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# Comparing three models to estimate transpiration of desert shrubs

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ABSTRACT

The role of environmental variables in controlling transpiration ($E_c$) is an important, but not well-understood, aspect of transpiration modeling in arid desert regions. Taking three dominant desert shrubs, *Haloxylon ammodendron*, *Nitraria tangutorum*, and *Calligonum mongolicum*, as examples, we aim to evaluate the applicability of three transpiration models, i.e. the modified Jarvis-Stewart model (MJS), the simplified process-based model (BTA), and the artificial neural network model (ANN) at different temporal scales. The stem sap flow of each species was monitored using the stem heat balance approach over both the 2014 and 2015 main growing seasons. Concurrent environmental variables were also measured with an automatic weather station. The ANN model generally produced better simulations of $E_c$ than the MJS and BTA models at both hourly and daily scales, indicating its advantage in solving complicated, nonlinear problems between transpiration rate and environmental driving forces. The solar radiation and vapor pressure deficit were crucial variables in modeling $E_c$ for all three species. The performance of the MJS and ANN models was significantly improved by incorporating root-zone soil moisture. We also found that the difference between hourly and daily fitted parameter values was considerable for the MJS and BTA models. Therefore, these models need to be recalibrated when applied at different temporal scales. This study provides insights regarding the application and performance of current transpiration models in arid desert regions, and thus provides a deeper understanding of eco-hydrological processes and sustainable ecosystem management at the study site.



## 1. Introduction

Transpiration is an important component of the hydrological cycle in terrestrial ecosystems (Jung et al., 2010; Zhang et al., 2016) and is affected by both biophysical and environmental processes at the interface between soil, vegetation, and atmosphere (Monteith, 1995). Understanding transpiration characteristics, its physiological responses to environmental conditions, and the mechanisms underlying it are critical for accurate prediction of long-term ecosystem carbon, water, and energy fluxes; this is especially important for arid and semi-arid regions, which cover 40% of the Earth's terrestrial surface and face the problem of serious water scarcity in the context of global warming (Reynolds, 2000).

Over the past few decades, the use of xylem sap flow sensors to estimate transpiration ($E_c$) at the whole tree level has been applied widely for different plants (Baker and van Bavel, 1987; Ford et al., 2007). However, previous studies on the characteristics of sap flow-scaled transpiration and its responses to environmental variables heavily focused on forest ecosystems (Mackay et al., 2010), with little work done in arid ecosystems (Allen and Grime, 1995; Dawson et al., 2007; Zhao et al., 2016). As desert ecosystems play a crucial role in stabilizing sand dunes and protecting oases from desertification, lack of sap flow field data in this area needs to be addressed to improve the understanding of eco-hydrological processes and water resource management.

Alternatively, models have been developed to estimate transpiration from a maximum rate by applying a set of functions of the relevant environmental variables (García et al., 2013; Whitley et al., 2008). These models are based on assumptions similar to the Jarvis-Stewart approach (Jarvis, 1976; Stewart, 1988) that the stress from each environmental variable on transpiration is independent of other environmental stresses. There have also been $E_c$

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models based on the knowledge of the physical processes at the cellular level. Buckley et al. (2003) developed a process-based canopy conductance model with clear physiological interpretations and later simplified it for transpiration modeling (Buckley et al., 2012). These models are much simpler to fit because they require fewer measurements and parameters.

Applications of artificial neural network (ANN) models in hydrology have provided many advantages in transpiration and rainfall-runoff modeling, river flow extrapolation, and sediment forecasting because of its availability in solving high nonlinear problems (Huntingford and Cox, 1997; van Wijk and Bouten, 1999). ANN models require less information than physically based models, and are unlike physically based models which are usually more complex, depending on the skill and experience of the modeler in model calibration (de Vos and Rientjes, 2005). Therefore, we used the ANN model as a statistical benchmark to compare the modified Jarvis-Stewart model and the process-based model.

Widely used environmental variables in $E_c$ modeling can be divided into two groups based on how they affect tree water uptake, i.e. atmospheric demand and water supply (Federer, 1982). The atmospheric demand group includes solar radiation, air temperature, and vapor pressure deficit. Damour et al. (2010) included both functions of air temperature and vapor pressure deficit while others have used only one. The water supply group mainly refers to the root-zone soil moisture, determined by water content, soil hydraulic properties, and root distribution. Soil water content in most studies has been measured in shallow soil layers, usually up to 20 cm. Because Xu et al. (2016) found that three of their study desert species developed deep root systems to obtain reliable water resources during a long drought period, a single measurement of the soil-water content at a shallow or a given depth can provide only limited information (Guyot et al., 2017), and may lower the accuracy of $E_c$ estimates. In our study, we use root-zone soil moisture (0–120 cm) in the simulation of $E_c$ for three desert shrubs.

Based on measurements of stem sap flow and the concurrent microclimate over the two main growing seasons in 2014 and 2015, we simulated transpiration of three typical sand-fixation desert shrubs using three models. Our objectives were: (1) to examine the performance of the three transpiration models for shrub species in arid climatic conditions; (2) to compare the difference in parameters of the transpiration models between hourly and daily scales within models; and (3) to analyze the role of environmental factors on transpiration at each temporal scale for the different models.

