doi:10.20944/preprints201906.0220.v1

Article

Tree Wind Breaks in Central Asia and Their Effects on Agricultural Water Consumption

Niels Thevs [1,*], Alina Joana Gombert [2], Eva Strenge [3], Kumar Aliev [4], and Begaiym Emileva [5]

[1] World Agroforestry; N.Thevs@cgiar.org
[2] Julius Kühn-Institute, Institute for Bee Protection; alina.gombert@julius-kuehn.de
[3] Technical University of Vienna, Institute of Water Quality and Resource Management; estrenge@iwag.tuwien.ac.at
[4] World Agroforestry; K.Aliev@cgiar.org
[5] World Agroforestry; bemileva93@gmail.com

* Correspondence: N.Thevs@cgiar.org;

Abstract: Across Central Asia, agriculture largely depends on irrigation due to arid and semi-arid climatic conditions. Water is abstracted from rivers, which are largely fed by glacier melt. In the course of climate change, glaciers melt down so that a reduced glacier volume and reduced water runoffs are expected being available for irrigation. Tree wind breaks are one option to reduce water consumption in irrigated agriculture and build resilience against climate change. This paper therefore assessed water consumption of major crops (cotton, wheat, corn, rice, potato, and barley) in Kyrgyzstan and adjacent areas in combination with tree wind breaks. Crop water consumption was assessed through the Penman Monteith approach. Tree wind break types investigated were single rows from poplars and multiple rows with undergrowth by elm and poplar, respectively. Tree water consumption was determined through sapflow measurements. Seasonal ETo for field crops was 876 mm to 995 mm without wind breaks and dropped to less than half through multiple row wind breaks with undergrowth (50 m spacing). Tree water consumption was 1125 mm to 1558 mm for poplar and 435 mm for elm. Among the wind break crop systems, elm wind breaks resulted in highest reductions of water consumption, followed by single row poplars, at spacing of 50 m and 100 m, respectively. Yet, elm grows much slower than poplar so that poplars might be more attractive for farmers. Furthermore, single row wind breaks might by much easier to be integrated into the agrarian landscape, as they consume less space.

Keywords: Agroforestry, *Populus*, *Ulmus*, cotton, corn, microclimate, evapotranspiration, irrigation

1. Introduction

Central Asia refers to the region from the Caspian Sea to Mongolia and northwest China. This region is covered by drylands and mountains [1,2,3]. Except for northern Kazakhstan, Agriculture is restricted to rivers valleys of e.g. the Amu Darya, Syr Darya, Chui, or Talas and to the forelands of the mountains like the northern slopes of the Tianshan [1]. Agriculture depends on irrigation throughout the growing season or at least during summers, as the climate is semi-arid to arid. This makes agriculture the major water consumer across Central Asia. Water for irrigation is abstracted from the rivers, with the desiccation of the Aral Sea being the most prominent result of this water consumption [3]. Climate change is expected to lead to water shortages for irrigation latest during the second half of this century as well as enhanced heat waves [2,4].

Currently, flood and furrow irrigation are the most prevalent irrigation methods across Central Asia, in particular in the post-Soviet countries. Against the background of increasingly expected water scarcity, water consumption in agriculture needs to be reduced through improved irrigation methods and/or through proper crop selection and agroforestry. Drip irrigation or plastic mulch can reduce water consumption substantially, as shown in Xinjiang, China [5,6].

Under conditions of lacking capital and water infrastructure suitable for drip or sprinkler irrigation, agroforestry systems, in particular tree wind breaks, are an option to reduce water consumption in irrigated agriculture. Such tree wind breaks were promoted during Soviet Union times and had a long tradition before [7], but were largely cut down, as people urgently needed fuel wood to compensate for collapse of regular energy supplies after the collapse of Soviet Union [8]. Now, most countries of Central Asia stated the importance of tree wind breaks as part of the forestry and agriculture related strategies, cf. [8] and further literature there.

Tree wind breaks reduce water consumption (evapo-transpiration) of crops, as found under many conditions in former Soviet Union [7,9,10,11] and internationally [12,13]. Crop water consumption is reduced, mainly because those wind breaks substantially reduce wind speed and [13]. A minor effect to reduce crop water consumption is that air temperature is lower and air humidity is higher inside a tree wind break system [12,13]. Wind speed on the leeward side of tree wind breaks was reduced to almost zero within a distance of 5 times shelterbelt tree height. At distances of 15 to 20 times tree wind break height, wind speed was about half of open field wind speed. At distances of 25 to 30 times tree height, wind speed reached 70% of open field wind speed [10]. This source [10] stated a reduction of wind speed by 36% for a whole tree wind break systems with all its different distances from the wind breaks compared to open field wind speed. After [13] though, in a distance of 25 times tree height, wind speed was only reduced 90% compared to open field conditions. Air temperature decreased by 1°C through the impact of tree wind breaks after [14]. A 15 to 30% reduction of crop water consumption were stated by [10] and [15], while [9] found a reduction of crop water consumption by 15-20%. Evapotranspiration was substantially decreased as far as 300 m leeward of tree wind breaks with a tree height of 8-10 m [16]. On the upwind side, evapotranspiration was reduced by 35-45% compared to open field conditions less than 50 m away from tree wind breaks [16].

