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Water consumption of *Populus alba* trees in tree shelterbelt systems in Central Asia – a case study in the Chui Valley, South Eastern Kazakhstan

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Abstract
Agriculture in Central Asia largely relies on irrigation. The water is withdrawn from the rivers of the region, which predominantly originate from snowfields and glaciers. Due to global warming, these water resources are expected to decline substantially, resulting in an aggravation of already existing water scarcity. Tree shelterbelt systems, as the most prominent practice of agroforestry in Central Asia, are reported to help to reduce water consumption in irrigated agriculture. Populus. alba is one of the most important shelterbelt trees in Central Asia. Though, studies about water consumption of shelterbelts are lacking. Therefore, the objectives of this study are to (1) investigate water consumption of Populus alba trees in a shelterbelt system in Central Asia and (2) analyze the influence of local climatic conditions on the sap flow of such a shelterbelt. Tree water consumption was assessed through sap flow measurements on three trees in a crop shelterbelt system in the Chui Valley in South Eastern Kazakhstan during June and July 2016. The average daily water consumption was 187.6 l/d, 44.8 l/d, and 160 l/d for the trees, respectively. These results were extrapolated for a representative shelterbelt section. Water consumption of that section was 7.8 mm/d, while average ETo was 5.3 mm/d. Considerable influences of water vapor saturation deficit, air temperature and relative humidity on the sap flow could be observed. Solar radiation played a role, too, whereas little or no influence of wind speed on tree water consumption was found.

Keywords: agroforestry, tree shelterbelt, Populus alba, sap flow, crop water consumption, Central Asia.

Paper type: Research Paper

1. Introduction

Throughout Central Asia, agriculture is a major contributor to GDP (https://data.worldbank.org/indicator/NV.AGR.TOTL.ZS?view=chart) and employment (https://data.worldbank.org/indicator/SL.AGR.EMPL.FE.ZS?view=chart) and is crucial to maintain food security (e.g. https://docs.wfp.org/api/documents/WFP-0000072415/download/?_ga=2.113481472.661130014.1531883056-81150002.1502173922). Due to the semi-arid to arid climatic conditions, agriculture is predominantly dependent on irrigation water, which is withdrawn from the rivers of the region (Kunze et al. 2010). The river water mostly originates from glaciers and snowfields of the surrounding mountains (ADB 2010; Unger-Shayesteh et al. 2013). Rising temperatures in the context of global warming cause melting of glaciers and snow reservoirs (Karthe 2017). As a result, already existing water scarcity and associated water conflicts among different water users and among economic and ecological purposes are expected to aggravate (ADB 2010; Unger-Shayesteh et al. 2013; Changkun et al. 2015). In particular, the water-dependent agriculture will be affected, as e.g. shown for Kyrgyzstan by Undeland (2015). Agroforestry systems, in particular tree shelterbelts, can help to reduce water consumption in irrigated agriculture and provide additional income to farmers (Thevs et al. 2017). Thereby, water consumption of crops is reduced as shelterbelts reduce wind speed. Wind speed is reduced by 30 % to 40 % close to the shelterbelt and by 20 % at greater distances of 8 times the shelterbelt height (Hana et al. 1997; Miller et al. 1975). Decrease of crop evapotranspiration was found to vary between 15 % and 30 % and crop yields were reported to increase (Vasilyev 1980; Stepanov 1987). Such shelterbelt systems have a long tradition in the region Central Asia and were applied on large scales during Soviet Union times (Djanibekov et al. 2016).

However, after Soviet Union has dissolved and the Central Asian states have gained independency, most of these shelterbelt systems were cut down, because the former centralized energy supply broke down and people therefore shifted to fuel wood as major energy source. Today, shelterbelts are listed by all countries in Central Asia in their development strategies as a target to combat erosion, improve microclimate for agriculture, and contribute to wood supply (UNECE 2018 and further literature there).

Previous research studies investigating the effects of shelterbelt systems in Central Asia so far largely neglected the water consumption of the shelterbelt trees. In an arid region as Central Asia knowledge about water consumption of shelterbelts is important for planning of water allocation when shelterbelts are promoted again. *Populus alba* is a very common tree species in tree shelterbelts in irrigated systems in Central Asia (Bulychev & Onischenko 1979). Therefore, the objectives of this study are to (1) investigate sap flow characteristics of *P. alba* trees in a shelterbelt system in Central Asia and (2) analyze the influence of local climatic conditions on sap flow of such a shelterbelt.

