# The transpiration and the spectral response of non-irrigated *Haloxylon ammodendron* at canopy scale

Xiao-ming CAO[a], Juan-le WANG[a,*], Zhi-qiang GAO[a,b,c] , Mao-si CHEN[b]
[a] Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Science, Beijing, China
[b] USDA UV-B Monitoring and Research Program, Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO, USA;
[c] Yantai Institute of Coastal Zone Research, Chinese Academy of Science, Yantai, China

## ABSTRACT

Transpiration, an essential component of surface evapotranspiration, is particularly important in the research of surface evapotranspiration in arid areas. The paper inverted the transpiration of non-irrigated *Haloxylon ammodendron* and its spectral responses at the canopy scale in the southern edge of the Gurbantunggut desert in Xinjiang, China. The results are as follows: The stem sap flow rate appeared biomadal or multi-peak course and maintained a certain flow in the night. The stem sap flow maintained at 0 ~ 0.1 L/h, with a peak appearing at 12:00 ~ 17:30, 0.316 L/h. "Noon peak" appeared from mid May to early September, at 14:00 ~ 16:00. For monthly changes, the peak value appeared in June, with the value varying (0.32 ± 0.20) L / h, followed by July (0.30±0.16) L/h, then, May and August, the minimum value appeared in September (0.15±0.03) L/h. At the canopy scale, the optimal exponential model of the sap flow rate based on the hyperspectrum is $y = 0.0015e^{3.8922x}$, $R^2 = 0.806$.

**Keywords: the stem sap flow rate, the canopy scale, *Haloxylon ammodendron*, the reflectance**

## 1 INTRODUCTION

Evapotranspiration (ET) is the final stage of water consumption in the inland water cycle of arid land. Transpiration plays a critical role in the configuration of water resources in arid land and the maintenance of the energy balance in the ecological system (Bodner et al. 2007). *Haloxylon ammodendron* is a dominant native desert shrub in central Asia. It is widely distributed in the Gurbantunggut desert on the northern slope of Tianshan Mountain. *Haloxylon ammodendron* has adapted well to high temperature and drought due to its degenerated scale leaves, which act as an assimilation organ (Xu et al. 2007). Studies on *Haloxylon ammodendron* have focused on factors such as ecological environment, distribution, physical characteristics and the water balance (Wang and Ma. 2003). Researchers have widely studied the ET of *Haloxylon ammodendron* on the canopy and stand scales (Zhang et al. 2003; Xu 2006; Xu et al. 2008). However, due to the complexity inherent in the process of ET in arid lands, and the difficulties in the upscaling in different scales, there have no studies focused on ET simulation of the dominant native desert shrub based on the Hyperspectral remote sensing data. Based on the measured sap flow rate and reflectance data, the paper studied the water use and its response to measured reflectance at canopy scale.

## 2 STUDY AREA

The study area is located at the southern edge of the Gurbantunggut desert on the northern slope of the Tianshan Mountains, where there is a large area occupied by native saline desert vegetation (Cao et al.

---

[*] Address correspondence to wangjl@igsnrr.ac.cn, phone 86 10 6488 8016

Remote Sensing and Modeling of Ecosystems for Sustainability IX, edited by Wei Gao,
Thomas J. Jackson, Jinnian Wang, Ni-Bin Chang, Proc. of SPIE Vol. 8513, 85130M
© 2012 SPIE · CCC code: 0277-786X/12/$18 · doi: 10.1117/12.928275

2011). The climate is temperate zone continental desert, where it is hot and dry in summer and cold in winter. The average annual temperature is 6.6 ºC, the average precipitation is 160 mm, the average annual ET is 2,000 mm (Xu et al. 2007). Precipitation and soil water are the main water sources for the vegetation. Typical desert subshrubs such as *Haloxylon ammodendron* are distributed here, and it is an important area for ecological processes and preservation in arid central Asia (Fig.1).