Next to reducing water consumption in agriculture, in a number of tree wind break and crop combinations crop yields are increased compared to open field conditions, as listed by [17] for Soviet Union and other locations under temperate climate, by [18] for northern China, and by [19] for African countries. In particular for Central Asia, [16] measured wheat yields and potato yields increased by 20-30% and 37% compared to open field conditions, respectively, in a tree wind break system in the Kazakh steppe.

Literature findings were based on tree wind breaks of multiple rows of trees often combined with shrubs as undergrowth, i.e. the type which was propagated during Soviet Union times. Today, small stretches of this wind break type still remain, but if people plant new tree wind breaks they opt for single rows largely from poplars without any undergrowth.

Against this background, this paper aims at assessing water consumption of major crops in Kyrgyzstan and adjacent areas in combination with major types of tree wind breaks. The crops taken into account were corn, wheat, potato, and barley for the Chui Valley (northern Kyrgyzstan and southeastern Kazakhstan) and cotton, rice, and corn for the Ferghana Valley (Jalalabad Region in Kyrgyzstan). Crop water consumption was assessed through climate data and calculation of the Penman Monteith approach [20]. The wind break types investigated were single rows from poplars and multiple rows with undergrowth by elm and poplar, respectively. Water consumption of trees in the wind breaks was determined through sapflow measurements after [21]. The impact of wind breaks on climate data and subsequently crop water consumption was measured with field climate stations and calculated for different potential tree wind break systems with a model developed in GRASS GIS.

2. Materials and Methods

As the single row tree wind break from poplars is the most common one for new wind breaks, the impact of this type was calculated for climatic and crop conditions in Ferghana Valley (study site Chek Village) and Chui Valley (study site Karasay Batyr Village) (Fig. 1). The multiple row type was only found in Chui Valley and adjacent areas in south eastern Kazakhstan, but not in Ferghana Valley (Fig.

1). Therefore, the impact of this type was only calculated for climatic and crop conditions in Chui Valley, i.e. based on measurements in Temen Suu Village (Fig. 1). For the multiple row type, water consumption together with crop water consumption was calculated for elm and poplar, because poplar is much more popular as tree than elm for any kind of new plantations.

Figure 1. Location of the three study sites Chek and Temen Suu, both in Kyrgyzstan, and Karasay Batyr, in Kazakhstan

Chek village is located on the border between Kyrgyzstan and Uzbekistan on an elevation of 639 m and represents the irrigated agriculture of the Ferghana Valley. Major crops are cotton, corn, and rice. Karasay Batyr, elevation of 1095 m, is on the northern bank of Chui River, i.e. located in Kazakhstan, and represents the conditions of the upper Chui Valley. Temen Suu is located on an elevation of 941 m in the plain north of the Tianshan Mountains. The forehills of the Tianshan are 3 km south of the site Temen Suu. The major crops in Karasay Batyr and Temen Suu are wheat, corn, barley, potato, and Lucerne.

In all sites, soils receive water from snow melt and rain fall in winter and spring (Tab. 1). But, from late spring through summer the climate is hot and dry, more pronounced in Chek than in the two other sites (Tab. 1) so that crops need to be irrigated. Irrigation is done through furrows.

Table 1. Monthly average climate data from Bazarkorgon (16 km from Chek), Kara Balta (17 km from Temen Suu), and Kemin (5 km from Karasay Batyr) for the growing season, i.e. from April to October, 112 years observation (http://www.weatherbase.com)

Month	Temperature [°C]	Relative air humidity [%]	Wind Speed [m/s]	Precipitation [mm]
Bazarkorgon				
April	14.2	58.8	1.9	64.7
May	19	52.7	2	54.5
June	23.3	45	2	28.7
July	24.8	47	1.8	15.1
August	23	51.3	1.7	7.9
September	18.2	54.4	1.5	8.3
October	11.7	62.5	1.3	43.5
Kara Balta				
April	11.4	57.4	2.2	60.9
May	16.2	53.8	2.2	58.2
June	20.8	46.1	2.2	37.5
July	23.3	44.2	2.2	19.8
August	21.6	45.2	2.1	12.2

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 22 June 2019 doi:10.20944/preprints201906.0220.v1

