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Scaling Up Sap Flow Measurements from the Stem Scale to the Individual Scale for Multibranched *Caragana Korshinskii* on the Chinese Loess Plateau

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Abstract: The traditional heat balance method for measuring plant sap flow (SF) becomes troublesome and uneconomic for multibranched shrub species if all their stems are used for the measurement. The objectives of this study were to explore specific relationships between stem-scale SF and plant morphological traits and then to scale up SF measurements from the stem scale to the individual scale for *Caragana korshinskii* Kom., a dominant shrub species on the Chinese Loess Plateau. Sap flow was measured for twenty-one stems from three representative individuals from July to September 2018 during the rainy season. The results indicated that the stem-scale SF in *C. korshinskii* presented a positive linear correlation with the stem base diameter (SBD), stem length (SL), primary branch numbers in the stem (PBN), and estimated stem biomass (W). The SBD-based statistical models performed well in estimating the stem-scale SF, with an R^2 value of 0.9726 and root mean squared error (RMSE) of 2.5389 g h⁻¹. Over the canopy projection area, the individual-scale transpiration flows for the three selected *C. korshinskii* were 1.91, 1.10, and 1.59 mm·d⁻¹. In addition, stem-scale SF was positively and linearly correlated with air temperature, photosynthetically active radiation, vapor pressure deficit, reference crop evapotranspiration, and variable transpiration. This study sheds light on morphological and meteorological influences on stem-scale SF and has made contributes to the accurate and rapid estimation of the plant sap flow from easily available morphological traits for multibranched shrub species in semiarid regions. Limitations, however, may exist for the established model when it is used to estimate SF of *C. korshinskii* during the water-limited dry season. Our study deserves further exploration of a more general model to have a better estimation of SF for *C. korshinskii* in both dry and rainy seasons.

Keywords: sap flow; morphological traits; meteorological factor; stem scale; individual scale

1. Introduction

Soil water is a key factor that limits vegetation growth in arid and semiarid areas. An understanding of plant water use patterns of vegetation could contribute to the effective management of limited water resources [1]. Sap flow (SF) is the water flux across a given section of stem diameter at a given period and is an important component of the water balance in forest ecosystems [2–4]. Sap flow can reflect water transportation and water utilization characteristics in plants. The heat balance technique was used to determine sap flow rate (g·h⁻¹) and sap flux density (m³·m⁻²·h⁻¹) [5]. The majority of

methods measuring sap flux density utilize the heat pulse (HP) method, which only measures heat velocity ($\text{m}\cdot\text{s}^{-1}$). The heat pulse method is limited to plants with stem diameters large enough to accommodate the physical insertion of probes, and it also normally causes sap velocities to vary with radial depth due to differences in tissue structure and xylem function in woody species [6]. However, there are also continuous heat sap flux density methods, including the heat pulse and thermal diffusion methods [5,7,8].

Currently, these methods are rarely used to determine shrub SF because the studied plants are always branched and have no obvious trunks [9,10]. A probe would need to be inserted into the base of the plants close to the main root, and thus, the shrub growth would be affected [10]. This method can accurately measure SF for each branch without damaging the growth of shrubs [11]. However, due to high equipment costs, only part of the stem is used to measure SF, thus making it difficult to estimate SF for the entire plant. To our knowledge, many scholars have used the heat balance method to study the SF characteristics of shrubs at the stem scale [8,12–16], but studies on how to scale up SF from the stem scale to the individual scale are still underrepresented in the literature [12,17–19]. For example, Chabot et al. [17] used stem leaf area and sugarcane leaf area to estimate the SF of individual sugarcane plants. Similar statistical estimation models were also established by Huang and Zhang [12] for *Caragana korshinskii* Kom. and *Artemisia ordosica* Krasch and by Zha et al. [19] for *Artemisia ordosica*. In addition, Yue et al. [18] estimated the mean daily stand transpiration of *C. korshinskii* using established models for stem leaf area, the plot-scale total leaf area, land surface area, and SF. These studies, however, only used the stem leaf area and individual leaf area to estimate SF and did not consider other morphological traits, such as stem length, diameter, and biomass.