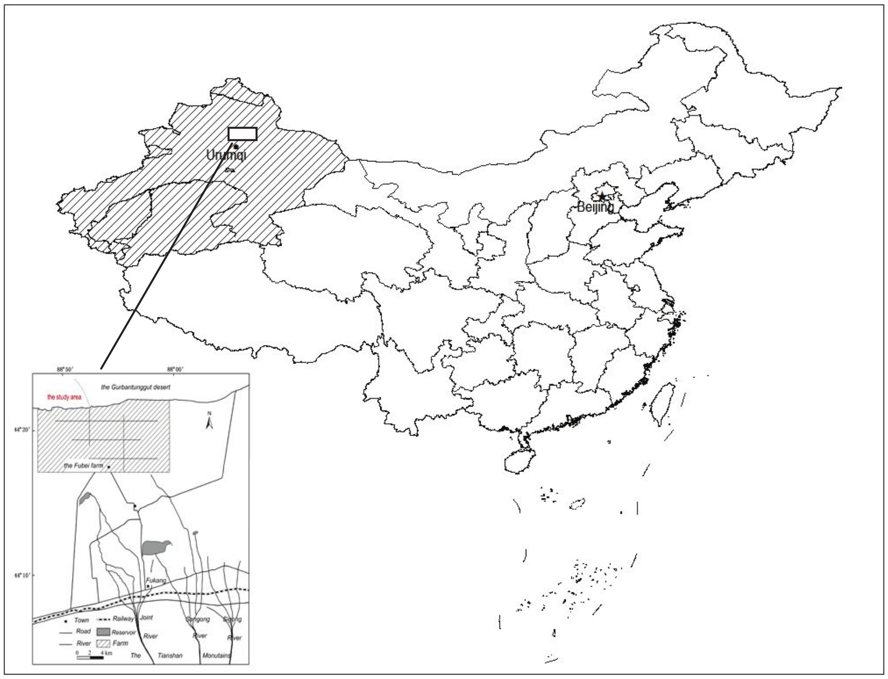

Fig.1 The study area

## 3 METHODS

### 3.1 The stem sap flow rate

The stem sap flow rate of *Haloxylon ammodendron* was measured by Sakuratani (1984) sap flow gauges, which were based on the heat balance method. A DT Logger80 was used to record and store the average data every 10 minutes. The diameters of all the branches were measured using a micrometer. The physical parameters of the each *Haloxylon ammodendron* in the quadrat (e.g. the height, the crown diameters, the stem base diameters) were also measured by a tape.

### 3.2 Calculation of vegetation transpiration

The vegetation transpiration was calculated using the cross-sectional area method (Vertessy et al. 1995; 1997):

$$Q = \frac{f}{s} \times S_A \times H \tag{1}$$

Where $s$ (cm$^2$) is the cross-sectional area of the branch installed a sap flow gauge; $S_A$ (cm$^2$) is the total cross-sectional area of one plant, all the cross-sectional area was calculated from the diameters of the branches; $f$ (g / h) is the stem sap flow rate of the branch installed a sap flow gauge; $H$ (h) is the period of collecting the stem sap flow rate; $Q$ (g) is the single-plant water consumption during the period of $H$.

### 3.3 Calculation and determination of the best spectral index

Regression analysis is the most widely used empirical method to study the relationship between two variables (Cohen et al. 2003). In general, one variable is difficult or costly to obtain (e.g. sap flow rate), while the other one is relatively easily to obtain (e.g. the measured reflectance of vegetation). In the paper, the regression analysis was used to explore the sensitive bands or bands combination to sap flow rate from 350 ~ 2500 nm. Four types of spectral index, ranging from the very simple (R) to more sophisticated (ND type) specifically designed to quantify the sap flow rate, were applied in the paper (Table 1). We firstly determined the best wavelength domains for a given type of index by screening all combinations using correlation analysis based on measurements, and then identify the best one from the four types of indices. The screening was made 5 nm step and indices were calculated for each combination.

