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

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9 **Abstract:** We developed a process-based water balance model for semi-arid ecosystems
10 (PWBSA) driven by daily meteorological data. The actual canopy transpiration and soil
11 evaporation processes were simulated separately based on the Penman–Monteith model, while
12 considering the energy partition with combined leaf area index (LAI) and canopy coverage,
13 process-based stomatal conductance, root distribution, and available soil water, among other
14 parameters. A simple bucket soil water model that considered preferential flow was used to
15 simulate the soil water content in four soil layers (0–10 cm, 10–20 cm, 20–40 cm, and 40–80 cm).
16 As a case study, the model was applied to the Mu Us Sandland, a temperate semi-arid region of
17 China, using parameters obtained from field experiments of two psammophytic communities. The
18 model validation using the observed leaf transpiration and daily soil water content measured in
19 2012 and 2013 showed that the PWBSA model simulated the water balance well for both
20 semi-arid ecosystems. Energy partition was sensitive to changes in the LAI and canopy coverage,
21 implying that the model is suitable for application to semi-arid ecosystems with patchy canopies.
22 Based on the water balance simulation of the two psammophytic ecosystems during 1955–2013,
23 differences in annual evapotranspiration, transpiration, and deep soil water loss were observed
24 between the fixed and semi-fixed psammophytic ecosystems due to variations in the LAI, canopy

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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.

Keywords: Energy partition; preferential soil water flow; process-based stomatal conductance model; psammophytic ecosystem; rainfall pattern

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 & 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 & Running, 2004; Ágreda et al., 2015).

Large models have been developed to simulate the water balance (Kremer & 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 & Running, 1996; Baird & Wilby, 1999), have become increasingly common. General ecosystem models, such as ForGro (Mohren, 1987), are usually highly complex;

consider water, carbon, and nitrogen cycles simultaneously; and contain many parameters and variables; thus, these models are difficult to apply (Tiktak & van Grinsven, 1995; Sawano et al., 2015). Several simple and widely applicable ecosystem models, such as FOREST-BGC (Running & Coughlan, 1988) and PnET (Aber & 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 & Harding, 1993; Metcalfe & Buttle, 1999; Kite, 2000).

The water balance of semi-arid ecosystems differs distinctly from humid ecosystems (Kremer & 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 & Ong, 2004; Eilers et al., 2007). These processes are often simulated in process-based water balance models (Kremer & Running, 1996; Jolly & 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 & Running, 1996; Raab et al., 2015). Moreover, soil water availability plays a major limiting role in arid and semi-arid regions (Jolly & Running, 2004; Eilers et al., 2007), while soil texture and structure may strongly regulate soil water

movement (Hu & 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 et al., 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.

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

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Table 1 Definition of the model variables and parameters.

Symbol	Unit	Definition
Interception module		
Ic	mm day ⁻¹	Canopy interception
LAI	m ² m ⁻²	Leaf area index
I_{ck}	/	Coefficient of canopy interception
Soil water module		
$\Delta\theta_i$	v/v%	Daily soil water recharge in i^{th} layer
P	mm	Daily rainfall
ET_i	mm	Evapotranspiration from the soil in i^{th} layer

D_i	mm	Deeper infiltration from layer i to layer $(i+1)$
z_i	m	Soil depth of layer i
K_{maxi}	/	Coefficient of preferential flow in i^{th} layer
Evapotranspiration module		
f_s	/	Partition coefficient of energy to soil
f_g	/	Partition coefficient of energy to the canopy
SCD	/	Canopy coverage
k	/	Light coefficient of extinction
TR	mm	Canopy transpiration
EV	mm	Soil evaporation
Rn	$\text{J m}^{-2} \text{s}^{-1}$	Net radiation
S	$\text{J m}^{-2} \text{d}^{-1}$	Soil heat flux
L	J kg^{-1}	Latent heat of vaporization
Δ	$\text{kPa } ^\circ\text{C}^{-1}$	Slope of the saturated vapor pressure curve at the temperature of the air
C_p	$\text{J kg}^{-1} ^\circ\text{C}^{-1}$	Specific heat of air at a constant pressure
ρ	kg m^{-3}	Air density
es	kPa	Saturated vapor pressure
e	kPa	Vapor pressure
γ	$\text{kPa } ^\circ\text{C}^{-1}$	Psychrometric constant
$DAYL$	s d^{-1}	Day length
ra	m s^{-1}	Corresponding aerodynamic resistance
rsc	s m^{-1}	Canopy surface resistance
rss	s m^{-1}	Soil surface resistance
g_i	/	Fraction of transpiration extracted from the soil of layer i

h_i	/	Fraction of evaporation extracted from the soil of layer i
r_i	/	Relatively extractable soil water in layer i
$root_i$	/	Root proportion in the soil of layer i
θ_i	v/v%	Soil water content in layer i
θ_{fc}	v/v%	Soil field capacity
θ_w	v/v%	Soil wilting point
z	cm	Soil layer depth
E	cm	Evaporation depth
g_s	$\text{mmol m}^{-2} \text{s}^{-1}$	Stomatal conductance
g_v	m s^{-1}	Canopy conductance
ψ_s	kPa	Soil water potential
P_{ar}	$\mu\text{mol m}^{-2} \text{s}^{-1}$	Photosynthetic active radiation
d_{vp}	/	Relative vapor pressure deficit
g_{om}	$\text{mmol m}^{-2} \text{s}^{-1}$	Maximum possible stomatal conductance in the dark with zero soil water potential
k_ψ	/	Elastic compliance of guard cell structure
$k_{a\beta}$	$\text{mmol } \mu\text{mol}^{-1}$	Sensitivity of stomatal conductance to photosynthetic activity
$k_{\beta g}$	/	Sensitivity of stomatal conductance to vapor pressure deficit

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 & Coughlan, 1988):

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

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).