## 2. Study site and material

### 2.1. Field site and study species

We conducted our experiments near the Linze Inland River Basin Research Station (LIRBRS), Chinese Academy of Sciences, located in the middle reaches of Heihe River Basin, northwest China (39°22′07″ N, 100°08′48″ E, elevation 1386 m (McVicar and Körner, 2013)) (Fig. 1a). The environment is characterized by a typical continental arid temperate climate with hot, dry summers and cold winters. LIRBRS meteorological station data for 2005–2014 showed the annual mean temperature is about 8.9 °C, with the lowest temperature of −26.2 °C occurring in January and the highest temperature of 38.6 °C occurring in July. The annual mean precipitation is about 125 mm, with approximately 80% of the annual total occurring from June to September. Soil at the site is loamy sand (sand 73.5%, silt 22.5% and clay 1.4%) (USDA texture class) with little organic matter and few mineral nutrients.

*Haloxylon ammodendron*, *Nitraria tangutorum* and *Calligonum mongolicum* are the target species (Fig. 1b–d) because they are critical for stabilizing sand dunes. The bushes occupy about 15% of the land surface area. *H. ammodendron* is the dominant species, comprising approximately 53% of the canopy cover, with subdominant *N. tangutorum* (ca. 45%), *C. mongolicum* (ca. 1.6%), and other shrubs species (e.g. *Hedysarum Scoparium*, *Tamarix ramosissima*). The dominant species contribute more than 99% of the standing biomass at the site and are typical psammophytes, with extensive, deep root systems that can reach underground water supplies. Five sampled plants with similar crown area for each species were selected for our experiments (Table 1).

### 2.2. Environmental measurements

At the field site, we constructed a standard automatic weather station at the top of a 6 m high scaffold tower to measure solar radiation ($R_s$, W m$^{-2}$) (CNRS, Kipp & Zonen, Delft, Netherlands), air temperature ($T$, °C) (HMP155A, Vaisala, Helsinki, Finlnd), relative humidity (%) (HMP155A, Vaisala, Helsinki, Finlnd), and precipitation (mm day$^{-1}$) (TE525, Texas Electronics Inc., Dallas, TX, USA). We also measured volumetric soil water content ($\theta$, cm$^3$ cm$^{-3}$) with time domain reflectometers (TDR, CS616, Campbell Scientific Inc., Logan, UT, USA) using 12 probes at depths of 10, 20, 40, 60, 80, and 120 cm and recorded all data with a CR1000 data logger at 30-min intervals. The air vapor pressure deficit ($D$, kPa) was calculated based on air temperature and relative humidity measurements.

The results of environmental measurements showed that, for the two consecutive growing seasons, there were no noticeable differences in air temperature, solar radiation, and vapor pressure deficit (Fig. 2). Air temperature, solar radiation, and vapor pressure deficit showed obvious seasonal trends with maximum values occurring in July, reflecting the high atmospheric evaporative demand in this month. The average daily air temperature was 19.7 °C in 2014 and 2015 (Fig. 2a). The average daily solar radiation was 241.5 W m$^{-2}$ in 2014 and 247.3 W m$^{-2}$ in 2015 (Fig. 2b). The average daily vapor pressure deficit was 1.5 kPa in 2014 and 1.6 kPa in 2015 (Fig. 2c). Air temperature had similar dynamics as vapor pressure deficit, which reflected a high interdependency between these two variables.

During the monitoring periods rainfall totaled 98.7 mm and 74.8 mm in 2014 and 2015, respectively. Weak precipitation events ($\leq$5 mm) were frequent, whereas strong precipitation events (5–10 mm) and the strongest precipitation events ($\geq$10 mm) were infrequent. Weak precipitation events accounted for 77% of all events and 38% of the total precipitation in 2014. The corresponding proportions were 91% and 72% in 2015. Strong precipitation events accounted for 17% of all events and 39% of the total precipitation amount in 2014. The corresponding proportions were 9% and 28% in 2015. The strongest precipitation events accounted for 6% of all events and 23% of the total precipitation amount in 2014, while the strongest events did not occur in 2015. Approximately 60% of all precipitation events occurred in June and July (Fig. 3a).

During the measurement period, the surface soil water content (0–20 cm) ranged from 0.03 to 0.10 cm$^3$ cm$^{-3}$ with a mean value 0.05 cm$^3$ cm$^{-3}$ in 2014, and ranged from 0.03 to 0.06 cm$^3$ cm$^{-3}$ with a mean value 0.04 cm$^3$ cm$^{-3}$ in 2015. The soil water content exhibited distinct pulses in response to strong rainfall events, but the soil was in a water deficit condition at all other times. Below the 20-cm depth, the soil water content was significantly higher. The average soil moisture in the whole layer (0–120 cm) ranged from 0.08 to 0.12 cm$^3$ cm$^{-3}$ with a mean value of 0.10 cm$^3$ cm$^{-3}$ in 2014, and from 0.08 to 0.09 cm$^3$ cm$^{-3}$ with a mean value of 0.09 cm$^3$ cm$^{-3}$ in 2015 (Fig. 3b).

### 2.3. Sap flow measurements

Transpiration was represented by stem sap flow. We used commercially available, constant power stem sap flow gauges