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A process-based water balance model for semi-arid ecosystems: A case study of psammophytic ecosystems in Mu Us Sandland, Inner Mongolia, China

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ABSTRACT

We developed a process-based water balance model for semi-arid ecosystems (PWBSA) driven by daily meteorological data. The actual canopy transpiration and soil evaporation processes were simulated separately based on the Penman–Monteith model, while considering the energy partition with combined leaf area index (LAI) and canopy coverage, process-based stomatal conductance, root distribution, and available soil water, among other parameters. A simple bucket soil water model that considered preferential flow was used to simulate the soil water content in four soil layers (0–10 cm, 10–20 cm, 20–40 cm, and 40–80 cm). As a case study, the model was applied to the Mu Us Sandland, a temperate semi-arid region of China, using parameters obtained from field experiments of two psammophytic communities. The model validation using the observed leaf transpiration and daily soil water content measured in 2012 and 2013 showed that the PWBSA model simulated the water balance well for both semi-arid ecosystems. Energy partition was sensitive to changes in the LAI and canopy coverage, implying that the model is suitable for application to semi-arid ecosystems with patchy canopies. Based on the water balance simulation of the two psammophytic ecosystems during 1955–2013, differences in annual evapotranspiration, transpiration, and deep soil water loss were observed between the fixed and semi-fixed psammophytic ecosystems due to variations in the LAI, canopy coverage, species ecophysiological traits, root distribution, and soil properties. Compared with other ecosystems in semi-arid regions, psammophytic ecosystems may be more sensitive to changes in rainfall patterns and should receive more attention in future global climate change research.

1. Introduction

Arid and semi-arid ecosystems represent 42–56% of the world's land (Melillo et al., 1993; Schimel, 2010) and are important components of the global water cycle. The water balance in these water-limited ecosystems is sensitive to global climate change, including intra- and inter-annual fluctuations (Martínez-Vilalta et al., 2002; Jolly and Running, 2004). The biodiversity, ecological services, and stability of semi-arid ecosystems have received much attention due to water shortages and global climate change (Jolly and Running, 2004; Ágreda et al., 2015).

Large models have been developed to simulate the water balance (Kremer and Running, 1996; Eilers et al., 2007) and conduct water resource management research (She et al., 2014). Empirical models have been used widely at the field level (Rockström et al., 1998; Reynolds et al., 2000; She et al., 2014). However, as empirical approaches have been developed under a constrained range of environmental variables, extreme conditions such as high vapor pressure deficits, low water availability, and extreme temperatures challenge the ability of these models to accurately estimate water balances (Raab et al., 2015). To improve the model performance and explain the mechanisms driving the water cycle, process-based water balance models, most of which work at the ecosystem scale (Kremer and Running, 1996; Baird and Wilby, 1999), have become increasingly common. General ecosystem models, such as ForGro (Mohren, 1987), are usually highly complex; consider

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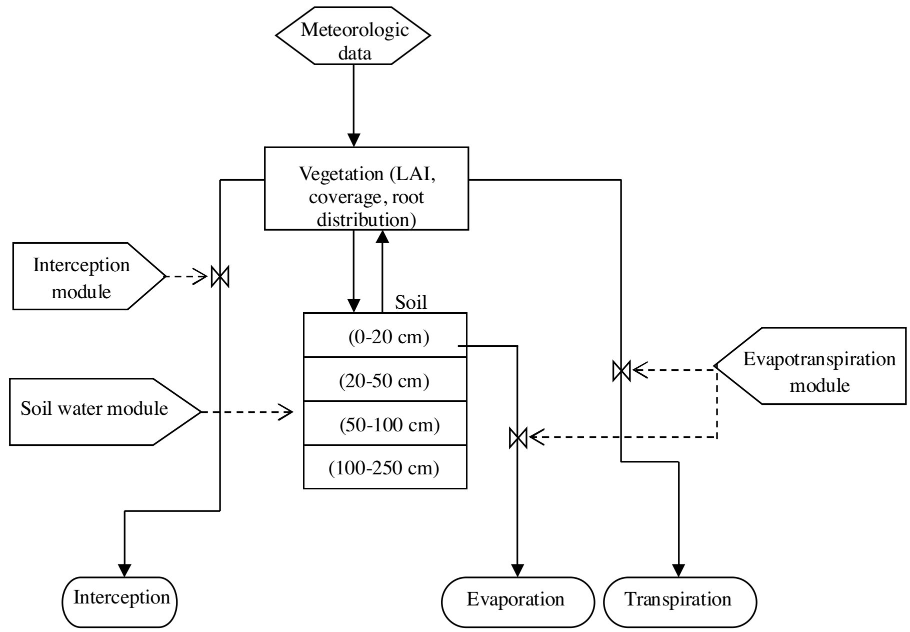