The Chinese Loess Plateau is a region that has experienced severe soil erosion, vegetation degradation, and soil desertification [20,21]. The national Grain for Green project was initiated in 1999 to control soil erosion and systemic degradation [22,23]. Most of the traditional farmlands on steep slopes were converted to pasture grasslands, shrublands, and forestlands during this process [24,25]. The runoff reduction was notable, reaching more than 50% after forestation in the semihumid and semiarid regions of China [26]. *Caragana korshinskii* was one of the main introduced shrub species, and understanding its transpiration characteristics is necessary to support its population development on the water-limited Loess Plateau. In this study, a field experiment was conducted in the Dingjia Mountains watershed in a typical semiarid region of the Loess Plateau. The SF of *C. korshinskii* was measured using the stem heat balance method (SHB), and relevant environmental and morphological factors were monitored simultaneously. The main objectives of this study were: (1) to explore the specific relationships between stem-scale SF and plant morphological traits and meteorological factors; and (2) to scale up the SF of *C. korshinskii* from the stem scale to the individual scale.

2. Materials and Methods

2.1. Study Area

The experiment was conducted in the Dingjia Mountains watershed ($35^{\circ}43'30''$ – $35^{\circ}44'10''$ N, $104^{\circ}33'40''$ – $104^{\circ}34'10''$ E) of Dingxi city, a typical shallow gully on the Loess Plateau (Figure 1). This area consists of perennial artificial bush and has a semiarid climate; the mean annual precipitation is 386 mm, and most of the rain falls during July and September. The annual potential evaporation is approximately 1439 mm. The mean annual temperature is 6.8°C , with the lowest mean value of -7.9°C in January and the highest mean value of 38.5°C in July. The soil thickness varies from 40 to 60 m [25]. The soil type is mainly loess soil that has low fertility and is vulnerable to erosion. The predominant land use types in the catchment are rain-fed farmland, sparse native grassland, pasture grassland, shrubland, forestland, and fallow cropland. The natural vegetation in the study area consists of sparse grass with shallow roots, such as *Stipa bungeana* Trin., *Leymus secalinus* (Georgi) Tzvel., and *Heteropappus altaicus* (Willd.) Novopokr. var. The introduced vegetation types include

Caragana korshinskii Kom., *Pinus tabulaeformis* Carr. var., *Platycladus orientalis* (L.) Franco, and *Amygdalus davidiana* (Carrière) de Vos ex Henry var.

Figure 1. Location of the study area (a) and photos of the devices used to measure sap flow in the stems (b, c).

The dynamics of the meteorological variables in the study site are shown in Figure 2. Altogether, 29 rain events occurred during the study period, and the total precipitation (P) was 177.8 mm. The average rainfall was $2.82 \text{ mm}\cdot\text{d}^{-1}$, with the maximum rainfall (46.0 mm) occurring on August 21 and the minimum rainfall (0.2 mm) occurring on September 16 and 17. The air temperature (T) averaged 17.9°C , ranging from 6.7 to 23.5°C . The photosynthetically active radiation (PAR) readings averaged $156.82 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, ranging from 27.3 to $264.3 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Both T and PAR tended to decrease from July to September during the study period.

Figure 2. Daily air temperature (T), photosynthetically active radiation (PAR), and precipitation (P) during the study period.

