Postprint: Sap Flow Characteristics in Haloxylon ammodendron Trunks Using Thermal Diffusion Technology

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Abstract

Using TDP (Thermal Dissipation Probe) sap flow sensors in conjunction with an automatic weather station, continuous monitoring of trunk sap flow and environmental factors of native Haloxylon ammodendron on the southern edge of the Gurbantunggut Desert was conducted. The response of Haloxylon ammodendron sap flow to environmental variables was analyzed, relationships between sap flow and environmental factors during the growing season were established, and daily and seasonal water consumption of the Haloxylon ammodendron community was estimated. The results showed: (1) Diurnal variation in sap flow velocity was primarily characterized by a unimodal curve, with bimodal curves occasionally occurring in summer. Sap flow velocity differed significantly among seasons; in summer, trunk sap flow initiated earlier, peak values appeared earlier, and weak sap flow persisted throughout the night; (2) Instantaneous sap flow velocity of Haloxylon ammodendron exhibited significant positive correlations with wind speed, net radiation, air temperature, and vapor pressure deficit (VPD), and extremely significant negative correlations with actual vapor pressure and air humidity. The key factors influencing variation in instantaneous sap flow velocity were net radiation and vapor pressure deficit; (3) Daily average sap flow velocity of Haloxylon ammodendron showed extremely significant positive correlations with net radiation, air temperature, actual vapor pressure, soil moisture content, and soil temperature, extremely significant negative correlations with air humidity, and non-significant correlation with wind speed. The key factors influencing variation in daily average sap flow velocity were net radiation, vapor pressure deficit, and air temperature.

Full Text

Characterization of Stem Sap Flow in *Haloxylon ammodendron* Using Thermal Dissipation Technology

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Abstract: Transpiration water consumption of *Haloxylon ammodendron* is an important physiological index strongly influenced by environmental factors. We continuously monitored stem sap flow dynamics and environmental factors of native *H. ammodendron* in the southern marginal zone of the Gurbantunggut Desert using thermal dissipation probe (TDP) technology combined with automatic weather stations. The response of sap flow velocity to environmental factors was analyzed, and relationships between stem sap flow and environmental factors were established during the growing season. Results showed that: (1) Sap flow velocity primarily exhibited a single-peak diurnal curve, occasionally showing a double-peak curve in summer. Daily variation amplitude and peak values were significantly greater in summer than in spring and autumn, with significant seasonal differences. In summer, sap flow initiation and peak occurred earlier, while weak nocturnal sap flow was observed. (2) During the growing season, net radiation, air temperature, and vapor pressure deficit were key factors driving instantaneous sap flow changes. Instantaneous sap flow rate was positively correlated with wind speed, net radiation, vapor pressure deficit, and air temperature, but negatively correlated with actual vapor pressure and air humidity. (3) Key factors affecting seasonal sap flow velocity changes included net radiation, vapor pressure deficit, and air temperature. Daily average flow rate was positively correlated with net radiation, air temperature, vapor pressure deficit, actual vapor pressure, soil water content, and soil temperature, but negatively correlated with air humidity. (4) Daily transpiration first increased then decreased throughout the growing season, beginning at 0.21 mm/d in early May, peaking in mid-June for about 40 days, then declining to 0.10 mm/d by late July. For *H. ammodendron* samples, daily transpiration averaged 0.35 mm/d, with total transpiration of 53.35 mm during the entire study period, demonstrating strong ecological adaptability to drought conditions. In this harsh high-temperature, low-rainfall environment, *H. ammodendron* showed very low water consumption, making it an ideal species for ecological restoration and reconstruction in arid lands.

Keywords: Gurbantunggut Desert; stem sap flow; TDP (thermal dissipation probe); environmental factors

Introduction

The Gurbantunggut Desert is the only desert in China' s arid region dominated by fixed and semi-fixed linear dunes, and its stability directly affects the ecological security of oasis areas along the northern foothills of the Tianshan Mountains. Due to human activities and climate change, desertification has become increasingly severe in this region. *Haloxylon ammodendron* is the main vegetation type in the Gurbantunggut Desert, playing an irreplaceable role in windbreak and sand fixation, and preventing desert encroachment on oases. However, with excessive exploitation of groundwater in oasis areas, lateral groundwater seepage to the desert has decreased, causing the shallow groundwater table in the southern margin of the Gurbantunggut Desert to decline and *H. ammodendron* communities to show signs of degradation.