2. Materials and Methods

2.1. Study area

The study area is located near the village Karasay Batyr in Korday Country, south-eastern Kazakhstan. The geographical position is 42.38 °N and 75.66 °E. The elevation is 1095 m a.s.l. The region belongs to the Upper Chui Valley, which stretches from the area of the border between Kyrgyzstan and Kazakhstan down to Bishkek, the capital of Kyrgyzstan (Popov et al. 2009; Akimaliev et al. 2013). The whole region is characterized by the Chui River, which formed the low-montane topography of the valley on elevations of 700 m to 1200 m a.s.l. The Chui Valley is primarily used for agriculture due to its relatively flat topography and comparatively fertile soils (Schuler 2007). Irrigation water is abstracted from the Chu River by irrigation channels in Kazakhstan and Kyrgyzstan. The climate of the region is semi-arid to arid and strongly continental (Akimaliev et al. 2013), as shown by climate data of Tokmok (Table I), which is the closest climate station to the study area. The wind regime during the study period was dominated by daily cycles of east wind during the night through the morning until noon, followed by west wind during afternoons till evenings.

Table I. Climate data from the climate station Tokmok over the time period of 2006 – 2016 (https://rp5.ru/Wetterarchiv_in_Tokmok).

annual average temperature [°C]	average temperature January [°C]	average temperature July [°C]	annual precipitation [mm]	average wind speed [m s^{-1}]	average air humidity [%]
11.6	-2.7	24.8	522	1.2	63.72

During Soviet Union times, a shelterbelt system of 250 m x 250 m was established with *P. alba*, *P. nigra pyramidalis*, and *Acacia* as tree species. *P. alba* was the most widely used tree in this village. In the fields in between, fruit trees, wheat, corn, and potato were planted. Today, most fields are used as meadows or are grown to Alfalfa. Most shelterbelts are degraded, i.e. trees have been cut, so that they are interrupted with gaps between trees and groups of trees. The shelterbelt, which was chosen for measurements of tree water consumption in this study (Figure 1) consisted of two rows of predominantly *P. alba*, some *P. nigra pyramidalis*, and single Acacia trees. The shelterbelt runs north to south with a length of about 200 m and an average tree height of 16.5 m. Due to a relatively uniform tree height, an uninterrupted row of shelterbelt trees and a continuous water supply by an irrigation channel next to the shelterbelt, the selected site was considered to represent an intact shelterbelt.

Figure 1. Location of the selected shelterbelt in Karasay Batyr (red pin). Image recording: 21st of May, 2016 (Google Earth).

2.2. Sap flow measurements

Three *P. alba* trees were chosen for the measurements of water consumption of the shelterbelt trees. These trees represent the range of trees found within this shelterbelt. The associated tree data are shown in Table II.

Table II. Tree characteristics of the selected *P. alba* trees.

tree no.	height [m]	age [yr]	crown area [m^2]	DBH [cm]	xylem area [cm^2]
1	16	27	39.1	42.6	874.6
2	16.4	14	11.1	19.2	183.3
3	15.2	19	62.3	31.5	553.8

Water consumption of shelterbelt trees was measured by sap flow measurements using the thermal dissipation probe method according to Granier (1987) with the PROSALOG system by UP GmbH from Germany. Thereby, two sensors were inserted radially into the sapwood of each tree on the northern side of each tree at a height of 1.4 m and 1.5 m, respectively. The downward sensor released a heat impulse of 1 min. Afterwards, the temperature difference between the two sensors was recorded. This was repeated every 10 min (Gibert et al. 2006; Lubczynski et al. 2012). These temperature differences were converted into sap flux densities by the determination of the maximum temperature difference, and thus minimum sap flow during two-weekly time periods. To identify the points in time of maximum temperature differences, water vapor pressure deficit (VPD) was calculated based on adjusted climate data of the station Tokmok. The equation for the sap flux density is expressed by:

$$u = 0.714 \left(\left(\frac{dT_{night}}{dT_{actual}} \right) - 1 \right)^{1.231} \tag{1}$$

where u = sap flux density (ml cm^{-2} min^{-1}) and dT = measured temperature differences (°C).

