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Evapotranspiration partitioning, stomatal conductance, and components of the water balance: A special case of a desert ecosystem in China

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SUMMARY

Partitioning evapotranspiration (*ET*) into its components reveals details of the processes that underlie ecosystem hydrologic budgets and their feedback to the water cycle. We measured rates of actual evapotranspiration (ET_a), canopy transpiration (T_c), soil evaporation (E_g), canopy-intercepted precipitation (E_I), and patterns of stomatal conductance of the desert shrub *Calligonum mongolicum* in northern China to determine the water balance of this ecosystem. The ET_a was 251 ± 8 mm during the growing period, while E_I, T_c, and E_g accounted for 3.2%, 63.9%, and 31.3%, respectively, of total water use (256 ± 4 mm) during the growing period. In this unique ecosystem, groundwater was the main water source for plant transpiration and soil evaporation, T_c and exceeded 60% of the total annual water used by desert plants. *ET* was not sensitive to air temperature in this unique desert ecosystem. Partitioning *ET* into its components improves our understanding of the mechanisms that underlie adaptation of desert shrubs, especially the role of stomatal regulation of T_c as a determinant of ecosystem water balance.

1. Introduction

Evapotranspiration (*ET*) is the largest process of ecosystem water loss and is a major determinant in the ecosystem water budget and energy balance (Law et al., 2002; Scott et al., 2006; Hu et al., 2009). In arid zones, *ET* can account for up to 95% of all water inputs (Wilcox and Thurow, 2006). Generally, *ET* is the aggregate of water loss measured using micrometeorological techniques and soil parameters and does not distinguish the pathway and components of water loss. In contrast, actual evapotranspiration (ET_a) is composed of and estimated by several of the *ET* components, including the linked vapor fluxes of canopy transpiration (T_c), soil evaporation (E_g), and canopy-intercepted precipitation (E_I) (Mitchell et al., 2009; Raz-Yaseef et al., 2012). As a consequence, ET_a can partition *ET* into its component fluxes, thereby contributing to our understanding of the relative controls of T_c *versus* E_g (Lawrence et al., 2007; Wang et al., 2010) and helping to resolve the critical uncertainties regarding the coupling of water and energy cycles in arid regions (Austin et al., 2004; Breshears, 2006; Wang et al., 2010). While partitioning *ET* involves the use of multiple technologies, including lysimeters, sap flow sensors, infrared thermometers, stable isotopes (Scott et al., 2006; Morana et al., 2009), and modeling (Reynolds et al., 2000; Hu et al., 2009), such studies remain both an observational and theoretical challenge (Huxman et al., 2005; Caylor et al., 2006; Morana et al., 2009; Wang et al., 2010), particularly in terms of scaling from whole-plant to ecosystem levels in arid regions. Therefore, the aim of this work was to provide independent measurements of *ET* and its components at different scales in order to unravel details of the processes that underlie ecosystem hydrologic budgets and feedback in a unique desert ecosystem in arid regions.

Global warming may increase the variability in precipitation and the likelihood of drought conditions, including within arid regions (Dai, 2011). Consequently understanding the partitioning of *ET* will become increasingly important for sustainable management of water resources at regional scales. Partitioning of *ET* has been intensively studied globally (e.g., Lei and Yang, 2010; McCulloh and Woodruff, 2012; Kool et al., 2014; Mendez-Barroso

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et al., 2014). The ratio T_c/ET varies greatly among ecosystems and timescales (Mitchell et al., 2009; Morana et al., 2009; Cavanaugh et al., 2010; Staudt et al., 2011) so that *ET per se* is often not a good indicator of productivity (i.e., contributing to vegetation carbon gain). These studies indicate that the ratio T_c/ET reflects forest productivity and survival in semi-arid ecosystems and is controlled by canopy conductance and leaf area index (LAI) (Hu et al., 2009; Mendez-Barroso et al., 2014). T_c is the dominant component of *ET* across a variety of ecohydrological ecosystems (Williams et al., 2004; Eamus et al., 2006) and is determined by interactions among plant physiology, environmental conditions, and stomatal regulation (Peters et al., 2010; Raz-Yaseef et al., 2012; Litvak et al., 2012). However, many such studies have failed to accurately measure E_l because scaling from individual measures of transpiration to an ecosystem scale remains problematic.

The sensitivity of stomata to atmospheric water deficits varies significantly among species (Oren et al., 1999a,b; McCulloh and Woodruff, 2012). The sensitivity of stomata to vapor pressure deficit (*VPD*) can be quantified as the magnitude of the response of stomatal conductance to increasing *VPD* relative to two reference conductances, one at *VPD* = 1 kPa and the second at the *VPD* that induces stomatal closure (Meinzer et al., 1997; Oren et al., 1999a, b). While stomatal closure prevents the failure of the water-conducting pathway in xylem arising from the formation of emboli, it also reduces photosynthetic rates—a trade-off that has important implications for plant function and growth, particularly under drought stress (Wullschleger et al., 2002; Addington et al., 2004). Thus, stomatal regulation of transpiration can improve water-use efficiency of vegetation and influences the productivity of terrestrial ecosystems (Maherali et al., 2003; McDowell et al., 2008). However, stomatal sensitivity to changes in T_c at canopy scales also varies greatly with a wide range of stomatal behaviors within and between species (Oren et al., 1999a,b). Currently, quantifying stomatal sensitivity can be performed using long-term field campaigns at the leaf and canopy levels (Bush et al., 2008; Peters et al., 2010), but predicting stomatal sensitivity based on hydraulic properties of plants remains a major challenge (Maherali et al., 2003; Litvak et al., 2012). Clearly there is a need for further quantification of stomatal sensitivities at canopy and community scales to improve our understanding and predictive ability of the patterns of T_c and *ET* at an ecosystem scale.