Water is the most direct and critical factor influencing ecological environment changes in arid regions, and its availability directly determines regional ecological development. Plant transpiration is the primary pathway of water consumption, and stem sap flow—the water flow in tree xylem caused by transpiration—accounts for the majority of total tree transpiration. Monitoring stem sap flow with sap flow meters can effectively reflect the transpiration process. Studies on sap flow characteristics have always been a major focus in ecological research. At the edge of the Gurbantunggut Desert, *H. ammodendron* is widely distributed as a dominant species. This deciduous small tree or large shrub has biological characteristics including short main stems and strong branching.

Previous studies have investigated sap flow characteristics and relationships with environmental factors in *H. ammodendron* using heat pulse sap flow meters and stem heat balance sap flow meters. However, heat pulse meters are excessively expensive and have delayed responses to sap flow, while stem heat balance meters can damage stems. The thermal dissipation probe (TDP), modified from the heat pulse method, avoids these drawbacks and is more suitable for extensive field monitoring. The TDP method can continuously measure stem sap flow under natural tree growth conditions with minimal disturbance, offering advantages of high temporal resolution, accuracy, and ease of operation, making it one of the most commonly used methods in tree water consumption research.

Sap flow dynamics are influenced by plant biological structure and meteorological factors: biological structure determines the potential capacity for sap flow, water supply determines the overall level, and meteorological factors control instantaneous variations. Investigating sap flow characteristics and their responses to environmental factors is a prerequisite for accurately calculating individual tree transpiration water consumption. Building models of sap flow velocity and environmental factors enables prediction of individual tree transpiration through environmental indicators. Based on continuous monitoring of sap flow velocity and environmental factors for *H. ammodendron* trees of different diameters in the southern margin of the Gurbantunggut Desert, this study examines sap flow variation patterns and environmental responses under natural conditions, constructs sap flow velocity-environmental factor models, estimates daily and seasonal transpiration water consumption of *H. ammodendron* communities using scaling methods, and explores the ecological adaptability of this species to provide a scientific basis for sand dune management.

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1. Study Area Overview

The experimental site is located in Beishawo on the southern edge of the Gurbantunggut Desert, 5 km from the Fukang Desert Ecological Station (44°22 N, 87°55 E) of the Chinese Academy of Sciences, 15 km from the Urumqi Desert Botanical Garden, and 80 km from Urumqi. This area represents a typical desert ecosystem in northern Xinjiang that maintains its original desert vegetation. The geomorphology consists primarily of north-south oriented dendritic sand ridges with fixed and semi-fixed dunes.

The region has a continental arid climate with an average annual precipitation of 128.6 mm, with snow cover lasting 100–160 days. Spring and summer rainfall accounts for about 2/3 of total precipitation. Spring snowmelt and spring-summer rainfall are the main water sources sustaining vegetation. The extreme maximum temperature is 41.5°C, with an average annual temperature of 7.19°C. Winter snow depth is 20 cm.

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2. Experimental Materials and Methods

2.1 Experimental Materials and Site Selection

The experimental material was *Haloxylon ammodendron*, a deciduous small tree or large shrub with extremely strong drought tolerance, widely used for windbreak and sand fixation in desert areas. In the Beishawo experimental site, a relatively flat and open forest plot was selected to install a Bowen ratio meteorological observation system. A 20 m × 20 m *H. ammodendron* sample plot was established around the Bowen ratio station, with natural density of 199 stems/192 cm^2 and canopy cover of 20%–30%.

Six sample trees were selected at distances of 3–5 m from the Bowen ratio station, with base diameters measured by vernier calipers as 1.1, 1.8, 1.55, 1.95, 1.9, and 1.65 cm. A plant growth cone was used to measure sapwood thickness of the six sample trees, yielding values of 4.55, 8.91, 8.44, 9.55, 8.28, and 6.49 cm. Color differences between sapwood and heartwood were observed, with sapwood thicknesses of 1.1, 1.8, 1.55, 1.95, 1.9, and 1.65 cm respectively.