Subsequently, the sap flux densities were extrapolated to the whole cross-sectional area based on calculations of the sap flow area of the *P. alba* trees at the height of the heated sensor probe. Xylem widths of trees were determined visually by two perpendicular wood cores taken with a Suunto 5 mm tree corer. Xylem widths were used to calculate the sap flow area.
Sap flow was recorded from 15th of June until 3rd of August 2016, in order to represent summer climatic conditions with the highest water consumption during a given growing season. Leaves emerged beginning of April. The first yellowing of leafs was observed beginning of October with a complete leaf drop by 24th of October. Data gaps were solely filled for daily sap flow values on the basis of regression equations between VPD and the sap flux density.
A section of 25 m length of the shelterbelt was chosen, in order to extrapolate sap flow of the sensor trees to an entire shelterbelt. In this section, DBH and xylem width of 25 randomly selected shelterbelt trees were measured. The subsequent regression equation between DBH and sapwood area revealed the following relationship: $SA = 0.4301\ DBH^2 + 0.235\ DBH$, with SA = sapwood area and $R^2 = 0.94$. Additionally, the DBH of all trees within this 25 m section were mapped in order to approximate SA based on the regression equation for all trees of those 25 m shelterbelt. Sap flow of these 25 m shelterbelt was calculated from the averaged sap flux density of the three sensor trees and the approximated SA. This calculation resulted in water consumption in litres per given time unit, e.g. day for this 25 m shelterbelt section. In order to be able to compare this shelterbelts water consumption with crop water consumption, which usually is given mm, i.e. litres/m², the shelterbelt water consumption was converted into mm, too. Therefore, the cumulated crown area of that shelterbelt section was measured with a crown mirror, and the shelterbelt water consumption (in litres) was divided by the crown area (in m²), in order to convert water consumption from litres into mm.
The local climate was measured in a distance of 160 m east of the shelterbelt. This position was the most uninfluenced and accessible position for a climate station in this given study location. For east wind, which was the prevailing wind direction during the night and until noon, this climate station reflects uninfluenced wind speed, while for west wind the measured wind speed is expected to be a bit reduced compared to wind speed not influenced by the shelterbelt. Still, the measured wind speed reflects the wind speed that impacts on the shelterbelt trees, as there is a fruit tree plantation (average tree height 5 m), which reduces wind speed of west wind (Figure 1). The following climatic features were measured, all with

sensors by METER, USA: relative air humidity and air temperature (VP-4), solar radiation (Model PYR), and wind speed and wind direction (DS2 Sonic Anemometer). Data were recorded by an EM50 data logger with a resolution of one minute. Later, those data were aggregated to 10 min values, in order to relate them to the sap flow data. Climate data were measured from 28th of May to 14th of June, from 28th of June until 10th of July, from 26th of July until 4th of August, and from 21st of August until 25th of September, in order not to conflict with farm operations.

These climate data were used to fit relationships with corresponding climate data from climate station Tokmok and fill data gaps for daily climate data (Thevs et al. 2017). These filled data were used to calculate the reference evapotranspiration (ETo) after Allen et al. (1998) as explained for this particular site by Thevs et al. (2017). ETo was calculated, in order to provide a widely applied meter with which water consumption of poplar trees and shelterbelts can be compared.

3. Results

3.1. Sap flow of P. alba

Sap flow values (SF) were calculated in litre per day and mm per day for a general assessment of the water consumption of the selected *P. alba* trees and for a comparison among the tree individuals representing the shelterbelt system. Figure 2 shows the sap flow values during the entire measurement period. The sap flow values of all *P. alba* trees range between 0 to 0.01 mm/min, with typical diurnal variations of maximum values around midday, followed by relatively constantly high values until 7:00 p.m. and a subsequent decline until 11:30 p.m. The range of SF was 3.5 l/d to 310.4 l/d, 0.8 l/d to 69.6 l/d, and 3.0 l/d to 262.8 l/d for tree no. 1, 2, and 3, respectively. Average SF were 187.6 l/d, 44.8 l/d, and 160.0 l/d, respectively. Expressed in mm per day, these values ranged from 0.09 mm to 7.9 mm, 0.07 mm to 6.3 mm, and 0.05 mm to 4.2 mm for trees no. 1, 2, and 3, respectively, with averages of 4.8 mm, 4.0 mm and 2.6 mm.