2.3 Soil water module

Preferential flow occurs under the action of gravity if soil water is held in soil macropores (Martinez-Mezaand & Whitford, 1996; Granier et al., 1999; Li et al., 2009), is common in rocky or sandy soils (Li et al., 2009), and is a major feature of soil water dynamics (Wilcox et al., 2003; Li et al., 2009). Because the Richards equation is usually unsuitable for determining the soil water dynamics in sandy or rocky soil (Granier et al., 1999; Reynolds et al., 2000), we developed a simple bucket model combined with preferential flow to portray the sandy soil water dynamic in our model. The preferential flow assumes that rainfall can recharge the lower soil layers directly at a fixed proportion, regardless of whether the soil water is higher than the soil field capacity (Hornberger et al., 1985).

Four horizontal layers (0–10 cm, 10–20 cm, 20–40 cm, and 40–80 cm) were partitioned in the soil profile to represent the sand characteristics and root distribution. Horizontal heterogeneity in the soil was neglected. Deeper infiltration can occur when the soil water content in the upper layer is higher than the field capacity of the soil (Eatherall, 1997; Cernusca et al., 1998). Daily soil water recharge in the first layer ($\Delta\theta_1$) and the other three layers ($\Delta\theta_i$) can be simulated with Eqs. (2) and (3), respectively:

$$\Delta\theta_1 = \frac{P(1 - \sum_{i=2}^4 K_{\max i} root_i) - ET_1 - D_1}{Z_1}, \quad (2)$$

$$\Delta\theta_i = \frac{K_{\max i} root_i \cdot P + D_{i-1} - ET_i - D_i}{Z_i},$$

(3)

where D_l and D_i are calculated based on the soil field capacity, as shown below.

$$\text{If } P(1 - \sum_{i=2}^4 K_{\max i} \text{root}_i) - ET_1 \leq \theta_{fc1}, D_1 = 0$$

$$\text{Else, } D_1 = P(1 - \sum_{i=2}^4 K_{\max i} \text{root}_i) - ET_1 - \theta_{fc1}$$

$$\text{If } K_{\max i} \text{root}_i \cdot P + D_{i-1} - ET_i \leq \theta_{fci}, D_i = 0$$

$$\text{Else, } D_i = K_{\max i} \text{root}_i \cdot P + D_{i-1} - ET_i - \theta_{fci}$$

2.3 Evapotranspiration module

Potential evapotranspiration was calculated using the Penman–Monteith equation. Evaporation and transpiration were separated by considering the LAI and canopy coverage. The process-based stomatal conductance model was scaled up to simulate canopy resistance combined with the LAI.

2.3.1 Energy partition of evapotranspiration

LAI is normally used to derive the available energy to soil from the canopy (Nouvellon et al., 2000), although only a few models use canopy coverage (Wegehenkel, 2000). The former is suitable for homogenous communities with high LAI values, and the latter is better suited to those with low LAI values. However, problems may arise when these models are applied to arid/semi-arid ecosystems with patchy canopies (Raz-Yaseef et al., 2010), because some ecosystems have similar LAIs but different coverages, or have similar coverages but different LAIs. In these cases, the energy partition would differ between evaporation and transpiration. In this PWBSA model, the available energy below the canopy is calculated with the Beer–Lambert function (Granier et al., 1999). The partition coefficients of energy to the canopy or soil (f_s and f_g ($f_s + f_g = 1$), respectively) are calculated based on the LAI and canopy coverage:

$$f_s = \frac{1 - SCD}{1 - 2SCD + SCD \cdot \exp(kLAI)}, \quad (4)$$

$$f_g = 1 - f_s, \quad (5)$$

where SCD is canopy coverage and k is the light coefficient of extinction ($k = 0.5$).

Then, the canopy transpiration (TR) and soil evaporation (EV) can be calculated separately based on the Penman–Monteith equation:

$$TR = f_g \cdot \left(\frac{1}{L} \cdot \frac{\Delta(Rn - S) + C_p \rho(es - e) / ra}{\Delta + \gamma(1 + rsc / ra)} \cdot DAYL \right) \cdot \sum_{i=0}^n g_i, \quad (6)$$

$$EV = f_s \cdot \left(\frac{1}{L} \cdot \frac{\Delta(Rn - S) + C_p \rho(es - e) / ra}{\Delta + \gamma(1 + rss / ra)} \cdot DAYL \right) \cdot \sum_{i=0}^n h_i. \quad (7)$$

Actual evapotranspiration is regulated by soil water content and root vertical distribution. As such, g_i and h_i are calculated as follows (Rockström et al., 1998; Wegehenkel, 2000):

$$g_i = r_i \text{ root}_i, \quad (8)$$

$$h_i = r_i h_i', \quad (9)$$

where

$$r_i = \frac{\theta_i - \theta_w}{\theta_{fc} - \theta_w}, \quad (10)$$

$$\int_0^E h'(z) dz = 1, \text{ and } h'(z) = h_0 \frac{1 - z / E}{1 + 20z / E}. \quad (11)$$

Soil water evaporation is affected by meteorological factors and soil water content. The maximum evaporation depth of sandy soil is about 10 cm in the study region (Liu et al., 2006; Wang et al., 2006). In the model, the depth of evaporation was set to 10 cm.

