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Modeling the effects of plant-interspace heterogeneity on water-energy balances in a semiarid ecosystem

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ABSTRACT

Close interactions of water-energy conditions at plant cover and interspace are so far largely overlooked in water-energy modeling for dryland ecosystems. This study focused on (i) introducing the plant-interspace heterogeneity into water-energy modeling for a dryland ecosystem, and (ii) investigating the influences of such heterogeneity on the ecosystem water-energy budgets. The plant-interspace heterogeneity was described using a two dimensional scheme. The soil-vegetation-atmosphere transportation processes were integrated with horizontal exchanges of water and energy. The model was parameterized and validated by field observations (Yanchi, China). The modeled sensible and latent heat fluxes were stronger at the shrub cover (SCA) compared to interspace, but soil surface was cooler. Moreover, the water-energy advections between the interspace and SCA showed mixed effects on the simulated water-energy budget of the ecosystem. The aboveground advections significantly enhanced the evapotranspiration rate at SCA. The root uptake and horizontal inflows from the interspace amounted to over 40% of the annual water loss from SCA, resulting in a tight water budget at ecosystem level. These results emphasized the necessity of considering the plant-scale heterogeneities and horizontal processes in estimating water-energy balances in such ecosystems. Our model can serve as a tool to simulate the water-energy dynamics in sparse-vegetated ecosystems regarding such interactions.

1. Introduction

Dryland (arid and semiarid) ecosystems cover over 40% of the land surface in the world, and the coverage is increasing due to climate change and anthropological disturbances such as deforestation and overgrazing (Asner et al., 2003; Yang et al., 2005). These ecosystems contribute to about 20% of the net primary productivity (NPP) of territorial ecosystems (Whittaker, 1975) and contribute significantly to the variations of global carbon budget (Poulter et al., 2014). In dryland environments, the harsh water-energy conditions such as the low and irregular precipitation, prolonged dry periods and extreme temperatures, affect the dynamics and functioning of ecosystems and limit plant growth and ecosystem productivity (Noy-Meir, 1973).

Better understanding on the mechanisms of the water-energy balances of dryland ecosystems and their controlling factors are crucial for adaptive management under the projected climate change. This requires numerical models that can delineate the water-energy flows and the feedbacks between the flow processes and controlling factors. Over the past few decades, water-energy models developed for dryland ecosystems generally employ soil-vegetation-atmosphere transportation schemes (SVAT) (e.g., Kremer and Running, 1996; Nouvellon et al., 2000; Xia and Shao, 2008). SVAT presume that the vertical water-energy gradients and the resistances from the rooting zone to boundary atmosphere dominate the flow processes over the horizontal heterogeneities at the stand or footprint scale. Consequently, the flow processes are usually simplified as one-dimensional. Such settings can be representative for ecosystems like boreal forests (e.g., Iritz et al., 1999), grasslands (e.g., Falge et al., 2005) and mires (e.g., Gong et al., 2013). However, for dryland ecosystems major gaps remain between the generality of current SVAT models and the reality of arid and semiarid environment.

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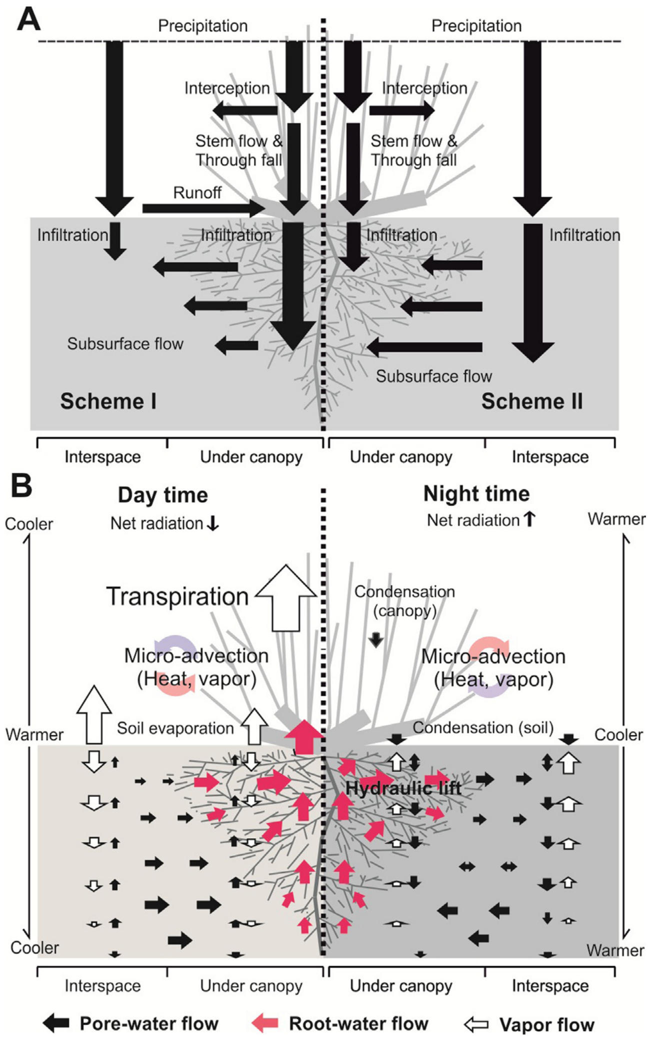

Fig. 1. Conceptual interactions of water and energy between a plant individual and nearby soil, as driven by rain events (A) and diurnal cycles of radiation and temperature (B).