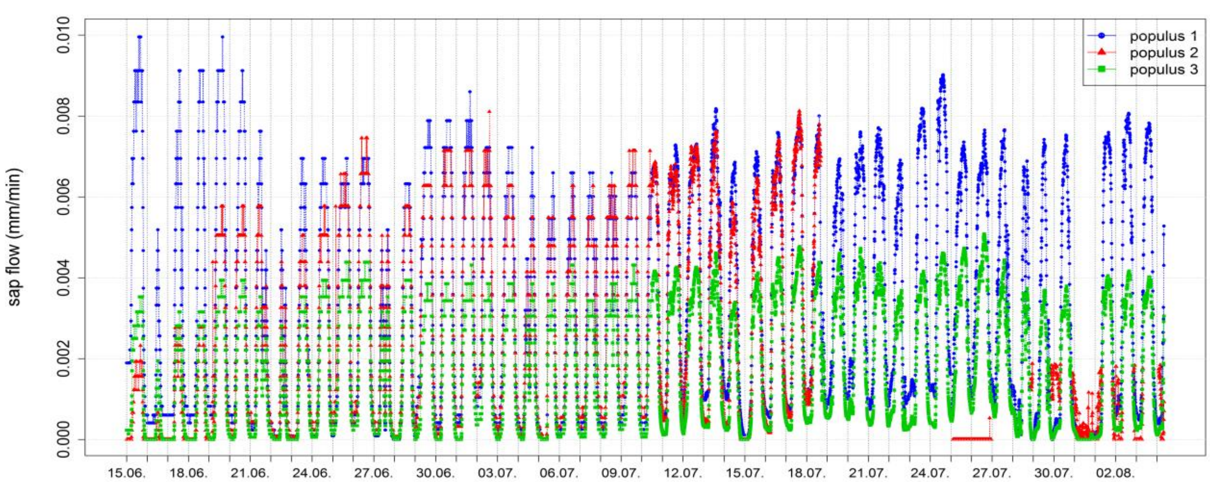

Figure 2. Sap flow values in mm/min of the three *P. alba* trees (2016).

75 percent of daily SF values of tree no. 1, 2, and 3, were found to vary between 4.0 to 5.9 mm/d, 3.0 to 5.4 mm/d, and 2.1 to 3.2 mm/d, respectively. The highest SF were measured end of July for the trees 1 and 3 and mid of July for tree 2. SF of the three selected *P. alba* behaved in a similar way and correlations between trees were close, $R^2 = 0.91$ and $R^2 = 0.87$ of tree 3 with trees 1 and 2, respectively (Figure 3). Tree 1 versus tree 2 yielded a correlation of $R^2 = 0.73$.

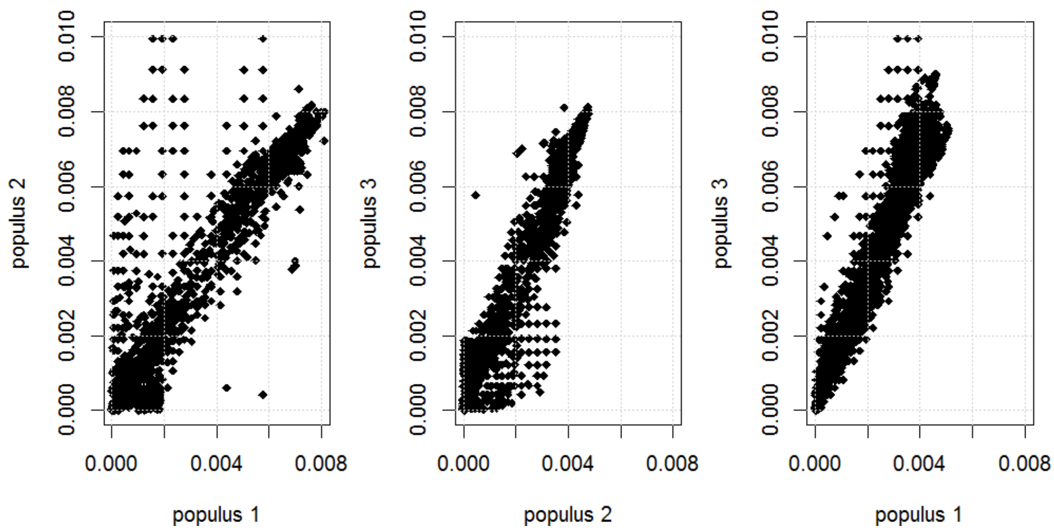

Figure 3. Scatterplots of the sap flow values in mm per minute of the selected *P. alba* trees; first and second tree (left), second and third tree (middle), first and third tree (right).