This study used the Plant Sensors PS-TDP8 tree sap flow monitoring system produced by Aoda Plant Sensors Company. Due to the narrow sapwood thickness of *H. ammodendron*, to avoid errors from probe insertion into heartwood and to minimize orientation effects, probes were uniformly installed on the north side of the trunk base at 20–30 cm above ground, with insertion depth of 2 cm. Probes were wrapped with soft foam plastic, then covered with aluminum foil and plastic paper to prevent thermal radiation and rainwater infiltration. TDP probes were connected via cables to an automatic data logger for data recording and storage at 30-minute intervals.

2.2 Environmental Factor Measurements

Environmental factors were monitored using a fully automatic Bowen ratio integrated observation system with a new integrated structural design. The system collected air temperature (Ta), relative humidity (RH), wind speed (WS), net radiation (TBB), soil temperature (Ts), and soil water content (SWC). Vapor pressure deficit (VPD) was calculated from air temperature and relative humidity. Data collection interval was set at 30 minutes with automatic storage.

2.3 Sap Flow Rate and Stand Transpiration Calculations

After data collection, original data were processed and calculated using analysis software provided by Aoda Plant Sensors Company.

Sap flow rate calculation formula:

$$V_s = 0.000119 \times \left(\frac{\Delta T_m - \Delta T}{\Delta T}\right)^{1.231}$$

Where V_s is sap flow velocity in trunk sapwood (m/s), ΔT is the instantaneous temperature difference between two probes, ΔT_m is the maximum temperature difference between probes, and the constant 0.000119 is an empirical constant.

Stand transpiration calculation formulas:

$$A_s = \pi(r - r_b)^2 - \pi(r - r_b - r_s)^2$$

$$E = V_s \times A_s$$

$$E_{stand} = \sum(V_{si} \times A_{si})$$

Where A_s is sapwood area, r is base diameter, r_b is bark thickness, r_s is sapwood thickness, E is individual tree transpiration water consumption, V_s is sap flow velocity at trunk base, A_s is sapwood area at trunk base, V_{si} is the average sap flow velocity of all sample trees in a diameter class, and A_{si} is the total sapwood area at trunk base for all trees in that diameter class.

2.4 Data Processing

Environmental factor data and *H. ammodendron* sapwood sap flow velocity data were preprocessed using EXCEL software. SPSS software was used for multiple regression analysis to obtain statistical relationships between sap flow velocity and meteorological and soil environmental factors. Path coefficients in regression analysis represent direct path coefficients expressed as standardized regression coefficients.

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3. Results

3.1 Patterns of Sap Flow Velocity in *Haloxylon ammodendron*

Haloxylon ammodendron sapwood sap flow velocity exhibited clear diurnal rhythms and seasonal variation patterns. Sap flow temporal variation characteristics include initiation time, peak time, duration of peak flow, and time entering low-flow periods. The diurnal sap flow curve typically showed a single peak, with occasional double peaks in summer under high temperature and drought stress. This "midday depression" phenomenon adjusts stomatal closure to reduce leaf transpiration rate, avoiding excessive water loss and enabling adaptation to high-temperature and drought climates.

In spring and autumn on clear sunny days, sap flow initiated at 8:30–9:00 in spring and 9:30–10:00 in autumn, with maximum flow rates of approximately 0.35 dm/h and 0.5 dm/h respectively. In summer, sap flow initiated at 7:00–8:00, peaking at 10:00–11:00 with maximum rates of 0.75–0.85 dm/h, showing the earliest initiation, longest duration, and highest peak values. Peak flow occurred between 12:30–13:00 in spring and 13:30–14:00 in autumn. Nocturnal sap flow was weak, essentially stopping in spring and autumn, but continuing weakly at night in summer to replenish tree water loss from intense daytime transpiration.