2.3.2 Process-based canopy conductance module

A process-based stomatal conductance (g_s) model (Gao et al., 2002) was applied to simulate

gas exchange per leaf area, as given below:

$$g_s = \frac{g_{om} + k_\psi \psi_s + k_{\alpha\beta} P_{ar}}{1 + k_{\beta g} d_{vp}} \quad (12)$$

A canopy conductance model (Olioso et al., 1996) was then applied to scale up from the leaf level to the ecosystem level by linking the LAI and stomatal conductance model. Next, the canopy surface resistance (rsc) is calculated as the reciprocal of canopy conductance (g_v):

$$g_v = g_s LAI / (0.5 LAI + 1), \text{ then, } rsc = 1/g_v \quad (13)$$

2.4 Study site and data description

Mu Us Sandland has an area of about 40,000 km², is located in northwestern China (N37°30'–N39°20'; E107°20'–E111°30'), and has a temperate semi-arid climate. The annual mean temperature is 6–8.5°C (1974–2013), and the annual mean precipitation is 372.9 mm (range: 177.4–678.7 mm), with 77% of precipitation occurring from June to September as rain (Figure 2). Soil water content is thought to be a main driver of psammophytic succession (Guo, 2000; Li, 2012; Li et al., 2013). There are five successional stages of psammophytic ecosystems in Mu Us Sandland (Guo, 2000). The two communities selected for our case study to simulate water balance: (1) semi-fixed dunes with *Artemisia ordosica* (CSF) and (2) fixed dunes with *A. ordosica* + *Stipa bungeana* (CF), are distributed extensively (Wang et al., 1997; Guo, 2000). *A. ordosica* is a deciduous sub-shrub in the Asteraceae family with a deep taproot and slightly fleshy, cleft linear leaf, while *S. bungeana* is a dominant grass in the Gramineae family of the temperate steppe with fibrous roots and narrow needle-like leaves.

Figure 2 Climate of Mu Us Sandy Land (1974–2013). (A) Mean annual rainfall and temperature. (B) Monthly mean temperature (light grey line) from 1974 to 2013 and the mean monthly temperature (bold line), as well as the monthly rainfall (histogram) from 1974 to 2013 and the monthly mean rainfall (bold line in histogram).

The field experiment was conducted at the Sand Land Grassland Ecological Research Station in Ordos Plateau, Institute of Botany, Chinese Academy of Sciences, China (N39°29.66', E110°11.47'). General features of the two communities were measured during the growing season (Table 2). Fine roots (<2 mm) in the four soil layers (0–10 cm, 10–20 cm, 20–40 cm, and 40–80 cm) were dug up and sieved. The gas exchange process (Li-6400; LI-COR Biosciences, Inc., Lincoln, NE, USA) and leaf water potential (WP4; Decagon, Pullman, WA, USA) were measured during the growing season in 2012 and 2013.

Table 2. General features of the two studied communities in Mu Us.

No.	Type	Coverage (%)	Height (m)	LAI_{max} ($m^2 m^{-2}$)	Species richness
CSF	<i>A. ordosica</i> in Semi-fixed dune	43	0.75	0.75	5
CF	<i>A. ordosica</i> + <i>S. bungeana</i> in fixed dune	65	0.41	1.08	21

In both communities, about 44–49% of the fine roots were found in the upper 20 cm, while

213 31% of fine roots in CSF were in the 20–40 cm layer, and 30% of fine roots of CF were in the
214 40–80 cm (Table 3). Soil water is simulated in the four soil layers in the model (0–10 cm, 10–20
215 cm, 20–40 cm, and 40–80 cm). Therefore, soil texture, bulk density, and pressure–volume curves
216 were measured in each layer (Table 3). The soil water content was measured automatically at
217 10-min intervals (ECH2O EC–5; Decagon, Pullman, WA, USA) from June 2011 to December
218 2013 in each layer. The soil water content data were calibrated according to the empirical
219 calibration equation to reach approximately ± 1 –2% accuracy for specific soil. Groundwater
220 replenishment was ignored in the model because the sand sediment is very thick (about 10–30 m
221 in depth) (Peking University et al., 1983). Sandy soils have porosities of about 70% (Peking
222 University et al., 1983).

Table 3. Soil properties, root distribution, and species stomatal parameters of the two communities.