Table 1 The spectral indices used in the paper

| The spectral indices | The formula |
|---|---|
| Reflectance (R) | $\rho\lambda_1$ |
| Difference (D) | $\rho\lambda_1 - \rho\lambda_2$ |
| Simple Ratio (SR) | $\rho\lambda_1 / \rho\lambda_2$ |
| Normalized Difference (ND) | $(\rho\lambda_1 - \rho\lambda_2)/(\rho\lambda_1 + \rho\lambda_2)$ |

$\lambda_1$ , $\lambda_2$ is the wavelength, and $\rho\lambda_1$ , $\rho\lambda_2$ is the corresponding reflectance.

A 2-D $R^2$ graph has been presented a two dimensional contour plot of the coefficient of determination ($R^2$) with the two wavelengths on the x and y axes. The map provided an overview of the statistical significance of SR for all combination of two wavelengths. It allows efficient extraction of significant peak-wavelengths as well as the extent of the effective regions for assessment of each target variable.

A linear regression was then fit between the indices and the sap flow rate. We have also tried the fitting with higher order polynomials while no significant improvement has been obtained. The coefficient of determination ($R^2$) is applied as the criterion to identify the best index.

$$R^2 = 1 - \sum_{i=1}^{n} (y_i' - \overline{y})^2 - \sum_{i=1}^{n} (y_i - \overline{y})^2 \tag{2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (y_i' - \overline{y})^2}{n}} \tag{3}$$

Where $R^2$ is the coefficient of determination, y' is the estimated value, y is the independent reference measurement, and RMSE (Root-mean-square error) is the absolute error in estimation. The group of $\lambda_1$ , $\lambda_2$ with the maximum $R^2$ formed the optimum spectral index. All the work was performed in MATLAB.

## 4 RESULTS AND DISCUSSION

### 4.1 The daily course of stem sap flow rate

Transpiration is affected by the physiological activities and environmental factors, acting a obvious circadian rhythm. Fig. 2 shows the stem sap flow rate appeared biomadal or multi-peak course and maintained a certain flow in the night. Krfnler revealed the day transpiration was resulted in the lower water potential in the ground parts. According to the theory of “transpiration pull-cohesion”, the day transpiration was resulted from the opening stoma, which formed leaves-crown-root water potential. The stoma closed after sunset, but the water potential gradient did not disappear immediately. Due to the presence of potential difference, there was some water going through from the roots to the leaves in a period of time, and formed compensation flow at night, so that the trunk parts of the water storage was restored. These have been similar findings. Fig 2 reveals that the stem sap flow maintained at 0 ~ 0.1 L/h, with a peak appearing at 12:00 ~ 17:30, 0.316 L/h. “Noon peak” appeared from mid May to early September, at 14:00 ~ 16:00.