The sap flow extrapolated to the 25 m shelterbelt section was 1921 l/d in average with a range between 36 l/d and 2927 l/d (Figure 4).

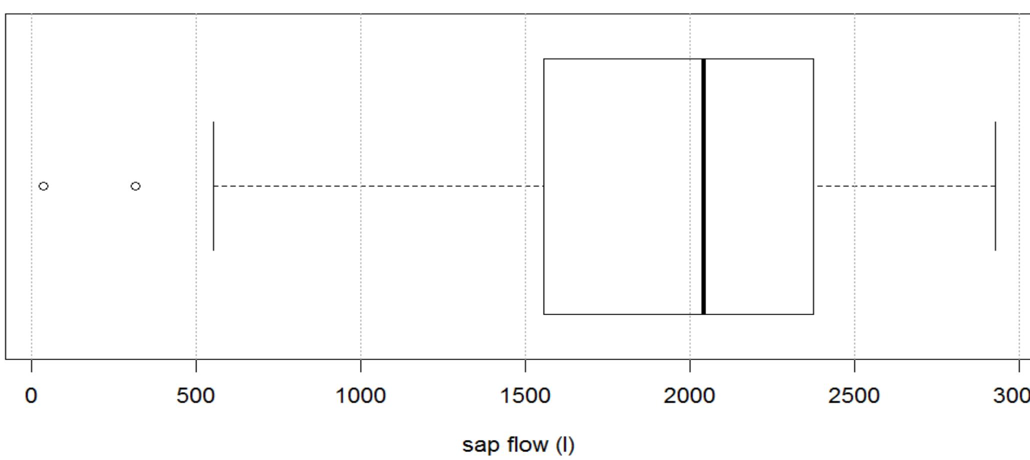

Figure 4. Box plot of the extrapolated sap flow values in liter per day of a shelterbelt system of 25 m length under the assumption of the existence of solely *P. alba* trees. Calculations are based on the averaged sap flux density of the three selected *P. alba* trees and a regression equation between DBH and SA of 25 randomly selected shelterbelt trees representing the entire 25 m shelterbelt section.

SF values of the shelterbelt show an increasing trend from the beginning of the measurement period in mid of June until 26th of July (Figure 5). The sharp decline on 31st of July coincides with a day with complete cloud coverage and continuous rainfall as observed by the climate station Tokmok.

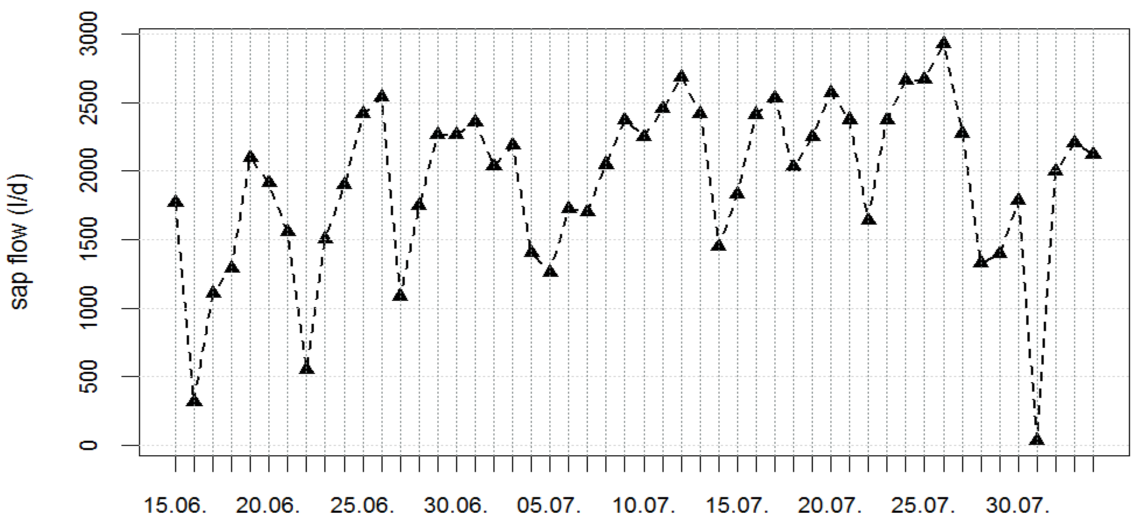

Figure 5. Extrapolated sap flow values of the 25 m shelterbelt section [l/d] in 2016.