2.2. Measurement of Sap Flow

Three robust 33-year-old *C. korshinskii* spaced 7.0 to 8.5 m apart were selected on a small slope with a steepness of approximately 21° [27]. The number of branches for the three sample shrubs was 60, 45, and 53, respectively, and they were divided into five groups according to different basal diameters (9.00–10.00, 10.00–13.00, 13.00–17.00, 17.00–19.00, and 19.00–21.00 mm). Then, 16 branches with good growth status and representative rows were selected for measurement. The height, canopy, stem base diameter (SBD), stem length (SL), and primary branch numbers in the stems (PBN) of the sample branches were investigated (Table 1). The SHB [28] was used to measure SF with the Dynagage Flow 32-1K system (Dynamax, Houston, TX, USA) from July 28 to September 28, 2018. Sixteen gauges that could measure SF for stem diameters ranging from 9 to 21 mm were separately installed on 16 branches selected from the three *C. korshinskii* plants. Smooth G4 mix oil was used to maintain a close connection and prevent adhesion between the gauges and stems. To reduce the influences of solar radiation, air temperature, and humidity on the performance of the gauges, three layers of aluminum foil were coated on the outer layer of the gauges. The data transmission cables of the gauges were connected with the corresponding interface of the data collector (CR1000), and the power cord was connected with a 12 v battery with solar panels. During the period of measurement, five branches were replaced with new branches due to abnormal data (Table 1). Once the abnormal data was eliminated, the normal data were analyzed, which came from 21 stems (including five new stems). The stem biomass was estimated using a statistical model (Equation (1)) that was established for the same species in a similar semiarid area on the Loess Plateau [29].

$$W = \beta_1 \times (D^2 \times H)^{\beta_2}, \quad (1)$$

where W is the estimated stem biomass, β_1 and β_2 are estimated parameters of 0.0059 and 0.9686, respectively, D is the base diameter, and H is the stem length.

Table 1. Morphological traits of the twenty-one stems used for the sap flow (SF) measurements for *Caragana korshinskii* Kom.

Shrub No.	Stem No.	PBN	SL (cm)	SBD (mm)	W (g)	Height (cm)	Canopy Size (cm)
1	1	5	153	10.0	77.8	310.0	410 × 374
	2	6	215	9.7	103.5		
	3	12	175	11.2	115.9		
	4	9	195	11.5	84.4		
	5	7	240	13.4	104.9		
	6	13	232	16.6	71.3		
	7	7	260	19.4	111.6		
2	8	12	195	10.8	91.9	280.0	340 × 340
	9	8	155	10.3	99.7		
	10	11	157	10.7	92.5		
	11	12	195	13.4	128.9		
	12	14	228	16.6	213.7		
	13	25	270	20.0	174.7		
3	14	10	233	9.4	204.7	320.0	350 × 330
	15	14	150	9.6	313.1		
	16	5	160	11.1	306.4		
	17	8	150	11.0	334.1		
	18	7	232	13.3	281.5		
	19	11	233	17.1	473.3		
	20	4	180	17.8	521.8		
	21	14	240	20.3	476.4		

Abbreviations: PBN, primary branch numbers in the stem; SL, stem length; SBD, stem base diameter; W, estimated stem biomass. Stem numbers 1, 2, 5, 9, and 12 were replaced with numbers 2, 4, 6, 10, and 13.

2.3. Soil Water Content Measurement

Soil water contents (SWC) were measured 10 times at depths of up to 1.8 m in 20-cm increments below the forest floor in each shrub using a time domain reflectometry (TDR) moisture measurement system (TRIME, IMKO Micromodultechnik, Ettlingen, Germany). Two Tecanat[®] plastic tubes 2 m in length and 42 mm in internal diameter were permanently placed in each shrub (approximately 30 cm away from the roots of the shrub) for repetitive TDR measurements. Measurements were made once per day from 16 September to 25 September.

2.4. Measurement of Meteorological Variables

Meteorological variables, including the solar radiation (R_s , $\text{MJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$), photosynthetically active radiation (PAR, $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), mean air temperature (T_{mean} , $^{\circ}\text{C}$), maximum air temperature (T_{max} , $^{\circ}\text{C}$), minimum air temperature (T_{min} , $^{\circ}\text{C}$), relative humidity (RH, %), precipitation (P, mm), and wind velocity (μ , $\text{m}\cdot\text{s}^{-1}$), were obtained from an automated meteorological station approximately 1.2 km away from the study site.