The desert–oasis ecotone is unique in arid regions of China where it plays an important role in preventing the movement of sand dunes and maintaining the ecosystem structure and function and hydrological balance (Liu and Zhao, 2009; Zhao and Liu, 2010; Liu et al., 2011). It is therefore also an important component of the desert–oasis ecosystem. Because rainfall is rare in this region, the uniqueness of the desert–oasis ecotone lies in the water resource derived from shallow groundwater and the seepage of river and farmland irrigation, and water is consumed through vegetation transpiration and soil evaporation. Consequently, the ecohydrologic processes result in discontinuous patterns of plaque distribution of vegetation, so this ecosystem is sensitive to changes in hydrologic processes (Zhao and Chang, 2014). However, few studies in China have partitioned *ET* or determined the components of ecosystem water balance, particularly in a desert ecosystem where the vegetation can utilize the shallow groundwater table. We therefore measured the T_c, E_g, E_l, and ET_a of a unique desert–oasis ecosystem of China. Our specific objectives were (1) to scale from whole-plant transpiration to the community level; (2) to partition *ET* into components of ecosystem water balance; (3) to examine the influence of stomatal regulation of T_c, and *ET* at canopy and community scales; and (4) to determine the effects of plant physiology and environmental conditions on the components of *ET* and on stomatal conductance. Such information will contribute to our understanding of the effects of climate change on the water resources of a unique desert ecosystem.

2. Materials and methods

2.1. Study area

Our study site is located in a desert–oasis ecotone in the middle of China's Heihe River Basin (between 39°21′N and 39°24′N, and between 100°06′E and 100°09′E; Fig. 1). The region has a continental and arid temperate climate. Annual rainfall averages 116.8 mm, of which about 65% falls between July and September. Annual temperature averages 7.6 °C and ranges from a minimum of −27.3 °C in January to a maximum of 39.1 °C in July. The growing season lasts from May to October, and the frost-free period is about 165 days. The zonal desert soil is characterized as unconsolidated sand with a high variability in soil thicknesses and grain sizes (grains between 0.05 and 0.25 mm in diameter account for 80–90% of the total) and low vegetation cover, which ranges from 15% to 20% and is highly susceptible to wind erosion (Zhao and Liu, 2010). The landscape is dominated by fixed and semi-fixed dunes that are separated by inter-dune lowlands. Vegetation comprises desert shrubs that are found on the fixed dunes and in the inter-dune lowlands, including *Calligonum mongolicum* and *Nitraria sphaerocarpa*. Annual herbs include *Bassia dasyphylla*, *Halogeton arachnoideus*, *Suaeda glauca*, and *Agriophyllum squarrosum*, which

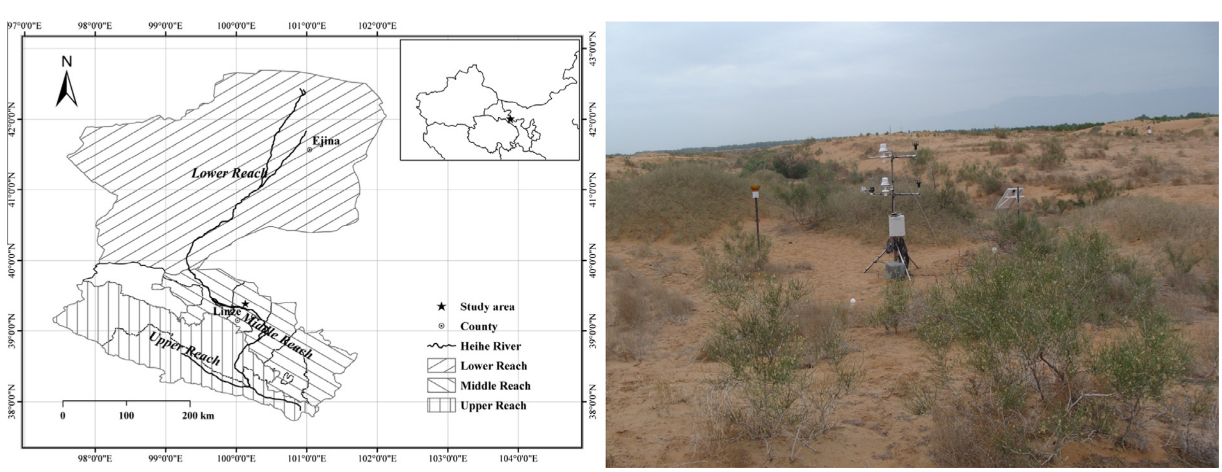

Fig. 1. Map of the study area and location in China.