3.2. Influence of the local climate on the sap flow

The water consumption of the 25 m shelterbelt section followed the trend of ETo, as shown in Figure 6, whereby the differences between peaks and lows of the shelterbelt water consumption were much larger than corresponding differences of ETo. During most days, water consumption of the shelterbelt was higher than ETo. In average, shelterbelt water consumption was 7.8 mm/d, while ETo was 5.3 mm/d. During four days, water consumption of the shelterbelt section was lower than ETo. All those days were rainy and cloudy with 100% cloud coverage during the whole day as recorded at Tokmok. Maximum temperature was lower and minimum air humidity was higher than neighboring days, e.g. on 31st of July maximum temperature was 17°C, in contrast to more than 25°C during neighboring days.

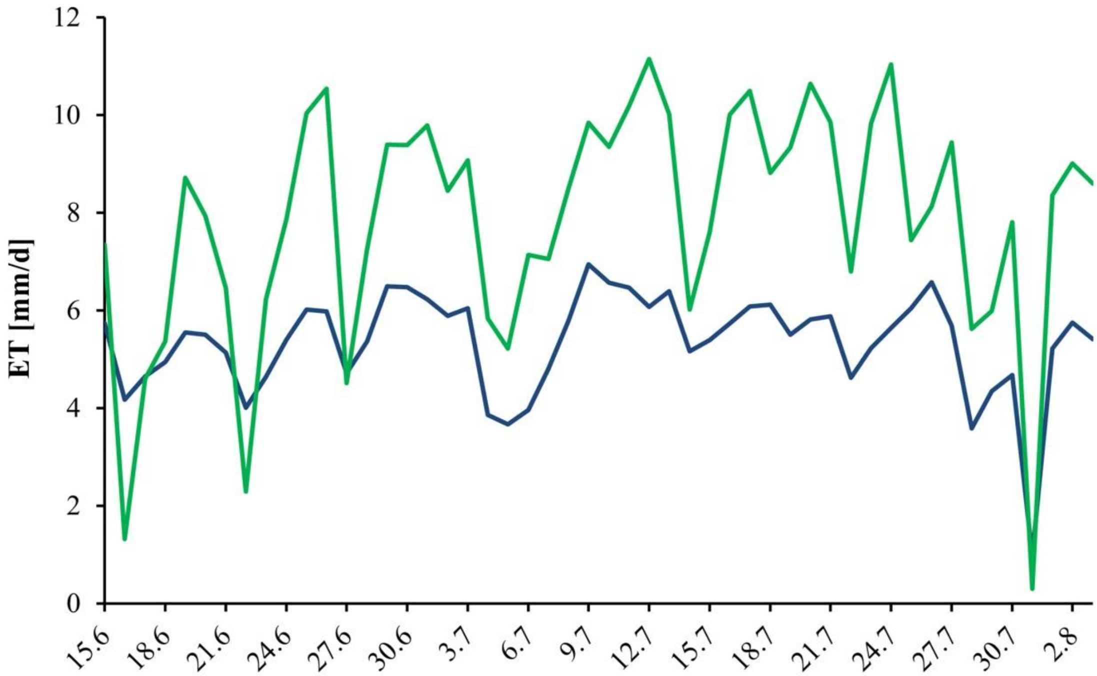

Figure 6. ETo (Thevs et al. 2017), in blue, and water consumption of shelterbelt, in green, both in mm/d from the growing season 2016.

Figure 7 shows a visual comparison of one of the two overlapping measurement periods of sap flow and the climatic features relative humidity (RH), air temperature (T), solar radiation (Rs), and wind speed (ws) from 26th of July until 4th of August.

During this selected measurement period, the second sap flow sensor dropped out. Generally, no relationship between wind speed and SF was observed, whereas remarkable interactions between RH and T with SF were visible on 28th of July, 31st of July and 1st of August (Figure 7, a and b). Short term changes of RH and T caused reverse responses of SF. The time between RH changes and SF changes was about 30 minutes. Relationships between Rs and SF, dropping Rs followed by declining SF, were visible on 27th, 28th, 29th and 31st of July and revealed the same time lag (Figure 6, b and c).