The vapor pressure deficit (VPD, kPa) was then calculated from T and RH following Equations (2) and (3) given by Campbell and Norman [30]. Additionally, considering that the influence of microclimate on SF means that vapor pressure accounts for more than two-thirds of total transpiration and solar radiation (R_s) accounts for one-third of total transpiration, the variable of transpiration (VT, $\text{kPa}(\text{W}\cdot\text{m}^{-2})^{1/2}$) was calculated from the VPD and R_s (Equation (4)) according to previous studies [10,31,32].

$$e_s = 0.611 \times \text{EXP}\left(\frac{17.502 \times T}{T + 240.97}\right), \quad (2)$$

$$\text{VPD} = e_s - \frac{e_s \times \text{RH}}{100}, \quad (3)$$

$$\text{VT} = \text{VPD} \times (R_s)^{\frac{1}{2}}, \quad (4)$$

Daily reference crop evapotranspiration (ET_0 , $\text{mm}\cdot\text{d}^{-1}$) was calculated using the Food and Agriculture Organization of the United Nations (FAO) Penman–Monteith Equation (5) [33]:

$$\text{ET}_0 = \frac{0.408 \times \Delta(R_n - G) + \gamma\left(\frac{900}{T + 273}\right)\mu_2 - (e_s - e_a)}{\Delta + \gamma(1 + 0.34\mu_2)}, \quad (5)$$

where Δ is the vapor pressure curve slope ($\text{kPa}\cdot^{\circ}\text{C}^{-1}$), R_n is the net radiation at the plant surface ($\text{MJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$), G is the soil heat flux density ($\text{MJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$), γ is a psychrometric constant ($\text{kPa}\cdot^{\circ}\text{C}^{-1}$), T is the mean daily air temperature at 2 m height ($^{\circ}\text{C}$), μ_2 is the wind speed at 2 m height ($\text{m}\cdot\text{s}^{-1}$), e_s is the saturation vapor pressure (kPa), and e_a is the actual vapor pressure (kPa). As the magnitude of the daily averaged soil heat flux density beneath the vegetation is relatively small, it can be ignored; therefore, $G \approx 0$ [9].

2.5. Model Establishment and Validation

The measured data of plant morphology and SF were divided into two parts. Seventy percent of the data (i.e., 14 stems) were used to build the stem-scale SF estimation models, and the remaining 30% of the data (i.e., 7 stems) were used to validate the model. The performance of the model was evaluated using the coefficient of determination (R^2), root mean squared error (RMSE), and mean error (ME), which were calculated as follows [34]:

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y}_i)^2}, \quad (6)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{n}}, \quad (7)$$

$$\text{ME} = \frac{\sum_{i=1}^n (y_i - \hat{y}_i)}{n}, \quad (8)$$

where n is the number of stems measured, y_i is the measured value of SF, $\hat{y}_i$ is an estimated value of SF, and $\bar{y}_i$ is the mean of the measured values.

2.6. Data Analysis

The stem heat balance method was described in detail by Kigalu [35], which was calculated briefly as follows:

$$Q_f = P_{in} - Q_{cd} - Q_r + Q_s, \quad (9)$$

$$F = \frac{(P_{in} - Q_{cd} - Q_r + Q_s)}{(C_s \times dT_{sap})}, \quad (10)$$

$$dT_{sap} = \frac{(dT_a + dT_b)}{2}, \quad (11)$$

where Q_f is the amount of heat (W) transported in the moving sap, P_{in} is the heater power input (W), Q_{cd} is the heat conduction loss along the stem up- and downstream (W), Q_r is the radial heat conduction loss (W), Q_s is the heat stored in the stem section (W), F is sap flow velocity ($\text{kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$), C_s is the specific heat capacity of the sap or water ($4.186 \text{ J} \cdot \text{g}^{-1} \cdot ^\circ\text{C}^{-1}$), dT_{sap} is the mean temperature between the heater and the stem section ($^\circ\text{C}$), and dT_a and dT_b are temperature differentials of the sap up- and downstream measured by thermocouples a and b, respectively.

Descriptive statistics were compiled for the plant morphological characteristics (height, canopy size, PBN, SL, SBD, and W). We analyzed the hysteresis effect based on the relationship between the 0.5 h average SF of 21 branches and the 0.5 h meteorological factors (T, VPD, VT, PAR, ET_0). The average SF per hour and the average value of meteorological factors during the day were used to analyze the relationship between SF and meteorological factors. Linear regression was used to quantify the specific relationships between stem-scale SF and the plant morphological traits for the three individual plants. Origin 9.0 software for Windows (Origin Software Inc., Fairview, TX, USA) and SPSS 21.0 software for Windows (SPSS Inc., Chicago, IL, USA) were used to draw the figures and for the statistical analyses, respectively.