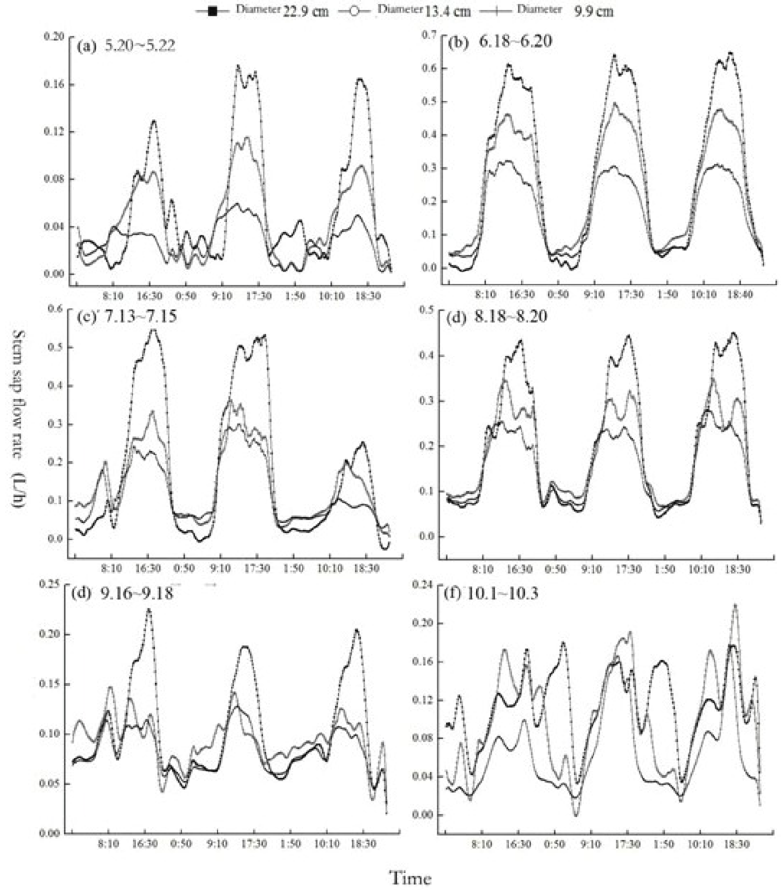

Fig. 2 Daily fluctuation of stem sap flow under different diameters

### 4.2 The monthly course of stem sap flow rate

For monthly changes, the peak value appeared in June, with the value varying (0.32 ± 0.20) L / h, followed by July (0.30±0.16) L/h, then, May and August, the minimum value appeared in September (0.15±0.03) L/h. The large of the diameter, the large of the average stem sap flow rate. There appeared some differences in the stem sap flow for different *Haloxylon ammodendron*, which may resulted from the individual size and assimilation of the number of branches required more exploration in the future (Table 2).

Table 2 The month variety of the stem sap flow rate (L/h)

| No. | May | June | July | August | September | the average value |
|---|---|---|---|---|---|---|
| 1 | 0.167 | 0.359 | 0.407 | 0.282 | 0.164 | 0.276 |
| 2 | 0.060 | 0.208 | 0.276 | 0.204 | 0.182 | 0.186 |
| 3 | 0.051 | 0.135 | 0.177 | 0.189 | 0.128 | 0.136 |

### 4.3 The spectral response of the sap flow rate at the canopy scale

The spectral response of the sap flow rate was studied (30 points) based on the measured canopy reflectance and the corresponding average sap flow rate. Table 2 presents the highest $R^2$, wavelength(s), RMSE and P for each spectral index.

