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Water use by a groundwater dependent maize in a semi-arid region of Inner Mongolia: Evapotranspiration partitioning and capillary rise

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ABSTRACT

This study aimed at assessing the soil water balance, groundwater contribution, crop transpiration and soil evaporation of a rainfed maize crop in Horqin sandy area, north-eastern Inner Mongolia, China. Two years of field data from the Agula site were used, 2008 with relatively high rainfall (363 mm) and high water table, and 2009 with low rainfall (125 mm) and lower water table. The SIMDualKc water balance model was calibrated with observed soil water content data of 2008 and validated with data of 2009. The model uses the dual crop coefficient approach for evapotranspiration (ET) partitioning, and parametric functions for computing capillary rise. The respective modelling results show that the groundwater contribution represented ca. 50% of crop ET in both years. Estimation errors are small, with root mean square errors of 0.007 and 0.008 $cm^3 cm^{-3}$ respectively in 2008 and 2009. The Nash and Sutcliffe modelling efficiency were high, 0.93 in both years, which indicates a low variance of residuals. The calibrated basal crop coefficient $K_{cb\ mid} = 0.95$ denotes a low density of the crop because it is much lower than common potential values. Soil evaporation was relatively low, 23% of ET in the wet year and 17% in the dry year, because capillary rise does not contribute to soil evaporation but to roots extraction only. Results show that capillary rise plays a main role in supplying the vegetation throughout the season, hence a strong dependence of vegetation upon groundwater.

1. Introduction

The Horqin sandy land (hereafter Horqin) is the largest of the four sandy lands with active dunes of Inner Mongolia. It has an area of 12,500 km^2 and is located in eastern Inner Mongolia. It is an ecologically fragile area, where wind erosion is very active (Li et al., 2004) and the process of desertification is important (Zhao et al., 2006). These sandy land areas are unique eco-systems considering climate, geo-hydrological conditions, physical geography and land and water use (Duan et al., 2011a).

Research has been developed in Horqin relative to the eco-hydrological processes and their relations with vegetation and soil (Duan et al., 2011a,b; Zhao et al., 2009; Zuo et al., 2009). The vegetation in Horqin consists of pioneer species in the mobile sandy dunes, shrubs and herbaceous vegetation in semi-fixed and fixed sandy dunes, forests in sandy soils of lowlands, and croplands and grasslands in more flat lands with sandy loam soils. Vegetation ecotypes vary with soil moisture and depth of the shallow groundwater (Ma and Liu, 2007; Shi et al., 2007). Zheng et al. (2012) assessed the importance of groundwater for various types of vegetation and the role of vegetation types on groundwater decline. However, the observations of the time variability of the soil water content at various soil depths and for diverse vegetation types were not followed by an adequate soil water balance. Therefore, despite the recognized importance of soil water and groundwater for the various vegetation types, knowledge on the various components of the water balance and estimates of the shallow groundwater contribution (GWC) to evapotranspiration (ET) are lacking.

Zhang et al. (2009) observed that farmland expansion is a major cause of steppe loss in northern China. In Horqin farmland is increasing with an average annual rate of 1.03%, mainly replacing steppe grassland by maize. Bagan et al. (2010) reported that the area of cropland doubled over the last three decades. In parallel, other studies refer the decline of the shallow groundwater associated with land use changes, including irrigated crops (Zhang and Zhao, 2003; Zhao et al., 2009; Zheng et al., 2012). In Horqin, maize water use studies refer only to irrigation (Li et al., 2003; Tang et al., 2011). No studies have been performed on rainfed maize supplied by shallow groundwater. Therefore, there is the need for better understanding the processes relative to water use

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by a groundwater-fed maize crop, thus performing a water balance study focused on the role of the shallow groundwater and on the crop evapotranspiration dynamics.

The importance of shallow groundwater for sustaining vegetation has been assessed in several water balance studies with lysimeters that evidenced the dependency of various ecosystems and crop systems from shallow groundwater (Kahlown et al., 2005; Kowalik, 2006; Gowing et al., 2009; Liu and Luo, 2011). However, models were not used in these studies. Differently, various deterministic models have been used to assess the GWC by simulating the upward fluxes from the water table, e.g., RZWQM (Stulina et al., 2005), WAVE (Liu et al., 2006), HYDRUS-1D (Soylu et al., 2011), and SWAP (Xu et al., 2013). Stochastic approaches were reported, among others, by Vervoort and Van der Zee (2008) and Tamea et al. (2009). Models referred above are able to produce good estimates of GWC but may be highly exigent in terms of soil water data, and require appropriate observation of the soil water content and of the soil water potential for their calibration and testing. Differently, when using a soil water balance model only the basic soil hydraulic properties are required and the model may be calibrated using only soil water content observation data. This is the case of the approach developed by Liu et al. (2006) that derived from the WAVE model a set of parametric equations for simulating upward and downward fluxes through the bottom of the root zone of a cropped soil. These parametric equations were then integrated in the water balance model ISAREG that produced good estimates of crop ET in presence of shallow water tables (Pereira et al., 2007; Cholpankulov et al., 2008). Those parametric equations are presently integrated in the water balance model SIMDualKc, formerly tested with a maize crop in presence of a shallow water table (Rosa et al., 2012b).