3. Results and Discussion

3.1. Diurnal Variations in Sap Flow

Sap flow had a sharp increase near 08:00, peaked at 14:30, and then decreased gradually down to the same level that was recorded before 08:00. The peak time of T and VPD were nearly same, and both lagged behind that of SF by 0.5 h (Figure 3a,c). The sharp increase of SF in the morning lagged behind in PAR by 2.0 h, and the peak time of SF lagged behind in PAR by 2.5 h (Figure 3b). The increase of SF in the morning was similar to that of VT, and the decrease of SF in the afternoon slightly lagged behind the decrease of VT. Sap flow then decreased to remain stable, lagging behind VT by 1.0 h (Figure 3d). The diurnal lag effects between SF and the meteorological factors and the diurnal hysteresis loops of SF are plotted in Figure 4. The direction of change with time tracked clockwise hysteresis for VPD, and the variation in VPD lagged behind that in SF (Figure 4c). The averaged relationship between SF with PAR and VT in a day revealed a hysteresis loop with a counter-clockwise rotation (Figure 4b,d), indicating that the variation in SF lagged behind those in PAR and VT.

Figure 3. Diurnal variations in SF, (a) air temperature (T), (b) photosynthetically active radiation (PAR), (c) vapor pressure deficit (VPD), and (d) variable of transpiration (VT) for the whole measuring period.

Figure 4. Hysteresis loops between the 0.5-hourly mean SF and (a) air temperature (T), (b) photosynthetically active radiation (PAR), (c) vapor pressure deficit (VPD), and (d) variable of transpiration (VT). Note that the arrows on the plots denote the sap flow change direction with time.

The observed hysteresis between SF, radiation, and VPD was consistent with other studies [9,36–38]. Note that SF sometimes declines with increasing VPD and solar radiation in the short term, suggesting the effect of stomatal regulation on transpiration [39]. In the early morning and late-night periods, SF apparently increased at low VPD levels. However, it has been pointed out that a time lag usually occurs at this time scale, and the lag is no longer obvious when scaled up to the day scale or longer time scales [40]. In this study, it seemed that at the diurnal scale, *C. korshinskii* had the maximum rate of SF when the VPD, PAR, and T were not particularly high. On the other hand,

favorable meteorological conditions for transpiration (i.e., higher PAR, VPD, and T levels) prevented further increases in SF. Therefore, the diurnal hysteresis between the peaks of SF and the meteorological variables was a self-protection mechanism to avoid *C. korshinskii* overlaps with peak SF times and peak meteorological variables that prevent excessive water extraction from the stems. This mechanism prevented xylem vessel embolism, causing the collapse of the hydrological conductive system of the xylem, and this response is also a conservative water use strategy of *C. korshinskii* for meteorological drivers [41].

3.2. Effect of Meteorological Factors on SF

Several studies have reported a close relationship between SWC and SF for a variety of tree species [16,19,40]. The results of regression analysis between SWC and SF are shown in Figure A1. However, we observed that there was no close relation between them in our study, and this result agrees well with the findings of Ma et al. [41] and Hortal et al. [42]. Ford et al. [43] concluded that tree transpiration is only limited by SWC for most forests when soil moisture is severely deficient. In this study, the experimental periods were mainly restricted in the humid, rainy seasons. The observed poor correlation between SF and SWC suggests that SWC in the 0–180 cm soil depth range was not a limiting factor on SF. It also could be attributed to that fact that *C. korshinskii* used SWC from the soil layer that is deeper than 180 cm [44]; however, this was not monitored in our study. Further study is justified to clarify the correlation between SF and deep SWC in both dry and rainy seasons.