[Figure 1: see original paper] The diurnal variation of sample tree sap flow velocity in different months and consecutive daily variation in different seasons

3.2 Correlation Between Seasonal Sap Flow Instantaneous Rate and Meteorological Factors

Due to geographical constraints at the experimental site, soil water content below 150 cm showed minimal daily variation and insignificant seasonal changes. Correlation between sap flow instantaneous rate and soil water content was not significant. Sap flow rate diurnal variation was primarily controlled by meteorological factors: actual vapor pressure, vapor pressure deficit, air relative humidity, and air temperature.

Correlation analysis was conducted between 30-minute average sap flow velocity data from sunny days and corresponding meteorological data throughout the growing season. Results showed sap flow rate was significantly positively correlated with wind speed, net radiation, vapor pressure deficit, and air temperature, but extremely significantly negatively correlated with actual vapor pressure and air humidity.

In spring, the main factors affecting sap flow rate diurnal variation were vapor pressure deficit, air temperature, and net radiation, with wind speed having minimal influence. In summer, the key factors were air humidity, air temperature, and net radiation, again with minimal wind speed influence. In autumn, vapor pressure deficit and air temperature were primary factors, with actual vapor pressure having the smallest influence on instantaneous sap flow rate changes.

Throughout the growing season, net radiation, vapor pressure deficit, and air temperature were the key factors causing instantaneous sap flow rate variations.

[Figure 2: see original paper] Relationship between sap flow velocity of *H. ammodendron* and main meteorological factors

Correlation and path coefficients between 30-minute average sap flow velocity and meteorological factors in different seasons

3.3 Correlation Between Daily Average Sap Flow Rate and Environmental Factors

While instantaneous sap flow rate changes are mainly affected by meteorological factors, larger temporal scale variations are influenced by both meteorological and soil environmental factors, as well as the tree' s own physiological structure. Soil moisture conditions and soil temperature have minimal impact on sap flow rate variations at daily time scales, but show significant correlations with daily average sap flow rate at seasonal time scales.

Analysis of daily average soil moisture content during the growing season revealed that at 30 cm depth, soil moisture gradually decreased, while at 70 cm and 110 cm depths, soil moisture gradually increased. Surface soil moisture was lower than deeper layers. As water infiltrated and evapotranspiration progressed, differences in soil moisture content among different depths gradually narrowed. Affected by snowmelt and rainfall, surface soil moisture at 30 cm showed a second peak in autumn.

The daily average soil moisture content at 110 cm depth showed a trend of first increasing then decreasing throughout the growing season, consistent with the variation trend of *H. ammodendron* daily average sap flow rate. In spring and autumn, soil moisture at 110 cm was extremely significantly positively correlated with sap flow rate, while correlation was not significant in summer.

Based on 152 days of observation data during the growing season, correlation analysis between daily average sap flow rate and meteorological and soil moisture factors showed that *H. ammodendron* daily average sap flow rate was extremely significantly positively correlated with net radiation, actual vapor pressure, vapor pressure deficit, and soil temperature, but extremely significantly negatively correlated with air humidity. Correlation with wind speed was not significant.

The key factors for seasonal sap flow rate variation were net radiation, air temperature, soil moisture content, and soil temperature.

Correlation and path coefficients between daily average sap flow rate and main environmental factors during the growing season

Correlation coefficients between daily average sap flow rate and soil moisture content at different depths

3.4 Environmental Factor Influence Models for Sap Flow Rate

Based on systematic long-term observations of *H. ammodendron* sap flow velocity, stepwise regression was performed using instantaneous meteorological data as independent variables to obtain regression equations for sap flow velocity and meteorological factors in different seasons. Using daily average sap flow velocity during the growing season as the dependent variable and daily average meteorological and soil factor data as independent variables, stepwise regression analysis yielded regression equations for sap flow velocity and environmental factors.

Seasonal instantaneous rate regression equations:

$$V_s = 0.144 + 0.001TBB - 0.005RH + 0.212e \quad (R^2 = 0.762)$$

$$V_s = -0.527 + 0.001TBB - 0.221e - 0.208VPD + 0.053Ta \quad (R^2 = 0.794)$$

$$V_s = -0.026 + 0.0003TBB + 0.080VPD + 0.016Ta \quad (R^2 = 0.838)$$

Growing season daily average rate regression equation:

$$V_s = -0.194 + 0.009Ta + 0.001TBB - 0.036VPD + 0.022RH + 0.005Ts \quad (R^2 = 0.750)$$

Where V_s is sap flow velocity (dm/h), TBB is net radiation (W/m²), e is vapor pressure (kPa), RH is relative humidity (%), VPD is vapor pressure deficit (kPa), Ta is air temperature (°C), and Ts is soil temperature (°C).