Parameters	CSF	CF
θ_{fc1} (0–10 cm)	9.79	16.5
θ_{fc2} (10–20 cm)	12.59	16.5
θ_{fc3} (20–40 cm)	9.21	16.5
θ_{fc4} (40–80 cm)	5.7	9.8
θ_w	0.3	1.4
$Root_1$ (0–10 cm)	0.38	0.38
$Root_2$ (10–20 cm)	0.11	0.06
$Root_3$ (20–40 cm)	0.31	0.26
$Root_4$ (40–80 cm)	0.20	0.30
g_{om}	501.43	1231.03
k_ψ	0.05	5.23
$k_{\alpha\beta}$	3.12	0.61
$k_{\beta g}$	1019.23	214.28

Daily meteorological data over 58 years (1955–2013) were obtained from the China Meteorological Administration, including precipitation, mean, maximum, and minimum air temperature, mean relative humidity, and wind speed. Daily horizontal radiation was calculated with the model of Thornton & Running (1999). Then, photosynthetic active radiation was calculated with an empirical equation (Zhou, 1997). Among the 40 years, we selected four typical years with similar annual rainfalls and two rainfall patterns to simulate the water balance of the psammophytic ecosystems (Fig. 3).

Figure 3. Four typical rainfall years with two different rainfall patterns used to simulate the psammophytic ecosystems.

3. Results and discussion

3.1 Model validation and sensitivity analysis

The parameters of the process-based stomatal conductance model (Gao et al., 2002) were validated with field measurements. The hourly transpiration rate of the two communities was well simulated (Figure 4). Stomatal conductance is commonly simulated to calculate canopy conductance, transpiration, and photosynthesis in land surface models (Jolly & Running, 2004) and water balance models (Rockström et al., 1998). Empirical stomatal conductance models are more popular for scaling up from the leaf to ecosystem and even watershed levels, due to its

relatively simple and linear relationship with environmental drivers (Rockström et al., 1998). However, process-based models are increasingly common in ecosystem and global models (Sitch et al., 2003; Wang et al., 2016). The stomatal model by Gao et al. (2002) is based on the ecophysiological mechanism of the stomata, which can be used to portray different stomatal dynamics among species. *A. ordosica*, found in both communities in this study, had different ecophysiological behaviors depending on the ecological features (Table 2) and environmental factors (Table 3) (Wang et al., 1997; Zhang et al., 2007), and thus could be simulated with the stomatal model (Fig. 4, Table 4).

Figure 4. Leaf transpiration rate observed and simulated with the process-based stomatal model.

Table 4 Comparison of the measured transpiration (T) and simulated transpiration of the two psammophytic ecosystems examined in this study.

Vegetation	Measured T (mmol m ⁻² s ⁻¹)	Simulated T (mmol m ⁻² s ⁻¹)	Error	
			(mmol m ⁻² s ⁻¹)	%
<i>A. ordosica</i>	5.65	5.38	-0.27	-4.7
<i>A. ordosica</i> + <i>S. bungeana</i>	6.82	6.31	-0.52	-7.6

The simulated and observed daily soil water contents of the two communities were compared in three soil layers (0–20 cm, 20–40 cm, and 40–80 cm) in 2012 and 2013 (Fig. 5, Table 5). In both communities, the soil water content was simulated well in the growing season,

while it was higher or lower than the observed soil water content in the non-growing season (Table 5). The simulated soil water content was lower than the observed soil water content in May (Fig. 5), possibly due to seasonal freezing during the non-growing season in the study area (Han et al., 2015), which was not accounted for in the PWBSA model. Although the annual and growing season soil water contents were not affected greatly, it would be better to consider soil freezing and melting processes in the future.

Figure 5. Observed and simulated daily soil water contents of three soil layers in the two communities in 2012 and 2013: (A) *A. ordosica* in semi-fixed dunes and (B) *A. ordosica* + *S. bungeana* in fixed dunes.

Table 5 Comparison of measured and simulated soil water content (SW) of two psammophytic ecosystems.

Vegetation	Period	Soil depth (cm)	Measured SW (%v/v)	Simulated SW (%v/v)	Error	
					(%v/v)	%
<i>A. ordosica</i>	Jun–Oct, 2012–2013	0–20	5.23	4.54	-0.68	-13.1
		20–40	4.39	5.74	+1.35	+30.9
		40–80	5.75	5.01	-0.74	-12.8
	Jan–May,	0–20	3.91	0.68	-3.23	-82.6

<i>A. ordosica</i> + <i>S. bungeana</i>	Nov-Dec, 2012-201 3	20-40	3.68	3.37	-0.29	-8.0%
		40-80	4.05	4.58	+0.53	+13.1
	Jun-Oct, 2012-201 3	0-20	9.48	10.54	+1.06	+11.2
		20-40	6.13	7.55	+1.43	+23.3
		40-80	9.77	6.88	-2.88	-29.5
	Jan-May, 2012-201 3	0-20	5.13	6.75	+1.63	+31.8
		20-40	3.97	0.93	-3.04	-76.5
		40-80	4.82	6.89	+2.06	+42.7

The combined LAI and canopy coverage energy partition formula is used in the PWBSA model to consider ecosystems with patchy canopies. We found that canopy transpiration and evapotranspiration were sensitive to the LAI and canopy coverage, respectively (Fig. 6). Canopy transpiration and evapotranspiration increased distinctly with increasing canopy coverage under the same LAI or with increasing LAI under the same canopy coverage. Patchy canopies are a common feature of arid/semi-arid ecosystems (Reynolds et al., 2000; Eilers et al., 2007), which experience evapotranspiration that changes with different LAIs or canopy coverage (Reynolds et al., 2000; Raz-Yaseef et al., 2010). The energy partition formula could help portray evapotranspiration in arid/semi-arid ecosystems.