Schultz et al. [45] considered that the hydrological process of tree transpiration is dominated by the evaporative demand and available energy, and it is often limited by water availability. Several studies have indicated that VPD, T, and radiation are the most important environmental factors controlling SF, especially VPD and radiation [32,46,47]. Therefore, we used PAR as a representative of the radiation factor in this study. Tie et al. [9] considered that radiation factor was the key environmental factor controlling SF, and found that the whole levels of VPD, T, PAR, and sap flux density were all significantly higher under the high radiation condition ($\text{PAR} > 231.48 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) than under the low radiation condition ($\text{PAR} < 231.48 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$). To remove the effect of PAR on the VPD component, we normalized SF with PAR to further analyze the relationship between VPD and SF residuals. The residual analysis showed linear and positive relationships between SF and VPD (Figure A2).

The meteorological variables showed a decreasing tendency during the measuring period and shared similar varying tendencies with SF (Figure A3). The regression analysis further indicated that all of the meteorological variables (T, PAR, VPD, VT, and ET_0) were linearly and positively correlated with SF (Figure 5). The different R^2 values in the regression models in Figure 5 indicate that meteorological factors had a variable control on SF. Specifically, SF had the weakest correlation with T (Figure 5) but had the strongest correlation with VPD (Figure 5).

These results suggest quite different controls of environmental factors on SF. In our study, VPD and ET_0 were the two main meteorological factors affecting SF, which were similar to those of other studies [11,44]. Our data indicated that VPD, VT, and ET_0 explained more of the variations in SF than T and PAR, and VPD was more closely correlated with SF than PAR and T. Plant transpiration becomes stronger with increasing VPD levels, which also has a direct influence on stem SF. Similarly, VT is determined by VPD and R_s . The effects of R_s on transpiration water consumption by plants include temperature and PAR. As the intensity of solar radiation increases, the temperature on the surfaces of plant leaves will also increase. Additionally, visible light controls the opening and closing of stomata, and in general, the stomata of most *C. korshinskii* plants close in the absence of light [11]. Photosynthetically active radiation can be a good representative radiation factor in the analysis of SF because PAR principally reflects the part of radiation used for photosynthesis, and SF is closely related to photosynthetic processes [33]. The observed diurnal variations in SF were mainly due to the large solar radiation intensity and temperature differences between day and night in semiarid areas [12].

Figure 5. Regression relations between daily SF and (a) air temperature (T), (b) photosynthetically active radiation (PAR), (c) vapor pressure deficit (VPD), (d) variable of transpiration (VT), and (e) reference evapotranspiration (ET₀).

3.3. Effect of Morphological Traits on Stem-Scale SF

Morphology is an important factor affecting SF in plant trunks. In our study, we observed that the stem-scale SF differed notably with the SBD despite sharing the same diurnal variation (Figure A4). Summarizing the different categories of plant morphological variables (Figure 6), the stem-scale SFs were significantly largest ($p < 0.05$) in the largest levels of PBN (18–25), SL (230–270 cm), SBD (17–21 mm), and W (350–550 g), followed by those in the middle levels of PBN (11–18), SL (190–230 cm), SBD (13–17 mm), and W (200–350 g), and lastly followed by those in the smallest levels of PBN (4–11), SL (150–190 cm), SBD (9–11 mm), and W (50–200 g). The regression analysis further indicated that the stem-scale SF of *C. korshinskii* had significantly positive linear correlations with PBN (Figure 7a), SL (Figure 7b), SBD (Figure 7c), and W (Figure 7d) ($p < 0.001$).

The increase of SF during the morning was stronger at larger SBD and had an apparent single peak diurnal curve (Figure 7), suggesting that there was no noon depression in any stem size. This result was similar with the finding in *C. korshinskii* and *A. ordosica* reported by Xia et al. [48], Huang et al. [12], and Chen et al. [32]. Sapwood area is considered an important metric for scaling up individual plant water consumption to stand water consumption [38,49,50]; therefore, knowing that plants with different stem diameters have different SF rates is especially important because caution should be taken when using branch and basal trunk sap flow measurements to estimate whole-plant water capacity [51].

Figure 6. Comparison of the average stem-scale sap flow (SF) for different categories of (a) primary branch numbers (PBN), (b) stem length (SL), (c) stem base diameter (SBD), and (d) estimated stem biomass (W). The different lower-case letters in the figure indicate significant differences at $p < 0.05$ using the least significant difference (LSD) method.