September	16.5	47.8	2.1	12.5
October	9.7	57.5	2	37
Kemin				
April	8.9	53.5	1.9	38
May	13.5	52.2	1.9	46.2
June	17.6	47	2.2	32.6
July	20.4	43.9	2.2	25.6
August	19.5	42.5	1.8	19.8
September	14.5	44.6	1.9	13.1
October	7.5	54.1	1.9	20.1

In this study, field data were collected to assess the impact of single row (in Chek Village) and multiple row tree wind breaks (in Temen Suu Village) on the micro climate of adjacent crop fields, because these are the two major wind break types in Kyrgyzstan and regions in neighboring countries. At each of the two locations, a climate station was placed as control out of the fetch of wind breaks. Four climate stations were operated within the fetch of the given tree wind break in different distances from the tree wind break, in order to capture data for leeward and upwind conditions. All climate stations were equipped with sensors for air temperature (VP-4, air humidity (VP-4), wind speed (DS-2), wind direction (DS-2), and solar radiation from Meter and recorded these data every minute with an EM50 logger from Meter.

The climate data of the four stations in the fetch of the tree wind break were used to fit relationships with the distance to the wind break as independent variable and deviations from the control as dependent variable. Thereby, distance to the wind break (D) was used in multiples of tree wind break height (H). These relationships allowed calculate profiles of the microclimate, in particular wind speed, across a crop field depending on direction of a given tree wind break and distances between wind breaks.

The data of the control climate stations were aggregated to daily values, in order to calculate reference evapotranspiration (ETo) and crop evapotranspiration (ETc) for the crops investigated after [20] and [22] as water consumption. Crop coefficients (Kc) were inherited from [23] for wheat, corn, potato, and barley in Chui Valley and through field observations for cotton, rice, and corn in Chek. Afterwards, these ETc values were compared with evapotranspiration of crops under impact of tree wind breaks and tree water consumption of the tree wind breaks themselves. This was done through a local GIS model developed in the software GRASS GIS (https://grass.osgeo.org/).

In this model, square shaped tree wind break systems of different square size, 50 m x 50 m, 100 m x 100 m, 200 m x 200 m, 400 m x 400 m, 500 m x 500 m, 750 m x 750 m, and 1000 m x 1000 m, were laid over a representative field structure of each study site. The relationships fitted for changes of climate data in dependence of distance to wind break were used in this GIS model to calculate an altered daily air temperature, air humidity, wind speed, and solar radiation and finally calculate altered ETo and ETc for each pixel of this GIS model. The ground resolution of this GIS model was 1 m x 1 m. The input data of daily climate data came from the control climate stations in Chek (2017), Temen Suu (2018), and from Karasay Batyr [23].

The water consumption of the tree wind breaks was included on this model, too. Tree water consumption was measured after [21] as used in [24, 23, 25, 26] for sites covered by this study. Tree water consumption for poplar in a single row wind break was measured in Chek in 2017 [25]. Tree water consumption for poplar and elm in a multiple row wind break was measured by [24] and [26] in Karasay Batyr and Sokuluk, respectively, both located in Chui Valley.

In Chek, a representative tree wind break of a single row of poplars was chosen to measure its tree water consumption and impact on climate data of adjacent fields in 2017. The tree wind break is oriented in north – south direction and therefore shelters against prevailing easterly winds. *Populus nigra* var. *pyramidalis* (local variety name: Bistrohod or California), had an average height of 14 m. Distance between trees was 1 m and the crowns covered a width of 6 m. Cotton and on small fields rice were grown adjacent to the tree wind break (Fig. 2). This type of tree wind break was also assumed for Karasay Batyr.

Figure 2. Single row tree wind break from poplars at the study site Chek

In Temen Suu the impact of a multi row tree wind break with undergrowth on climate data of adjacent fields was measured in 2018. The tree wind break is composed of elm (*Ulmus minor*) and Acacia spec. with berry shrubs as undergrowth (Fig. 3). The tree wind break runs in 81° - 261° direction, in order to shelter against the prevailing south winds which come down from the nearby Tianshan Mountains (Fig. 1). The average tree height of the shelterbelt was 10 m.

Figure 3. Multiple row wind break with elm and shrub undergrowth in Temen Suu

3. Results

The reference evapotranspirations (ETo) were 945 mm, 939 mm, and 876 mm in Chek (in 2017), Karasay Batyr (in 2016), and Temen Suu (in 2018), respectively. The monthly averages of ETo and relevant climate data as measured during this study are listed in Tab. 2.