Figure 6. Sensitivity of canopy transpiration and evapotranspiration to changes in the LAI and canopy coverage. (A) Simulated canopy transpiration under different LAIs and canopy coverages. (B) Simulated evapotranspiration under different LAIs and canopy coverages.

3.2 Water balance of two psammophytic ecosystems at different successional stages

The annual mean water balance features of the two communities were analyzed based on a daily water balance simulation from 1955–2013 (Table 6). The annual mean and maximum actual evapotranspiration values of CF were higher than those of CSF. Moreover, the ratios of the mean or maximum actual evapotranspiration to annual mean precipitation of CF were higher than those of CSF. In addition, the ratios of the mean or maximum canopy transpiration to actual evapotranspiration were higher than those of CSF. The differences between the two ecosystems may have been caused by the higher LAI and canopy coverage in CF than in CSF (Table 2), leading to more soil water drawn out by evapotranspiration, and more deeper soil water extracted for eventual evapotranspiration due to the deeper root distribution (Table 3), leading to less deep soil water loss in CF.

Deep soil water loss is predominantly affected by the water holding capacity and root depth (Eilers et al., 2007). The amount of available water is a main driver for vegetation succession in psammophytic ecosystems in Mu Us Sandland and other semi-arid regions (Reynolds et al., 2000; Khaertidova & Longobardi, 2013; Ágreda et al., 2015), as interactions between soil water storage and vegetation promote community succession (Zavala et al., 2000; Reynolds et al., 2000). In addition, changes in the LAI, canopy coverage, species ecophysiological traits, root distribution, and soil properties may result in variations in water partitioning among transpiration, evaporation, soil water vertical distribution, and deep loss in the ecosystem water balance (Rockström et al., 1998; Bellot et al., 1999; Reynolds et al., 2000). In the future, plant growth and species competition should be considered in the model to better understand the mechanisms of vegetation succession.

Table 6. Annual mean simulated water balance of *A. ordosica* in semi-fixed dune and *A. ordosica* + *S.*

bungeana in fixed dune. Mean annual precipitation, MAP; actual evapotranspiration, AET; transpiration, T; evaporation, E.

	MAP	AET	AET/MAP	Deep loss	T	T/AET	E	E/AET
	(mm)	(mm)	(%)	(mm)	(mm)	(%)	(mm)	(%)
<i>A. ordosica</i> in semi-fixed dunes								
Mean	384.16	322.85	84	61.31	112.95	35	209.90	65
Minimum	181.52	183.23	101	-7.88	69.95	38	113.28	62
Maximum	673.26	440.13	65	237.37	144.79	32	305.18	68
<i>A. ordosica</i> + <i>S. bungeana</i> in fixed dunes								
Mean	384.16	355.10	92	29.05	194.86	55	160.24	45
Minimum	181.52	179.72	99	-14.79	94.12	52	85.60	48
Maximum	673.26	532.57	79	142.63	291.24	55	241.33	45

3.3 Evapotranspiration of psammophytic ecosystems under different rainfall patterns

Because global climate change models have predicted that temperature will continue to increase and rainfall patterns will change (Raab et al., 2015), ecosystem responses to rainfall patterns are drawing increasing attention (Corradini et al., 1997; Reynolds et al., 2000; Fay et al., 2002; Raz-Yaseef et al., 2012). In this study, we selected four years (1968, 1985, 1996, and 2002) with similar annual rainfalls (377.9–396.9 mm) to analyze the response of evapotranspiration in psammophytic ecosystems to rainfall patterns. There was higher rainfall in autumn (August–October) in 1968 and 1985 (autumn rain year), and higher rainfall in spring (April–July) in 1996 and 2002 (spring rain year) (Figure 3, Table 6). The annual mean evapotranspiration in the spring rain years was higher than that in the autumn rain years (Table 7). The proportion of

annual evapotranspiration to rainfall was 79.5–87.8% in the spring rain years, and 65.5–70.3% in the autumn rain years. However, the proportion of annual evapotranspiration to rainfall was higher in an autumn rain year in a rain-fed maize ecosystem (Hao et al., 2013). Therefore, this parameter should be determined based on plant phenology and functional type (Reynolds et al., 2000; Fay et al., 2002; Raz-Yaseef et al., 2012). More soil water recharged into deeper soil layers in autumn rain years. Given that more intra-annual rainfall evaporation occurred in spring rain years, the net primary productivity may increase in semi-arid/arid regions (Wang et al., 2014). Increases in the normalized difference vegetation index and vegetation coverage have been observed during past climate change in arid/semi-arid regions (Herrmann et al., 2005; Fensholt et al., 2012). Meanwhile, the dominant species of semi-arid/arid ecosystems is likely to change in response to changes in long-term rainfall patterns (Reynolds et al., 2000). Actual evapotranspiration may vary more drastically in response to changing rainfall patterns in psammophytic ecosystems than other ecosystems due to their particular soil properties (Laio et al., 2001; Pan & Peters-Lidard, 2008). Finally, ecosystems in semi-arid regions may become more fragile due to a reduction in the inter-annual adjusting capacity of soil water in response to increased rainfall evaporated intra-annually with more frequent spring rainfalls (Ágreda et al., 2015). Therefore, future studies should examine the response of psammophytic ecosystems in semi-arid regions to changes in climate.