Figure 7. Regression relationships between the stem-scale SF and stem morphological traits.

3.4. Established Models for Estimating Stem-Scale SF and Its Validation

The established multivariate linear regression models between stem-scale SF and stem morphological variables are shown in Table 2. The results show that the SBD-based model (No. 10) had a satisfactory R^2 value (0.8046), and most importantly, all of its regression coefficients were statistically significant ($p < 0.05$). The validation dataset further indicated good agreement between the measured and estimated SF values, as indicated by the high R^2 value (0.9726) and low RMSE (2.5389) and ME (6.4460) values (Figure 8). We further scaled up SF from the stem scale to the individual scale using the established model and the measured SBD data for all the stems. The results indicated that the individual-scale SF averaged 1111.7, 528.7, and 789.9 $\text{g}\cdot\text{h}^{-1}$ for the three *C. korshinskii* plants during the intensive rainfall study period. Over the canopy projection area, the average water use of *C. korshinskii* was 1.91, 1.10, and 1.59 $\text{mm}\cdot\text{d}^{-1}$ for the three *C. korshinskii* plants (Table 3).

Our results were comparable with previous findings. Huang et al. [52] reported that the daily transpiration rates of *C. korshinskii* and *A. ordosica* communities were 0.36 and 0.28 $\text{mm}\cdot\text{d}^{-1}$, respectively, during the growing season (April–October) in the central part of Western China. The higher water use in our study might be attributed to the stronger growth period of *C. korshinskii* and the larger rainfall input (177.8 mm), which differed from the previous study (125.2–127.4 mm). Zhang et al. [53] found that stand transpiration of black locust averaged 0.49, 0.33, and 0.32 $\text{mm}\cdot\text{d}^{-1}$ during the growing seasons, respectively, with maximum values of 1.07, 0.74, and 0.90 $\text{mm}\cdot\text{d}^{-1}$ for the whole measuring period in Shanxi Province. McJannet et al. [54] reported that the canopy transpiration rates ranged from 2.2 to 3.8 $\text{mm}\cdot\text{d}^{-1}$ in North Queensland, and canopy transpiration rates of conifer stand ranged from 0.4 to 1.5 $\text{mm}\cdot\text{d}^{-1}$, with a mean value of 0.9 $\text{mm}\cdot\text{d}^{-1}$ [55]. The SF value predicted in our study (1.10–1.91 $\text{mm}\cdot\text{d}^{-1}$) is comparable to that in previous studies. Estimating transpiration water use for individual trees is usually achieved by multiplying the average stand SF by the total sapwood area of the stand [13,17–19]. Shrubs, however, typically have many branches, and their basal diameter is small. Zha et al. [19] estimated stem-scale SF for *A. ordosica* by measuring the SF per leaf area, total leaf area per stem, and the number of stems. The authors then determined the transpiration amount per stand by the stem-scale SF and the leaf area index of shrubs. Huang et al. [13] calculated plant canopy transpiration for *C. korshinskii* and *A. ordosica* using the same method. In this study, we established a regression model between stem SF and the SBD of *C. korshinskii*. The established SF estimation model in our study may have limitations if the model is used to estimate SF of *C. korshinskii* in the water-limited dry season. However, this method has several advantages—it is relatively easy to use, continuous monitoring can occur over a period of time that is as short as necessary, the measurements do not modify the environment, and the method is nondestructive to the plants [17]. Additionally, the SF of branches with different base diameters can be accurately measured. Combined with the growth of branches, we can also calculate the water use efficiency and water use strategy of vegetation. In addition, plants with a low stem porosity, high transpiration rate, and multiple lateral branches, such as *A. ordosica* and *C. korshinskii*, are particularly suitable for the application of this method [12].

Table 2. Established linear regression models between sap flow and stem morphological variables using 70% of the whole dataset.

