetation patches (densely and sparsely vegetated; solid lines and dashed lines, respectively) and (B) their difference as a function of rainfall event intensity (mm/h). Data were recorded by fixed time domain reflectometry (TDR) sensors during three years (2011–2014). Arrows indicate the same four events sampled on the transects and shown in Fig. 1. Only >20 mm events were considered.

Whitford 2002). Our observations are consistent with the current literature, but highlight the separate effect of rainfall intensity, which would have been missed by focusing on event size. The importance of rainfall intensity highlights the need for more available hourly, or better yet, sub-hourly, rainfall data for studying dryland ecohydrology (Nicholson 2011) and the development of methods for the reconstruction of intensity values from daily series based on multiple sources of information such as pre- and post-event temperature, season of the year, and records of the synoptic conditions during the event.

This study expands our perspective on dryland water capture by highlighting how water redistribution varies with rainfall intensity, generating different water capture patterns for each rainfall event. Our results imply that, as the "trigger-transfer-pulse-reserve" framework (Noy-Meier 1973, Ludwig et al. 2005) becomes increasingly used to understand and manage drylands, rainfall intensity in addition to event size should be explicitly considered. Our findings reveal that not only the magnitude but even the sign of inter-patch redistribution can change under shifting rainfall intensities, suggesting that the interplay of topography, climate, and vegetation characteristics can create very different, yet predictable, patterns of redistribution across dryland vegetation patches. Consequently range managers need to account for the distribution of rainfall event intensity as well as event size to assess the consequences of climate variability and change on forage production as well as species conservation. Our results have direct relevance to the Dry Chaco, where the entire region depends economically on livestock production, but may also reveal a process operating more generally in drylands. Rainfall intensity should be considered in addition to event size to understand vegetation patch dynamics.

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SUPPLEMENTAL MATERIAL

Ecological Archives

Appendices A–D are available online: http://dx.doi.org/10.1890/15-0550.1.sm