All F-tests for the equations reached significance at the 0.001 level, with multiple correlation coefficients (R^2) above 0.75, indicating good fit. The seasonal water consumption models had slightly lower R^2 values than diurnal models because diurnal models used data from consecutive sunny days unaffected by weather differences, while seasonal models included rainy weather data.

3.5 Seasonal Transpiration Water Consumption Characteristics of *H. ammodendron* Stands

Using TDP data and scaling methods, stand water consumption and transpiration totals were calculated for different periods during the growing season. Stand daily transpiration showed an increasing then decreasing trend throughout the growing season, consistent with the variation pattern of soil moisture content at 110 cm depth.

Daily transpiration was 0.21 mm/d in early May, peaked in mid-June, remained at peak for about 40 days, then declined to 0.10 mm/d by late September. In the 20 m × 20 m sample plot, total water consumption was 4,428.924 L in May, 5,736.361 L in June, 6,911.580 L in July, 5,511.651 L in August, and 2,905.286 L in September. Over the entire 152-day study period, total transpiration reached 53.35 mm, with average daily transpiration of 0.35 mm/d.

Changes of water consumption and transpiration during different periods in the growing season

[Figure 4: see original paper] Dynamic changes of stand daily transpiration and soil moisture content at 110 cm depth during the growing season

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4. Discussion and Conclusions

The diurnal sap flow velocity curve of *H. ammodendron* was primarily unimodal, occasionally bimodal in summer, with significant seasonal differences in pattern and peak values. Summer transpiration rates were greater than spring and autumn, consistent with findings from Cao (2011) and Sun et al. (2010). Nocturnal sap flow was weak with significant day-night differences. In summer, sap flow initiation and peak occurrence were earlier, demonstrating clear diurnal rhythms and significant seasonal variation.

However, some studies found different patterns. Sun et al. (2010) reported that in July, *H. ammodendron* sap flow showed insignificant diurnal variation with a flat, multi-peak pattern and decreasing daily flow, which differs from our results. This discrepancy may be attributed to different soil water conditions (their study area had groundwater depth >16 m, while ours had shallow groundwater at 3–5 m) and different sap flow monitoring methods. *H. ammodendron* may directly utilize shallow groundwater in our study area. Different water stress conditions lead to different sap flow patterns, yet trees can grow normally under all conditions, indicating strong drought adaptation capacity.

Instantaneous sap flow rate changes were mainly affected by net radiation, air temperature, and vapor pressure deficit, with seasonal differences in responses. Daily average sap flow rate changes were primarily influenced by net radiation and air temperature, showing extremely significant positive correlations with actual vapor pressure, soil moisture content, and soil temperature, and extremely significant negative correlations with air humidity. Wind speed correlation was not significant.

These results confirm that different temporal and spatial scales have different dominant factors affecting tree transpiration, demonstrating the complexity and relativity of transpiration regulation mechanisms. Multiple linear regression models for different seasons all had R^2 values above 0.75, effectively simulating sap flow responses to meteorological factors. The growing season daily average model ($R^2 = 0.75$) could simulate seasonal sap flow patterns but reduced data samples and simulation accuracy by ignoring daily weather fluctuations.

This study used TDP to measure individual tree transpiration and scaled up to estimate stand-level transpiration. In the 20 m × 20 m plot, stand average daily transpiration was 0.35 mm/d, with total transpiration of 53.35 mm during the study period. Despite high temperatures, low rainfall, and strong evaporation at the southern margin of the Gurbantunggut Desert, *H. ammodendron* communities maintained low transpiration rates, demonstrating strong ecological adaptability to harsh desert environments.