Fig. 1. Structure of the ecosystem-scale PWBSA model developed in this study.

water, carbon, and nitrogen cycles simultaneously; and contain many parameters and variables; thus, these models are difficult to apply (Tiktak and van Grinsven, 1995; Sawano et al., 2015). Several simple and widely applicable ecosystem models, such as FOREST-BGC (Running and Coughlan, 1988) and PnET (Aber and Federer, 1992), have since been developed to simulate plant growth and water balance separately, which connect these parameters via the soil water content. However, most of these models emphasize plant growth, and require too many parameters and variables to simulate the water cycle. To understand the water cycle on both ecosystem and landscape scales, specialized water balance models have been developed (Sawano et al., 2015) that calculate evapotranspiration and soil water movement with simplified models of plant growth based on daily meteorological data (Hall and Harding, 1993; Metcalfe and Buttle, 1999; Kite, 2000).

The water balance of semi-arid ecosystems differs distinctly from humid ecosystems (Kremer and Running, 1996); for example, evapotranspiration and soil water dynamics are given more attention in semi-arid ecosystems (Patanè, 2011; She et al., 2014; Sela et al., 2015). In addition, transpiration is often separated from evapotranspiration to evaluate water use efficiency (Eilers et al., 2007). Stomatal conductance is the main path through which plants control both leaf transpiration and carbon dioxide intake (Gao et al., 2002; Patanè, 2011; Raab et al., 2015), and root distribution can contribute greatly to water regulation through the soil–plant–air system (Martínez-Vilalta et al., 2002; Radersma and Ong, 2004; Eilers et al., 2007). These processes are often simulated in process-based water balance models (Kremer and Running, 1996; Jolly and Running, 2004). However, a number of simulation studies do not include any information on the mechanisms that explain the responses of the different plant species (Eilers et al., 2007). Sparse canopies and patchy patterns of semi-arid vegetation have a strong influence on latent heat flux partitioning (Kremer and Running, 1996; Raab et al., 2015). Moreover, soil water availability plays a major limiting role in arid and semi-arid regions (Jolly and Running, 2004; Eilers et al., 2007), while soil texture and structure may strongly regulate soil water movement (Hu and Si, 2014). Soil preferential flow is a main regulation mechanism in arid and semi-arid ecosystems with high proportions of macroporosity in the soil profiles (Granier et al., 1999; Li et al., 2009).

In this study, we developed a process-based water balance model based on the stomatal conductance behavior of dominant species to simulate the water balance of semi-arid ecosystems. A series of successional ecosystems, from shrub-dominated to grass-dominated communities, exists in Mu Us Sandland, China, and soil water availability is considered to be the key factor in the succession process (Guo, 2000; Li, 2012; Li et al., 2013). Therefore, we validated our process-based water balance model for semi-arid ecosystems (PWBSA) model with data collected from both shrub-dominated and grass-dominated ecosystems.

2. Materials and methods

2.1. Model framework and general assumptions

The PWBSA model can simulate canopy interception, soil water content, transpiration, and evaporation on a daily temporal scale (Fig. 1). Runoff is ignored, because there is almost no runoff in Sandland (Nian and Li, 2000). All of the variables and parameters used in the model are defined in Table 1. The meteorological data used as inputs include daily precipitation, mean temperature, maximum temperature, minimum temperature, mean relative humidity, and mean wind speed.

2.2. Interception module

Canopy interception can be calculated from the leaf area index (LAI) with the constant interception parameter I_{ck} ($I_{ck} = 0.25$) (Running and Coughlan, 1988):

$$Ic = I_{ck} LAI. \quad (1)$$

Variations in the LAI for the ecosystems are interpolated between the minimum and maximum LAI values. It is assumed that LAI increases linearly from zero to the maximum value during the leaf unfolding period, and the maximum value remains unchanged until the occurrence of leaf coloration, after which it decreases linearly to zero at the end of the growing season (Granier et al., 1999).