Dryland ecosystems are characterized by patchy vegetation and large fractions of bare soils (Domingo et al., 2000). In such environment, the water-energy processes can be highly heterogeneous and align to the distribution of plants (e.g., Rodríguez-Iturbe et al., 2001; Caylor et al., 2008; Ma et al., 2011). For example, foliage can enhance stem flow but reduce soil compaction under canopy (Rango et al., 2006). Whereas at interspace, the soil surface could be less infiltratable (Belnap, 2006; Chen et al., 2013). As a result, runoffs are readily generated from the open area and run towards under canopy (Fig. 1A, Scheme I), a phenomenon referred to as "hydrological islands" (Rango et al., 2006). Yet, recent studies have suggested that the surface clogging by crusts in some ecosystems may limit runoff generation rather than promote it (Kidron et al., 2012). In this case, greater infiltration may occur at the interspaces, and drive the horizontal movement of water via subsurface flows to soils under canopy (Fig. 1A, Scheme II).

The water movement between planted patches and interspace couple closely with the heterogeneity of surface energy balance. It is known that net radiation, surface temperature and evapotranspiration (ET) demand can vary significantly from the plant-covered patches to the bare soils nearby (Flerchinger et al., 1998; Domingo et al., 2000). During daytime, the transpiration and shading tend to decrease the water storage faster but maintain a cooler temperature under canopy than interspace (Domingo et al., 1999; Rango et al., 2006; see Fig. 1B). During nighttime, the surface soil tends to be recharged by multiple sources (Fig. 1B), e.g., by vapor condensation (Pan et al., 2010; Agam and Berliner, 2006), upward thermal/isothermal fluxes (Milly, 1996) and root-mediated hydraulic lift (Horton and Hart, 1998; Caldwell and Richards, 1989). These flows tend to differ between plant-covered and bare soils, due to the different profiles of temperature, root density and water storage. The heterogeneous water-thermal conditions, on the one hand, can drive micro-advections of heat and vapor over the different surfaces (Allen et al., 2011). On the other hand, horizontal exchanges of water, vapor and heat may occur between the soils under canopy and at interspace, as driven by the gradients of temperature and water potential. These diurnal dynamics are interacted with the seasonality of solar forcing, precipitation, plant phenology and physiology (Unland et al., 1996), leading to further complexity of the plant-soil interactions at the seasonal course.

Currently, the plant-interspace interactions have not yet been considered in available SVAT-based dryland models and the understanding on the effects of plant-interspace heterogeneities is still limited. In this work, we modeled the effects of plant-interface heterogenity on the water-energy balances in a semiarid desert shrubland ecosystem in northwestern China by employing a two-dimensional scheme in process-based modeling. Model outputs (e.g., diurnal and seasonal dynamics of the surface energy balance, and soil temperature and water content) were evaluated against the field measurements. The sensitivity of water-energy balances to the plant-interface heterogenity was also studied.

2. Materials and methods

2.1. Outlines for the modeling

The modeled semiarid shrubland ecosystem located at the southern edge of the Mu Us desert (37°42′31″N, 107°13′47″E, 1560 m above sea level), Ningxia, northwestern China. The long-term mean temperature (1954–2004) is 8.1 °C and the frost-free season is 165 days on average (Wang et al., 2014). The mean annual precipitation is 287 mm, 62% of which falls from July to September (Jia et al., 2014). The radiation and evaporation demand are high in this area, i.e., the annual incoming shortwave radiation is $1.4 \times 10^{5}\,\mathrm{J\,cm^{-2}}$ and the annual potential evaporation is 2024 mm on average. The ecosystem covers a flat plateau of about 8 ha (Fig. 2A), and is dominated by scattered crowns of *Artemisia ordosica* (about 30% coverage, Fig. 2B). A layer of biological soil crust (mainly lichens, cyanobacteria and alges) covers about 90% of interspace soil. The thickness of the crust layer was 0.5 cm–2.5 cm.

Regarding the site conditions, the following assumptions were made to simplify the modeling work: (i) the landscape can be structured as the replication of similar land units, which consist of the area covered by shrubs and the surrounding bare soil (interspace); (ii) the water-energy exchanges and the flow processes at the ecosystem level can be resembled by those of the land units with representative properties (e.g., crown sizes, LAI, root biomass, soil texture, etc.,); and (iii) each land unit can be considered as horizontally isotrophic, assuming that the spacing of shrubs is random, the crowns are centrosymmetric (see also net radiation citation) and the soil texture is horizontally homogeneous.

Following the above assumptions, the target ecosystem was outlined based on the setting of "representative land units" (RLU) with a cylinderical structure (Fig. 2C). Vertically, the RLU included the soil-plant-atmosphere continuum (SPAC) from the lower boundary of rooting zone to a reference height in the boundary atmosphere. Horizontally, the RLU comprised the SPAC volumes occupied by a shrub individual and the surrounding spaces, within which the soil hydrology was influenced mainly by the shrub at the center. Based