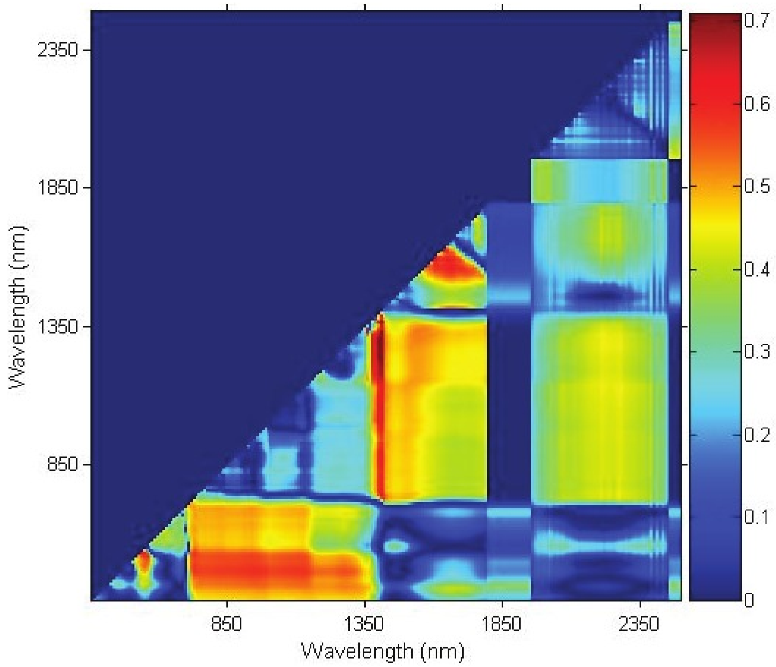

Fig. 3 Matrix representing the $R^2$ of stem sap flow rate

A statistically significant correlation ($R^2 > 0.43$, $P < 0.0001$) to the sap flow rate could be shown for all indices derived from spectra taken from the canopy (Table 3). The correlation coefficients between the measured sap flow rate and spectral indices varied among indices ($R^2 = 0.43$~0.62). SR showed the highest correlation coefficient ($R^2 = 0.62$) to all measured sap flow rate, followed by ND ($R^2 = 0.61$). SR and ND had a similar $R^2$; however, the RMSE of SR (RMSE = 1.124 kg/h) was much smaller than that of ND (RMSE = 1.167 kg/h). Substantially lower correlation coefficients could be observed for D ($R^2$=0.48, RMSE =1.358 kg/h) and R ($R^2$=0.43, RMSE =1.395 kg/h).

Because of its simplicity, significant correlation coefficient and lowest RMSE, the SR index is used as the sensitivity index for the sap flow rate estimation. Fig. 3 provides an overview of the statistical significance of SR for all combinations of two wavelengths. There are several narrow parks (reddish) and broad regions (yellowish). The first region, 750 ~ 1310 nm vs. 1380 ~ 1500 nm, has the highest $R^2$ values. The second region of high $R^2$ values is approximately 1540 ~ 1600 nm vs. 1550 ~ 1700 nm. The third region of high $R^2$ values is approximately 350 ~ 750 nm vs. 700 ~1150 nm. However, the 1380 ~ 1500 nm region is within the atmospheric window, it cannot be used with remote sensing images. We selected the second region (1540 ~ 1600 nm vs. 1550 ~ 1700 nm) as the SR index. Fig 3 reveals that the SR spectral index calculated by the reflectance at 1580 nm and 1600 nm has the highest SR, which was used with remote sensing images.

Table 3 The sensitive bands of every spectral index

| The spectral index | $\lambda_1$ (nm) | $\lambda_2$ (nm) | a | b | $R^2$ | RMSE(kg/h) | P |
|---|---|---|---|---|---|---|---|
| R | 1970 | --- | 8.24 | -0.14 | 0.43 | 1.358 | <0.0001 |
| D | 2070 | 2310 | 7.81 | -0.93 | 0.48 | 1.395 | <0.0001 |
| SR | 1580 | 1600 | 0.76 | 3.65 | 0.62 | 1.124 | <0.0001 |
| ND | 1580 | 1600 | 4.37 | 16.61 | 0.61 | 1.167 | <0.0001 |

Based on the least square method (Das and Basudhar 2006), the relationship between the measured canopy sap flow rate and $SR_{(1580,1600)}$ was fitted by several fitting types, including simple linear regression, quadratic polynomial, cubic polynomial, logarithmic equation, index equation and power function (Table 4). Table 4 reveals a good relationship between them, with the maximum $R^2$ of 0.806 and the minimum $R^2$ of 0.650. There was the most significant relationship between sap flow rate and SR by index function ($R^2$=0.806, $P < 0.001$), with the equation of $y = 0.0015e^{3.8922x}$.

Table 4 The fitting models between the measured canopy sap flow and $SR_{(1580,1600)}$

| Fitting type | The models | $R^2$ | P |
|---|---|---|---|
| Simple linear | $y = 3.405x - 4.423$ | 0.722 | 0.001 |
| Quadratic polynomial | $y = 4.736x^2 - 11.53x + 7.208$ | 0.742 | < 0.001 |
| Cubic polynomial | $y = -12.365x^3 + 63.7x^2 - 104.41x + 55.51$ | 0.754 | < 0.001 |
| Logarithmic equation | $y = 5.214\ln(x) - 1.393$ | 0.650 | 0.001 |
| Index equation | $y = 0.0015e^{3.8922x}$ | 0.806 | < 0.001 |
| Power function | $y = 0.047x^{6.0528}$ | 0.791 | < 0.001 |

## 5 CONCLUSION

(1) The stem sap flow rate appeared biomadal or multi-peak course and maintained a certain flow in the night. The stem sap flow maintained at 0 ~ 0.1 L/h, with a peak appearing at 12:00 ~ 17:30, 0.316 L/h. “Noon peak” appeared from mid May to early September, at 14:00 ~ 16:00.