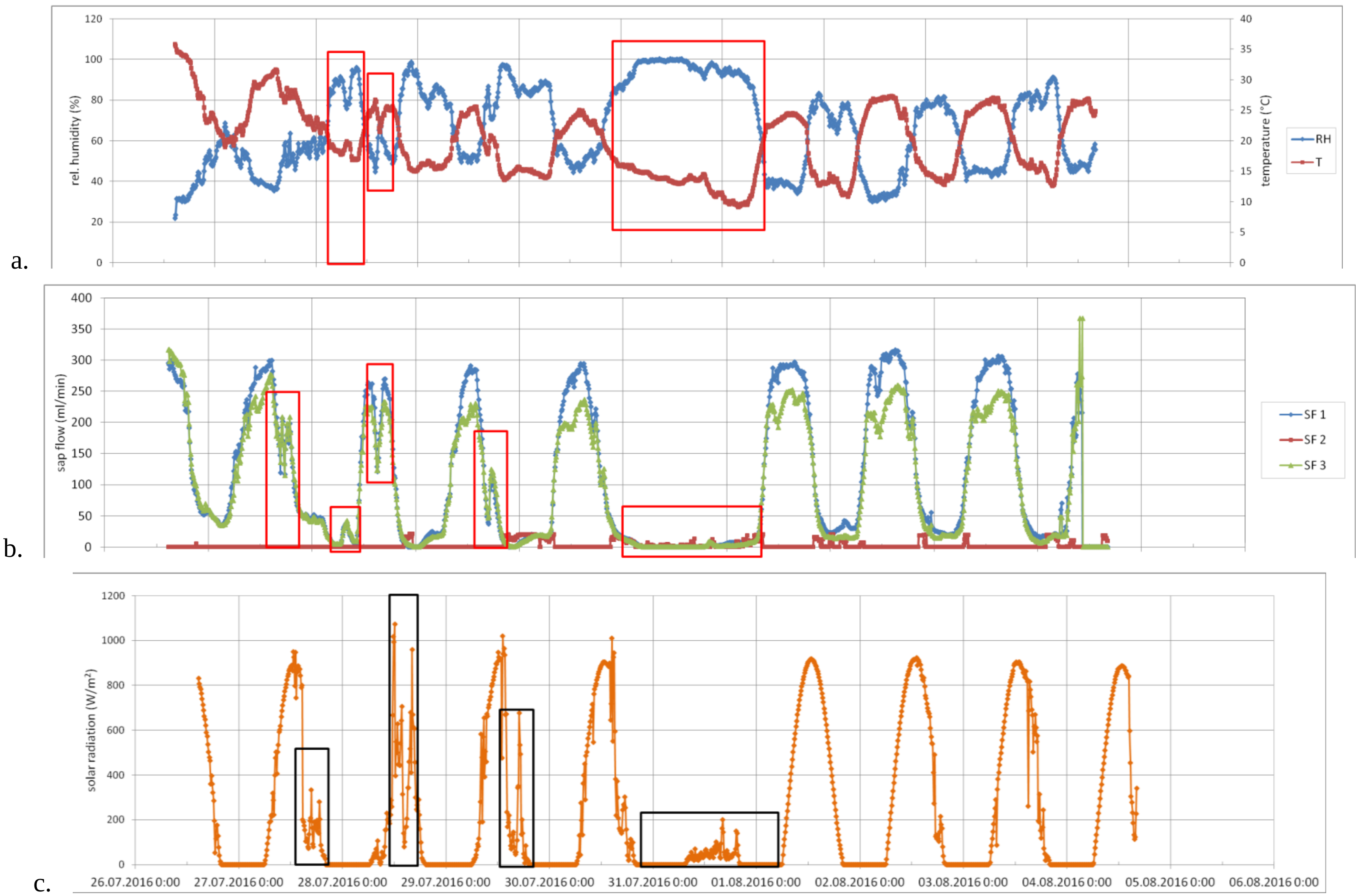

Figure 7. Measurements of RH and T (a), SF of the three P. alba trees (SF1, SF2, SF3; b) and Rs (c) during the time period of 26th of July until 4th of August 2016. The boxes indicate time periods, during which SF and climateic features were visually compared.

