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Overland flow from plant patches: Coupled effects of preferential infiltration, surface roughness and depression storage at the semiarid Patagonian Monte

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SUMMARY

The objective of this study is to characterize and quantify the overland flow generated from the plant patch areas of spotted vegetation toward the immediate surrounding bare ground including the coupled effects of preferential infiltration, surface roughness and depression storage. To this aim a series of overland flow plot experiments were designed in areas of the Patagonian Monte where evidence of patch-to-soil overland flow was observed. The experiments produced data on the plot micro-topography and physical properties of the soil, root density and the frictional parameters of the overland flow as well as the extent of the areas of water depression storage. The obtained data were used to calibrate a spatial-explicit (CREST) hydrological model of the flows and pathways generated by stemflow and throughfall during characteristic storms in the area. Good agreement between the model estimates and the measured data was found. This work provides physically-based metrics of runoff redistribution from the plant patch areas toward the immediate surrounding bare soil areas, including the effect of plant roots and depression storage as influenced by various shapes of the plant patch slopes. It is concluded that water transport can result from stemflow and throughfall at the patch areas during typical rainfall events at the semiarid Patagonian Monte. Implications of this phenomenon in the surface distribution of water, nutrients and seeds may feasibly follow.

1. Introduction

The distribution of the vegetation cover in arid and semiarid environments around the world occurs in patterns that can be either spatially periodic or random, in regular bands, spotted clumps, gap patterns and labyrinths (Bisigato et al., 2009; Couteron and Lejeune, 2001; Klausmeier, 1999; Malam Issa et al., 2011; von Hardenberg et al., 2001). In these systems the effect of vegetation generates contrasting differences in the physical characteristics of the soil beneath plant patches and neighboring bare soil (Casermeiro et al., 2004; Merino-Martín et al., 2015). In semi-arid regions a high proportion of fine roots are found in the superficial soil layers (Gill et al., 1999; Silva and Rego, 2003). Decayed and fresh root channels generate soil macroporosity and contribute to preferential infiltration flow resulting in higher infiltration than expected as based on the textural properties of the surface soil (van Schaik, 2009). The combined effect of the plant canopy and ground cover conditions in vegetated patches has been proved to be important in regulating runoff processes (Archer et al., 2012; Bautista et al., 2007; Pueyo et al., 2013; Wainwright et al., 2002), as they are responsible for rainfall interception and the decrease of raindrop impact energy, while ground cover promotes rainfall infiltration into the soil and reduces overland flow velocities (Vásquez-Méndez et al., 2010).

Stemflow and throughfall are highly variable between and within types of vegetation (Llorens and Domingo, 2007) and vary for a same canopy with the peak intensity of the rainfall events (Dunkerley, 2013). The interception of precipitation by a shrub canopy promotes the accumulation of surface water from stemflow at the plant base (Abrahams et al., 2003) and from throughfall which reaches ground by passing through or dripping from the plant structures. These processes also influence overland flow paths. When the intensity of precipitation exceeds the water infiltration rate, the excess of water initially fills surface depressions and then flows downslope over the soil surface (Mao et al., 2008; Rango et al., 2006).

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Nomenclature

Acronyms

BS	bare soil
DEM	digital elevation map
RP	runoff plume
TDI	Tension Disk Infiltrometer
TDR	Time-Domain Reflectometer
VS	vegetated soil
S	sample