Table 7. Simulated water balance of *A. ordosica* in four years with typical rainfall. Mean annual precipitation, MAP; actual evapotranspiration, AET; transpiration, T.

Year	MAP (mm)			AET (mm)	T (mm)	Deep soil water loss (mm)	AET/MAP (%)	T/AET (%)
	Annual	Apr–Jul	Aug–Oct					
1968	395.5	103.1	290.5	278.2	121.1	117.3	70.3	43.5
1985	391.2	114.7	271.6	256.2	110.0	135.0	65.5	42.9

1996	377.9	128.8	228.8	300.5	110.4	77.4	79.5	36.7
2002	396.9	272.8	100.8	348.4	132.5	48.5	87.8	38.0

4. Conclusions

In this study, we developed a PWBSA model driven by daily meteorological data. To address the patchy canopies of arid/semi-arid ecosystems, we derived a new energy partitioning formula by combining the effects of the LAI and canopy coverage and simulated transpiration and evaporation separately in the model. As a case study, the model was applied to two psammophytic ecosystems, CF and CSF, in Mu Us Sandland, China. The model showed good performance, and may be applied to arid and semi-arid regions for ecosystem- and landscape-scale studies. The results showed clear differences in annual mean and maximum transpiration, actual evapotranspiration, and deep soil water loss between the two studied psammophytic communities. CF used more soil water for transpiration, and had less deep soil water loss than CSF. The simulated response of actual evapotranspiration to rainfall patterns indicated that the psammophytic ecosystems were highly sensitive to changes in rainfall pattern. Future research should focus on the responses of psammophytic ecosystems to global climate change.

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References

Aber J D, Federer C A. 1992. A generalized, lumped-parameter model of photosynthesis, evapotranspiration and net primary production in temperate and boreal forest ecosystems. *Oecologia*,

374 92: 463-474

375 Ágreda, T., Águeda, B., Olano, J., Vicente-Serrano, S. M., Fernández-Toirán, M., 2015. Increased

376 evapotranspiration demand in a Mediterranean climate might cause a decline in fungal yields under

377 global warming. *Global Change Biology*, 21, 3499-3510

378 Baird A J, Wilby R L. 1999. *Eco-Hydrology: plants and water in terrestrial and aquatic environments*. New

379 York: Routledge

380 Bellot, J., Sanchez, J. R., Chirino, E., Hernandez, N., Abdelli, F., Martinez, J. M., 1999. Effect of different

381 vegetation type cover on the soil water balance in semi-arid areas of south eastern Spain. *Phys. Chem.*

382 *Earth (B)*, 24(4), 353-357

383 Cernusca A, Bahn M, Chemini C, Graber W, Siegwolf R, Tappeiner U, Tenhunen J. 1998. ECOMONT: a

384 combined approach of field measurements and process-based modelling for assessing effects of

385 land-use changes in mountain landscapes, *Ecological Modelling*, 113: 167-178

386 Corradini C, Melone F, Smith R E. 1997. A unified model for infiltration and redistribution during complex

387 rainfall patterns. *Journal of Hydrology*, 192: 104-124

388 Eatherall A. 1997. Modelling climate change impacts on ecosystems using linked models and a GIS.

389 *Climatic Change*, 35: 17-34

390 Eilers, V. H. M., Carter, R. C., Rushton, K. R., 2007. A single layer soil water balance model for estimation

391 deep drainage (potential recharge): an application to cropped land in semi-arid North-east Nigeria.

392 *Geoderma*, 140, 119-131

393 Fay P A, Carlisle J D, Danner B T, Lett M S, McCarron J K, Stewart C, Knapp A K, Blair J M, Collins S L.

394 2002. Altered rainfall patterns, gas exchange, and growth in grasses and forbs. *International Journal of*

395 *Plant Science*, 163(4): 549-557

396 Fay P A, Carlisle J D, Knapp A K, Blair J M, Collins S L. 2003. Productivity responses to altered rainfall

397 patterns in a C4-dominated grassland. *Oecologia*, 137: 245-251

398 Fensholt, R., Langanke, T., Rasmussen, K., Reenberg, A., Prince, S. D., et al., 2012. Greenness in semi-arid

399 areas across the globe 1981-2007-an earth observing satellite based analysis of trends and drivers.