(2) For monthly changes, the peak value appeared in June, with the value varying (0.32 ± 0.20) L / h, followed by July (0.30±0.16) L/h, then, May and August, the minimum value appeared in September (0.15±0.03) L/h.

(3) There are several narrow parks (reddish) and broad regions (yellowish). The first region, 750 ~ 1310 nm vs. 1380 ~ 1500 nm, has the highest $R^2$ values. The second region of high $R^2$ values is approximately 1540 ~ 1600 nm vs. 1550 ~ 1700 nm. The third region of high $R^2$ values is approximately 350 ~ 750 nm vs. 700 ~1150 nm.

(4) A statistically significant correlationto the sap flow rate could be shown for all indices derived from spectra taken from the canopy. A good relationship between them, with the maximum $R^2$ of 0.806 and the minimum $R^2$ of 0.650. There was the most significant relationship between sap flow rate and SR by index function ($R^2$=0.806, $P < 0.001$), with the equation of $y = 0.0015e^{3.8922x}$.

## ACKNOWLEDGE

The authors are grateful for the support from Natural Science Foundation of China (41171334， 41071278) and USDA NIFA project (2010-34263-21075), Public Welfare Special Program, Ministry of Environmental Protection of the People’s Republic of China (Grant No. 201109075). The basic work items by the Ministry of Science the norms for the comprehensive scientific investigation of the grid-based resources and environment of the People’s Republic of China (Grant No. 2011FY110400). National Natural Science Foundation of China (41171334 and 41071278).

## REFERENCES

[1]. Bodner G, Loiskandl W, Paul HP., “Cover crop evapotranspiration under semi-arid conditions using FAO (Food and Agriculture Organization) dual crop coefficient method with water stress compensation,” Agricultural Water Management. papers 93(3):85-98 (2007)

[2]. Cao XM, Chen X, Bao AM, Wang Q., “Response of vegetation to temperature and precipitation in Xinjiang

during the period of 1998-2009," Journal of arid land. papers 3(2): 94-103 (2011)

[3]. Cohen WB, Maiersperger, TK, Gower ST., "An improved strategy for regression of biophysical variables and Landsat ETM+ data," Remote Sensing of Environment. papers 84(4): 561-571. (2003)

[4]. Li ML, Zhou HF, Sun PF., "Comparative study on the rule of stem-sap flow of *Haloxylon ammodendron* in the southern marginal zone of Junggar basin," Arid Zone Research. papers 29(1):101-108 (2012)

[5]. Sakuratani T., "Improvement of the probe for measuring water flow rate in intact plants with the stem heat balance method," Journal of Agricultural Meteorology. papers 40: 273-277(1984)

[6]. Wang JH, Ma QL., "Study on restoration strategies, characteristics and status of degenerated artificial *Haloxylon ammodendron* communities at the edge of Minqin oasis. Acta Botanica Boreali-occidentalia Sinica. papers 23(12):2107-2112(2003)

**[7].** Xu H., "Study on plants water consumption of Tarim desert highway protection forest," The PHD thesis of the graduate school of Chinese Academy of Sciences(2006)

[8]. Xu H, Li Y, Zou T, Xie JX, Jiang LX., "Ecophysiological response and morphological adjustment of *Haloxylon ammodendron* towards variation in summer precipitation," . papers 27(12):5019-5028 (2007)

[9]. Xu H, Zhang XM, Yan HL., "The plant water status of the shelterbelt along the Tarim desert highway,"Science Bulletin. papers 53:131-139(2008)

[10]. Zhang XY, Gong JD, Zhou MX., "A study on the stem sap flow of *Populus euphrtaicr* and *Tamaris spp*. By heat pulse technique," Journal of glaciology and geocryology. papers 25(5):584-590 (2003)