The SIMDualKc (Rosa et al., 2012a) is not only able to simulate water use by a crop in presence of a shallow water table, but has also the advantage of partitioning crop ET (ET_c) into actual crop transpiration (T_a) and soil evaporation (E_s) using the dual crop coefficient approach proposed in FAO56 (Allen et al., 1998). Modelling using this approach or for the quantification of the groundwater contribution to ET has not been applied in Inner Mongolia. Therefore, considering the importance of better understanding crop water use in the fragile Horqin sand land and, in particular, the need for improved knowledge on the interactions between vegetation and shallow groundwater, that may support a better policy on water and landscape management in Horqin, the objectives of this study consist of: (a) calibration and validation of the SIMDualKc model to assess water use components of rainfed maize; (b) evaluating the groundwater contribution to crop ET; and (c) assessing impacts of changes in water table levels on the dynamics of maize water use, transpiration, soil evaporation and groundwater contribution.

2. Materials and methods

2.1. Site and crop characteristics

The study area is located in the southern Horqin sandy area (43°18′48″ to 43°21′24″ N, 122°33′00″ to 122°41′00″ E), in the Agula eco-hydrological study area, eastern Inner Mongolia (Fig. 1). As mapped in Fig. 1, the main vegetation type between dunes is presently cropland followed by grassland meadows, groundwater-fed (Duan et al., 2011a). The dunes have various types of shrubs vegetation. The cropland is mainly occupied with maize; other crops are sunflower, black beans and millet. The maize farm field used in this study was located within a large maize crop area.

The climate is semi-arid continental with cold and dry winter; according to the Köppen classification, the climate is a Bsk, cold arid steppe (Kottek et al., 2006). The average annual precipitation is 389 mm, which mainly occurs during the summer monsoon. The temperature varies from −13 °C in January to 24 °C in July (Duan et al., 2011a). An automatic meteorological station is installed at about 200 m from the maize study site. Observed weather data included precipitation (mm), air temperature (°C), relative humidity (%), wind speed (m s^{-1}) with the anemometer installed at 2 m

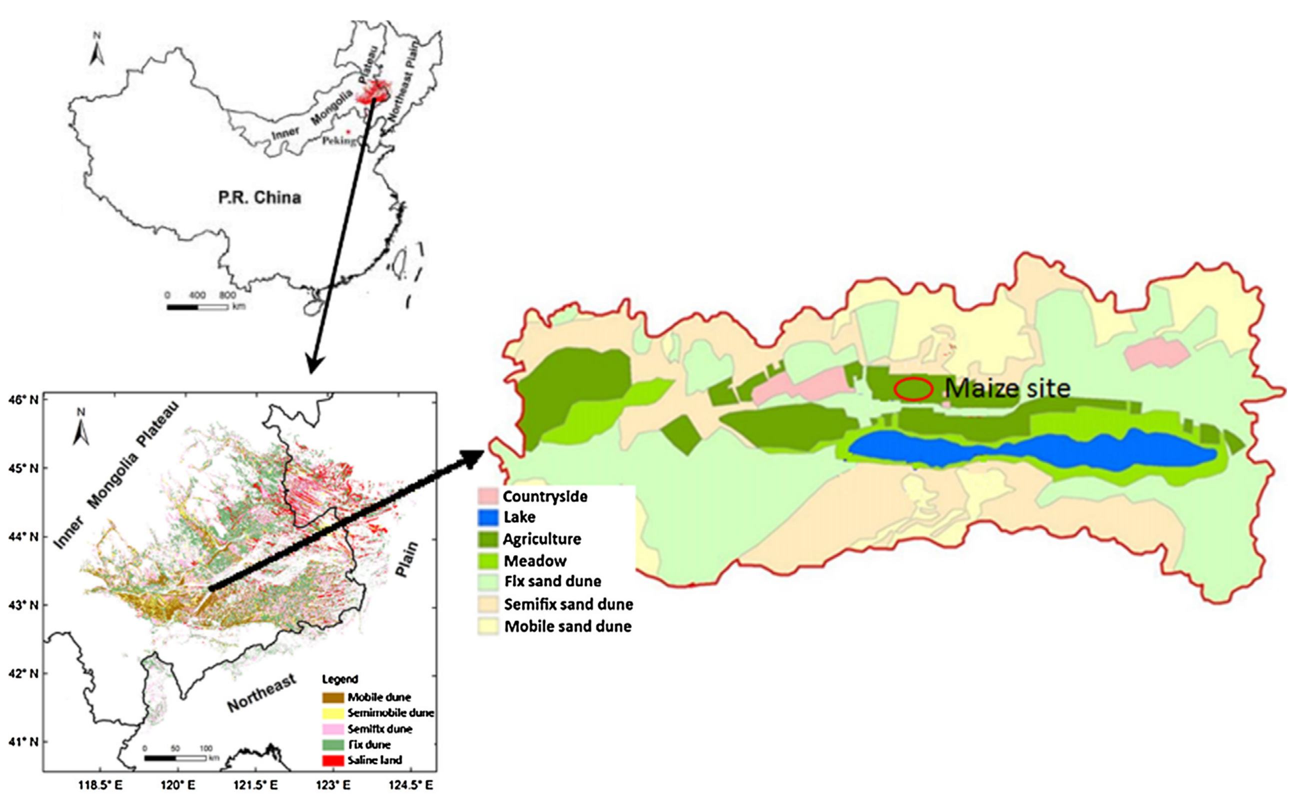

Fig. 1. Location of the study area, land use map and location of the study site.