400 *Remote Sensing of Environment*, 121, 144-158

401 Gao Q, Zhao P, Zeng X, Cai X, Shen W. 2002. A model of stomatal conductance to quantify the

- relationship between leaf transpiration, microclimate and soil water stress. *Plant Cell Envir.* 25: 1373-1381
- Granier, A., Bréda, N., Biron, P., Vilette, S., 1999. A lumped water balance model to evaluate duration and intensity of drought constraints in forest stands. *Ecological Modelling*, 116, 269-283
- Guo, L., 2000. Cyclic succession of *Artemisia ordosica* Krasch community in the Mu Us Sandy Grassland. *Acta Phytocologica Sinica*, 2000, 24(2): 243-247. (in Chinses with English abstract)
- Hall R L, Harding R J. 1993. The water use of the Balquhiddar catchments: a processes approach. *Journal of Hydrology*, 145: 285-314
- Han, J. C., Liu, Y. S., Zhang, Y., 2015. Sand stabilization effect of feldspathic sandstone during the fallow period in Mu Us Sandy Land. *J. Geogr. Sci.*, 25(4): 428-436
- Hao F H, Chen S Y, Ouyang W, Shan Y S, Qi S S. 2013. Temporal rainfall patterns with water partitioning impacts on maize yield in a freeze-thaw zone. *Journal of Hydrology*, 486: 412-419
- Herrmann. S. M., Anyamba, A., Tucker, C. J., 2005. Recent trends in vegetation dynamics in the African Sahel and their relationship to climate. *Glob. Environ. Change-Human Policy Dimens*, 15, 394-404
- Hornberger G M, Beven K J, Cosby B J. 1985. Sheandoah watershed study: calibration of a topography-based, variable contribution area hydrological model to a small forested catchment. *Water Resources Research*, 21(12): 1841-1850
- Hu, W., Si, B. C., 2014. Revealing the relative influence of soil and topographic properties on soil water content distribution at the watershed scale in two sites. *Journal of Hydrology*, 516, 107-118
- Jolly, W. M., Running, S. W., 2004. Effects of precipitation and soil water potential on drought deciduous phenology in the Kalahari. *Global Change Biology*, 10, 303-308
- Khaertidova E, Longobardi A. 2013. Analysis of inter-storm period soil moisture dynamics [J]. *Procedia Environmental Sciences*, 19: 208-216.
- Kite G. 2000. Using a basin-scale hydrological model to estimate crop transpiration and soil evaporation. *Journal of Hydrology*, 229: 59-69
- Kremer, R. G., Running, S. W., 1996. Simulating seasonal soil water balance in contrasting semi-arid vegetation communities. *Eco. Model.* 84, 151-162
- Laio F, Porporato A, Ridolfi L, Rodriguez-Iturbe I. 2001. Plants in water-controlled ecosystems: active role

in hydrologic processes and response to water stress. *Advances in Water Resources*, 24: 707-723.

Li, X.R., Zhang, Z.S., Huang, L., Wang, X.P., 2013. Review of the ecohydrological processes and feedback mechanisms controlling sand-binding vegetation systems in sandy desert regions of China. *Chinese Science Bulletin*, 58(13),1483-1496.

Li, X.Y., Yang, Z.P., Li, Y.T., Lin, H., 2009. Connection ecohydrology and hydropedology in desert shrubs: stemflow as a source of preferential flow in soils. *Hydrology and Earth System Sciences*, 13: 1133-1144.

Li, X. R., 2012. *Ecohydrological study on biological and soil crust in desert*. Beijing: High Education Press. (in Chinses)

Liu, X.P., Zhang, T. H., Zhao, H. L., He, Y. H., Yun, J. Y., Li, Y. Q., 2006. Influence of dry sand bed thickness on soil moisture evaporation in mobile dune. *Arid Land Geography*, 29(4), 523-526 (in Chinses with English abstract)

Martinez-Meza E, Whitford WG.1996. Stemflow, throughfall and channelization of stemflow by roots in three Chihuahuan desert shrubs. *Journal of Arid Environments*, 32, 271-287.

Martínez-Vilalta, J., Piñol, J., Beven, K., 2002. A hydraulic model to predict drought-induced mortality in woody plants: an application to climate change in the Mediterranean. *Ecol. Model.* 155, 127-147

Melillo, J., McGuire, A., Kichlighter, D., et al., 1993. Global climate change and terrestrial net primary production. *Nature*, 263, 234-240

Metcalf R A, Buttle J M. 1999. Semi-distrubuted water balance dynamics in a small boreal forest basin. *Journal of Hydrology*, 226: 66-87

Mohren G M J. 1987. *Simulation of forest growth, applied to Douglas fir stands in the Netherlands*. Ph.D. thesis, Agricultural University, Wageningen, the Netherlands.

Nian, F. H., Li, X., 2000. A comprehensive review of the research on hydrography in arid lands in China. *Arid Land Geography*, 2000, 23(1): 91-95. (in Chinses with English abstract)

Nouvellon Y, Rambal S, Lo Seen D, Moran M S, Lhomme J P, Bègué A, Chehbouni A G, Kerr Y. 2000. Modeling of daily fluxes of water and carbon from shortgrass steppes. *Agric. For. Meteorol*, 100: 137-153

Olioso A, Carlson T N, Brisson N. 1996, *Simulation of diurnal transpiration and photosynthesis of a water*

458 stressed soybean crop. *Agric. For. Meteorol.*, 81: 41-59

459 Pan FF, Peters-Lidard CD. 2008. On the relationship between mean and variance of soil moisture fields [J].

460 *Journal of the American Water Resources Association*, 44(1): 235-242.

461 Patanè, C., 2011. Leaf area index, leaf transpiration and stomatal conductance as affected by soil water

462 deficit and VPD in processing tomato in semi arid Mediterranean climate. *J. Agronomy & Crop*

463 *Science*, 197, 165-176

464 Peking University, et al., 1983. Physical environment, remediation, and utilization of Mu Us Sandland.

465 Beijing: Science Press. (in Chinses)

466 Raab, N., Meza, F. J., Franck, N., Bambach, N., 2015. Empirical stomatal conductance models reveal that

467 the isohydric behavior of an *Acacia caven* Mediterranean Savannah scales from leaf to ecosystem.