Generally, the climatic factors VPD, T, Rs, and ws correlated positively, whereas RH correlated negatively with SF. The highest correlations were found between VPD and SF with $R^2 = 0.92$ and $R^2 = 0.88$ for trees 1 and 3, respectively. Second highest was the correlation between SF and T for tree no. 2, with $R^2 = 0.79$. The order of decreasing correlations between SF and climatic features of trees 1 and 3 were VPD > T > RH > Rs >> ws. The second tree revealed the following order of correlation: T > VPD > Rs > RH >> ws. Remarkably low coefficients of determination between $R^2 = 0.16$ and $R^2 = 0.18$ were observed for correlations of wind speed and the sap flow of all three sensor trees.

4. Discussion and conclusion

The analysis of SF of the selected *P. alba* trees resulted in typical diurnal variations with relatively constantly high SF during daytime indicating an overall high water consumption of the trees. The range of the SF from 0.05 mm to 7.9 mm per day for all three sensor trees with averages of 4.8 mm, 4.0 mm and 2.6 mm for the first, second and third tree, respectively, are in good agreement with other studies of sap flow measurements of poplar trees (Meiresonne et al. 1999). Maximum SF of all three sensor trees in July also coincide with the results of Xu et al. (2010) and indicate a seasonal trend with increasing water consumption until the peak in mid to end of July. Despite the different ranges of SF of the *P. alba* trees, which are associated with varying xylem and crown areas of the trees, a similar pattern of SF of all sensor trees was clearly visible. As SF of the selected trees is comparable, it is assumed representative for the selected shelterbelt. Hence, an extrapolation of SF of the three sensor trees to a shelterbelt section was possible.

Relationships between climate and SF were predominantly found for VPD, T, RH and to a lesser extent Rs, whereby VPD is a combination of RH and T. Other researchers highlighted the same strong relations between these climatic factors and SF (Zhou et al. 2014; Ma et al. 2011; Zhang et al. 2011). Additionally, a time lag of 10 minutes between change in climate data and response of SF was also reported by Zhou et al. (2014) for poplar trees in China. This time lag indicates a belated response of the poplar trees to environmental changes. Relationships between wind speed and SF were weak. This is in contrast to the major impact of wind speed on the evapotranspiration of crops, as it is reflected by the ETo and ETc calculations by Allan et al. (1998). Wind decreases the boundary surface resistance between the leaf and its surrounding air, which results in higher water losses of the plant (Grace 1988; Drake et al. 1970). But, the findings regarding the relationships between tree water consumption and climatic features are in line with Jarvis (1985), who distinguished between coupled and decoupled plants regarding their transpiration. The former refers to plants which transpiration is largely driven by VPD, while transpiration of the latter is mainly driven by incoming radiation. Trees, as they are tall, tend to be strongly coupled to VPD with respect to transpiration. On the other hand, Lundblad & Lindroth (2002) found a wide range of coupling and decoupling in one forest area with the same tree species. This is in line with the finding here that Rs shows a relationship with sap flow, too, which indicates that the *P. alba* trees were not completely coupled to VPD. Higher wind speeds result in a stronger coupling of transpiration to water vapor saturation deficit, whereby strong changes of coupling occur at wind speeds between 1 m/s and 5 m/s (Jarvis 1985). As wind speeds in this study were below 2.5 m/s, these wind speeds might have been too low to translate into significant changes of transpiration and sap flow.

Shelterbelts from *P. alba* are a major water consumer, which needs to be considered when establishing shelterbelt systems, despite the frequently reported advantages of those systems. Under wind speeds similar to this study, i.e. below 2.5 m/s, *P. alba* shelterbelt helps to reduce wind speed and thus crop water consumption, while its own water consumption is not increased by wind speed. As an open question remains the behavior of *P. alba* at higher wind speeds. Under conditions of higher wind speeds, the potential protection against wind erosion also needs to be taken into consideration for planning decisions with respect to establishment of shelterbelts.

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6. Author Contributions

Eva Strenge did large parts of the data collection, data analysis, and wrote large parts of the manuscript.

Niels Thevs contributed to data analysis, in particular the upscaling from sap flow to water consumption of a shelterbelt and did major editing of the manuscript.

Kumar Aliev contributed to editing of the English version and in particular edited the Russian version.

Maksat Eraaliev contributed to the data analysis by ETo calculations and discussions.

Petra Lang contributed to conceptualizing the sap flow measurements.

Azim Baibagysov provided the knowledge of the study area and related the findings to the study area.

7. Conflicts of Interest: The authors declare no conflict of interest.

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