No.	Function	R^2 -adj	p	p_{con}	p_{PBN}	p_{SL}	p_{SBD}	p_W	VIF_{PBN}	VIF_{SL}	VIF_{SBD}	VIF_W
1	SF = 0.166 PBN − 0.012 SL + 0.069 W + 1.691	0.766	<0.0001	0.880	0.688	0.879		0.007	1.112	3.143	2.956	
2	SF = 0.229 PBN + 0.034 SL + 2.233 SBD − 24.086	0.766	<0.0001	0.009	0.582	0.605	0.007		1.097	4.354		4.163
3	SF = 0.151 PBN + 0.067 W + 0.119	0.541	<0.0001	0.977	0.693			<0.0001	1.079			1.079
4	SF = 0.293 PBN + 2.517 SBD − 21.931	0.781	<0.0001	0.004	0.448		<0.0001		1.015		1.015	
5	SF = −0.007 PBN+0.212 SL − 25.610	0.781	0.005	0.031	0.990	0.002			1.032	1.032		
6	SF = 0.045 SL + 2.169 SBD − 23.089	0.781	<0.0001	0.007		0.464	0.005		2.868		2.868	
7	SF = −0.004 SL + 0.068 W + 2.033	0.784	<0.0001	0.849		0.954		0.005		4.096		4.096
8	SF = 1.0.597 PBN + 9.570	0.036	0.473	0.271	0.473				1.000			
9	SF = 0.218 SL − 25.644	0.579	0.001	0.020		0.001				1.000		
10	SF = 2.552 BD − 19.586	0.788	<0.0001	0.002			<0.0001				1.000	
11	SF = 0.0767 W + 7.429	0.802	<0.0001	0.542				<0.0001				1.000

Note: p_{con} , p_{PBN} , p_{SL} , p_{SBD} , and p_W represent p values of the regression coefficients of constant, PBN, SL, SBD, and W, respectively. VIF_{PBN} , VIF_{SL} , VIF_{SBD} , and VIF_W represent variance inflation factor values (VIF) of the regression coefficients of PBN, SL, SBD, and W, respectively.

Figure 8. Comparison of the measured and estimated SF values using the remaining 30% of the validation dataset.

Table 3. Estimation of individual-scale SF for the three *C. korshinskii* plants.

SF	Shrub 1	Shrub 2	Shrub 3	Average	SD
SF (g·h ⁻¹)	1111.71	528.73	789.86	810.10	195.89
SF (mm·d ⁻¹)	1.91	1.10	1.59	1.53	0.22

4. Conclusions

Sap flow (SF) is typically measured only at the stem scale for multibranched shrub species, which limits the overall evaluation of plant water use on individual scales. In the present study, we explored suitable regression models for stem sap flow (SF) and stem morphological parameters and scaled up SF from the stem scale to the individual scale for *Caragana korshinskii*, a dominant shrub species on the Chinese Loess Plateau, from July to September 2018 in the rainy season. The results indicated that stem-scale SF was significantly and positively correlated with stem base diameter (SBD), stem length (SL), primary branch numbers in the stem (PBN), and estimated stem biomass (W). The SBD-based statistical model ($SF = 2.552 \text{ SBD} - 19.586$) performed better than the models established using other plant morphological variables. Thus, this model can be used to scale up SF of *C. korshinskii* from the stem scale to the individual scale in the rainy season. However, the SF model that was established for the rainy season could perhaps be restricted when used to estimate SF of *C. korshinskii* in the water-limited dry season. Our model, we believe, has still made much progress in the rapid and accurate estimation of SF for *C. korshinskii* and also similar multibranched shrub species on the Chinese Loess Plateau. Future study is justified to focus on the establishment of an integrated SF estimation model for both dry and rainy seasons.

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Appendix A

Figure A1. Relationship between SF and soil water content: (a) 0–40 cm; (b) 40–80 cm; (c) 80–120 cm; (d) 120–180 cm.

Figure A2. Regression relationships between the daily SF residuals and VPD.

Figure A3. Dynamics of sap flow (SF) for (a) air temperature (T), (b) photosynthetically active radiation (PAR), (c) vapor pressure deficit (VPD), (d) variable of transpiration (VT), and (e) reference evapotranspiration (ET_0).

Figure A4. The daily variation in stem-scale SF for different stem base diameters for the whole measuring period.

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