468 *Agric. For. Meteorol.* 213, 203-216

469 Radersma, S., Ong, C. K., 2004. Spatial distribution of root length density and soil water of linear

470 agroforestry systems in sub-humid Kenya: implications for agroforestry models. *Forest Ecology and*

471 *Management*, 188, 77-89

472 Raz-Yaseef, N., Rotenberg, E., Yakir, D., 2010. Effects of spatial variations in soil evaporation caused by

473 tree shading on water flux partitioning in a semi-arid pine forest. *Agricultural and Forest Meteorology*,

474 150, 454-462

475 Raz-Yaseef N, Yakir D, Schiller G, Cohen S. 2012. Dynamics of evapotranspiration partitioning in a

476 semi-arid forest as affected by temporal rainfall patterns. *Agricultural and Forest Meteorology*, 157,

477 77-85

478 Reynolds, J. F., Kemp, P. R., Tenhunen, J. D., 2000. Effects of long-term rainfall variability on

479 evapotranspiration and soil water distribution in the Chihuahuan Desert: A modeling analysis. *Plant*

480 *Ecology*, 150, 145-159

481 Rockström, J., Jansson P-E, Barron, J., 1998. Seasonal rainfall partitioning under runoff and runoff

482 conditions on sandy soil in Niger. On-farm measurements and water balance modelling. *Journal of*

483 *Hydrology*, 210, 68-92

484 Running S W, Coughlan J C. 1988. A general model of forest ecosystem processes for regional

485 applications: I hydrologic balance, canopy gas exchange and primary production processes. *Ecological*

486 Modelling, 42: 125-154

487 Sawano, S., Hotta, N., Tanaka, N., Tsuboyama, Y., Suzuki, M., 2015. Development of a simple forest
488 evapotranspiration model using a process-oriented model as a reference to parameterize data from a
489 wide range of environmental conditions. Ecological Modelling, 309-310, 93-109

490 Schimel, D. S., 2010. Drylands in the earth system. Science, 327, 418-419

491 Sela, S., Svoray, T., Assouline, S., 2015. Temporal variability of soil water content in a semiarid hillslope
492 across time scales: effect of soil surface condition. Journal of Arid Environments, 112, 64-74

493 She D. L., Liu D. D., Xia Y. Q., Shao, M., 2014. Modeling effects of land use and vegetation density on soil
494 water dynamics: implications on water resource management. Water Resour. Manage., 28, 2063-2076

495 Sitch S, Smith B, Prentice I C, Arneth A, Bondeau A, Cramer W, Kaplan J O, Levis S, Lucht W, Sykes M T,
496 Thonicke K, Venevsky S. 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial
497 carbon cycling in the LPJ dynamic global vegetation model. Global Change Biology, 9: 161-185

498 Thornton P E, Running S W. 1999. An improved algorithm for estimation incident daily solar radiation
499 from measurements of temperature, humidity, and precipitation. Agricultural and Forest Meteorology,
500 93: 211-228

501 Tiktak H A, van Grinsven J M. 1995. Review of sixteen forest-soil-atmosphere models. Ecological
502 Modelling, 83: 35-53

503 Wang H L, Guan H D, Simmons C T. 2016. Modeling the environmental controls on tree water use at
504 different temporal scales. Agricultural and Forest Meteorology, 225: 24-35

505 Wang, Q. S., Dong, X. J., Chen, X. D., Yang, B. Z., 1997. Study on some features of *Artemisia ordosica*
506 community at the different successional stages. Acta Phytocologica Sinica, 1997, 21(6): 531-538. (in
507 Chinses with English abstract)

508 Wang, Z., Wang, L., Liu, L. Y., Zheng, Q. H., 2006. Preliminary study on soil moisture content in dried
509 layer of sand dunes in the Mu Us Sandland. Arid Zone Research, 23(1), 89-92 (in Chinses with
510 English abstract)

511 Wegehenkel M. 2000. Test of a modelling system for simulation water balances and plant growth using
512 various different complex approaches. Ecological Modelling, 129: 39-64

513 Wilcox BP, Breshears DD, Turin HJ. 2003. Hydraulic conductivity in a Piñon-Junipor woodland: influence

- 1
2
3
4 514 of vegetation. Soil Science Society of America Journal, 67(4): 1243-1249.
5
6 515 Zavala, M. A., Espelta, J. M., Retana, J., 2000. Constraints and trade-offs in Mediterranean plant
7
8 516 communities: the case of Holm Oak – Aleppo Pine forests. The Botanical Review, 66(1): 119-149
9
10 517 Zhang, J., Huang, Y. M., Jiao, H. J., Xia, X. D., 2007. Ecophysiological characteristics of *Artemisia*
11
12 518 *ordosica* community succession in Mu Us Sandy Grassland. Journal of Desert Reserch, 27(6):
13
14 519 977-983 (in Chinses with English abstract)
15
16 520 Zhou Yunhua, Xiang Yueqin, Luan Lukai. 1996. Climatological estimation on quantum flux densities. Acta
17
18 521 Meteorologica Sinica, 54(4): 447-454 (in Chinese with English abstract)
19
20 522
21
22
23
24
25
26
27
28
29
30
31
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