Variables

υ	kinematic viscosity ($mm^2\ s^{-1}$)
α	inverse of the air-entry parameter (kPa^{-1})
θ_g	gravimetric soil moisture (g)
θ_i	antecedent water content of the soil ($mm^3\ mm^{-3}$, mm)
θ_r	residual volumetric moisture ($mm^3\ mm^{-3}$)
θ_s	saturated moisture content ($mm^3\ mm^{-3}$)
θ_v	volumetric soil moisture ($mm^3\ mm^{-3}$)
$\Delta A(t)$	instantaneous expansion of RP area during the *n-th* time interval (mm^2)
$A(t_n)$	instantaneous RP area at *n-th* time interval (mm^2)
A_{BS}	area of RP over bare soil surrounding plant patch (mm^2)
A_{DS}	depression storage area (mm^2)
A_{end}	RP total area at the end of the flow experiment (mm^2)
A_{VS}	area of RP occupied by plant patch (mm^2)
d^*	average depth of the RP (mm)
DS	depression storage (%) (Base: total runoff plume (RP) area)
F	accumulated infiltration (mm)
$f(t_\infty)$	steady state infiltration rate ($mm\ s^{-1}$)
$f(t)$	instantaneous infiltration rate at *n-th* time interval ($mm\ s^{-1}$)
$IN(t)$	instantaneous total infiltration flow at *n-th* time interval ($mm^3\ s^{-1}$)
$IN_{pref}(t)$	instantaneous preferential infiltration flow at *n-th* time interval ($mm^3\ s^{-1}$)
$IN_{sat}(t)$	instantaneous saturated infiltration flow at *n-th* time interval ($mm^3\ s^{-1}$)
$IN_{unsat}(t)$	instantaneous un-saturated infiltration flow at *n-th* time interval ($mm^3\ s^{-1}$)
$K_h(\theta(t))$	variable hydraulic conductivity ($mm\ s^{-1}$)
K_{sat}	saturated hydraulic conductivity ($mm\ s^{-1}$)
$K_{sat}BS$	K_{sat} estimated by the TDI at the patch surrounding area ($mm\ s^{-1}$)
$K_{sat}VS$	K_{sat} estimated by the TDI at the central area of the plant patch ($mm\ s^{-1}$)
L	soil tortuosity connectivity
Q_o	water stored at the RP as overland flow (mm^3)
$Q_o(t)$	instantaneous overland flow at *n-th* time interval ($mm^3\ s^{-1}$)
Q_v	water stored at the upper vadose zone (mm^3)
r	TDI disk radius (mm)
Re	Reynolds number
$s(t_n)$	terrain height change along the contour of the RP area at time *t* (mm)
s^*	average terrain height change along the contour of the RP (mm)
SBD	soil bulk density ($g\ cm^{-3}$)
SG	gravel content in soil % (Base: weight of dry (105°), sieved (2 mm mesh) soil)
SR	amount of roots in soil % (Base: weight of dry (105°), sieved (2 mm mesh) soil)
SS	sand content in soil % (Base: weight of dry (105°), sieved (2 mm mesh) soil)
t	time (min)
v^*	mean overland flow velocity ($mm\ s^{-1}$)
$W(t)$	instantaneous water inflow rate ($mm^3\ s^{-1}$)
$z_f(t)$	instantaneous water infiltration depth at *n-th* time interval (mm)
σ_s	surface roughness (mm)
$\psi_f(\theta)$	suction at the wetting front of infiltration (mm)

As infiltration rates are greater under plant canopies, at large spatial scales more surface runoff is generated at bare interspaces than at areas with plant cover. Extensive research in semiarid regions with banded shrubby vegetation and mulga environments (Bromley et al., 1997; Cornet et al., 1992; Dunkerley and Brown, 1995; Dunkerley, 2002; Ludwig et al., 1999; Moreno-de las Heras et al., 2012) and at semiarid patchy landscapes (Li et al., 2008; Reid et al., 1999; Rango et al., 2006) showed that the combination of bare ground and vegetation patches creates a spatial mosaic of sources and sinks where bare ground typically carries runoff and sediments (source) and vegetation traps water and sediments (sink).

At a finer spatial scale (1–2 m) field evidence shows that under circumstances at semiarid areas overland flow can also occur from the plant patch areas to the surrounding bare soil (Fig. 1) in apparent inversion of the well-known source-sink trend observed at large spatial scales. Some experimental work has also been aimed to characterize runoff within (Archer et al., 2012) and around (Vásquez-Méndez et al., 2010) plant patches. Since these flows may imply spatial redistribution of water, nutrients and seeds (Bochet, 2015; Thompson et al., 2014) between patches and bare soil around, there seems to be a need for studies involving direct measurement of water fluxes at this scale aimed to understand the water transport processes at vegetation patches at relatively flat spotted semiarid landscapes (Harman et al., 2014; Thompson et al., 2011).

The objective of this study is to characterize and quantify the overland flow generated from the plant patch areas of spotted vegetation toward the immediate surrounding bare ground including the coupled effects of preferential infiltration, surface roughness and depression storage within the plant patch areas. To this aim the coupled overland and infiltration flows and pathways generated by stemflow and throughfall under vegetation patches were simulated with a spatial-explicit (CREST) calibrated hydrological model. The CREST model input parameters were estimated by sampling soil properties, characterizing the micro-topography, and estimating dynamic water mass balances of 12 field overland flow experiments with different vegetation patches.

2. Materials and methods

2.1. Site description

The experiments here presented were performed at the Wildlife Refuge "La Esperanza" (Fig. 2; UL corner: S: −42.16972, W: −64.9934; LR corner: S: −42.2144, W: −64.96193), a representative site of the Monte Phyto-geographical Province in Argentina, in northern Patagonia (Abraham et al., 2009).