References

[1] Study on summer stem sap flux of *Quercus liaotungensis* in Taiyue Mountain, Shanxi. *Journal of Forestry*, 2004, 40(2): 174–177.

[2] Main methods for measuring tree transpiration. *Chinese Journal of Ecology*, 2005, 24(1): 88–96.

[3] Study on spatiotemporal variation characteristics of transpiration rate of different shrub species and their influencing factors. *Journal of Soil and Water Conservation*, 2005, 19(3): 184–187.

[4] Baker J M, Van Bavel C H M. Measurement of mass flow of water in the stems of herbaceous plants. *Plant, Cell & Environment*, 1987, 10(9): 777–782.

[5] Lundblad M, Lagergrén F, Lindroth A. Evaluation of heat balance and heat dissipation methods for sapflow measurements in pine and spruce. *Annals of Forest Sciences*, 2001, 58(6): 625–638.

[6] Granier A. A new method of sap flow measurement in tree stems. *Annales des Sciences Forestières*, 1985, 42(2): 193–200.

[7] Granier A. Sap flow measurements in Douglas-fir tree trunks by means of a new thermal method. *Annales des Sciences Forestières*, 1987, 44(1): 1–14.

[8] Smith D M, Allen S J. Measurement of sap flow in plant stems. *Journal of Experimental Botany*, 1996, 47(12): 1833–1844.

[9] Lu P, Urban L, Zhao P. Granier' s thermal dissipation probe (TDP) method for measuring sap flow in trees: Theory and practice. *Acta Botanica Sinica*, 2004, 46(6): 631–646.

[10] Relationship between transpiration intensity and ecological factors in secondary oak forest. *Journal of Plant Resources and Environment*, 2000, 9(2): 27–29.

[11] Transpiration water consumption characteristics of *Haloxylon ammodendron* under non-irrigation conditions in the southern margin of Gurbantunggut Desert. *Arid Land Geography*, 2013, 36(2): 292–302.

[12] Relationship between stem sap flow and ecological factors of *Haloxylon ammodendron* in desert areas. *Acta Ecologica Sinica*, 2007, 27(5): 1826–1837.

[13] Transpiration water consumption 规律 of *Haloxylon ammodendron* in the hinterland of Taklimakan Desert. *Acta Ecologica Sinica*, 2008, 28(8): 3713-3720.

[14] Spatiotemporal variation characteristics of soil moisture in fixed dunes in the southern margin of Gurbantunggut Desert. *Acta Ecologica Sinica*, 2016, 53(1): 117-126.

[15] Meinzer F C, Goldstein G, Andrade J L. Regulation of water flux through tropical forest canopy trees: do universal rules apply? *Tree Physiology*, 2001, 21(1): 19-26.

[16] McDowell N G, White S, Pockman W T. Transpiration and stomatal conductance across a steep climate gradient in the southern Rocky Mountains. *Ecohydrology*, 2008, 1(3): 193-204.

[17] Seasonal variation of whole-tree transpiration of *Cyclobalanopsis glauca* in karst areas. *Chinese Journal of Applied Ecology*, 2009, 20(2): 256-264.

[18] Study on transpiration characteristics and environmental response mechanisms of several desert plants. *Research of Soil and Water Conservation*, 2007, 14(1): 184-186.

[19] Effects of *Cistanche* harvesting pits on soil moisture in *Haloxylon ammodendron* rhizosphere. *Forest Research*, 2005, 18(3): 315-320.

[20] Relationship between stem sap flow variation of moso bamboo and meteorological factors. *Journal of Forestry*, 2011, 47(7): 73-81.

[21] Study on sap flow variation patterns in peach roots and stems under different water conditions. *Transactions of the Chinese Society of Agricultural Engineering*, 2001, 17(4): 34-38.

[22] Stem sap flow and water consumption of native *Haloxylon ammodendron* in Gurbantunggut Desert. *Acta Ecologica Sinica*, 2010, 30(24): 6901-6909.

[23] Study on transpiration water consumption of triploid *Populus tomentosa* individuals and stands based on thermal diffusion technology. *Acta Ecologica Sinica*, 2016, 36(10): 2945-2953.

Note: Figure translations are in progress. See original paper for figures.