Table 2. Monthly averages of temperature, air humidity (RH), wind speed, solar radiation (Rs), and ETo for the three study sites Chek, Karasay Batyr, and Temen Suu, as measured during this study

Month	Temperature [°C]	RH	Wind speed [m/s]	Rs [MJ/d m²]	ETo [mm/d]
Chek (in 2017)					
April	15.2	0.6	1.9	18.6	3.5
Mai	22.0	0.6	1.5	22.1	4.9
Juni	24.2	0.6	2.1	23.4	5.7
Juli	26.5	0.6	1.1	23.3	5.3
August	23.9	0.6	1.2	20.6	4.5
September	22.2	0.6	2.1	16.5	4.0
Oktober	15.9	0.6	1.9	12.2	2.4
Karasay Batyr (in 2016)					
April	12.7	0.6	2.0	20.5	3.5
Mai	16.5	0.5	2.0	24.0	4.6
Juni	21.3	0.5	1.9	26.8	5.9
Juli	22.0	0.5	2.0	22.3	5.3
August	21.2	0.4	2.2	22.0	5.4
September	19.9	0.4	2.3	16.0	4.4
Oktober	8.7	0.6	2.3	12.8	2.2
Temen Suu (in 2018)					

April	11.5	0.7	1.9	19.9	3.1
Mai	14.9	0.6	2.0	23.2	4.3
Juni	20.2	0.5	2.1	23.6	5.3
Juli	23.1	0.5	1.9	25.1	5.9
August	21.6	0.5	2.0	20.5	4.9
September	15.4	0.5	1.8	16.8	3.4
Oktober	9.9	0.6	1.7	12.7	2.0

The development stages from which the crop coefficients (Kc) were derived are given underneath in Table 3.

Table 3. Development stages of the investigated crops after field observations. Definitions of the development stages were inherited from [20]

Development stage	Initial	Development	Mid-stage	Late
Chek				
Cotton	13-Apr to 9-May	10-May to 26-Jun	27-Jun to 24-Aug	25-Aug to 17-Oct
Corn	12-Apr to 11-May	12-May to 29-Jun	30-Jun to 29-Aug	30-Aug to 2-Oct
Rice	15-May to 14-Jun	15-Jun to 13-Jul	14-Jul to 12-Sep	13-Sep to 12-Oct
Karasay Batyr and Temen Suu				
Barley	4-Apr to 19-Apr	20-Apr to 14-May	15-May to 23-Jun	24-Jun to 11-Jul
Corn	26-May to 8-Jun	9-Jun to 24-Jul	25-Jul to 15-Oct	16-Oct to 24-Oct
Potato	3-Apr to 28-Apr	29-Apr to 14-Jun	15-Jun to 15-Jul	16-Jul to 15-Aug
Wheat	15-Apr to 4-May	5-May to 29-May	30-May to 28-Jul	29-Jul to 28-Aug

The tree wind breaks only showed limited effects on temperature, air humidity, and radiation, but showed substantial effects on wind speed leeward of the wind breaks. Upwind no consistent effect was measured. For the single row tree wind breaks the following relationship was fitted (Fig. 4):

$$\text{Wind speed reduction} = 0.0101 * D + 0.614 \ (R^2 = 0.58), \tag{1}$$

For the multiple row tree wind breaks with undergrowth this relationship was fitted (Fig. 5):

$$\text{Wind speed reduction} = 0.2859 * \ln(D+1) - 0.1159 \ (R^2 = 0.86), \tag{2}$$

Thereby, D refers to the distance from the tree wind break expressed in multiples of the average tree height of the tree wind break. The relationship for the single row tree wind break applies for $D < 38$, i.e. further away from the tree wind break than 38 x tree height the wind speed is the same as under open field conditions. The relationship for the multiple row tree wind break was found to apply for $D > 0.5$ and $D < 48.5$.

doi:10.20944/preprints201906.0220.v1

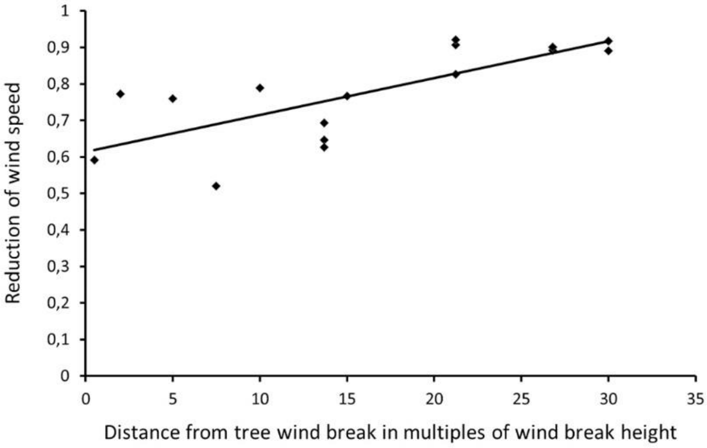

Figure 4. Reduction of wind speed along increasing distance from the single row tree wind break. Reduction of wind speed is given as multiple of open field wind speed.

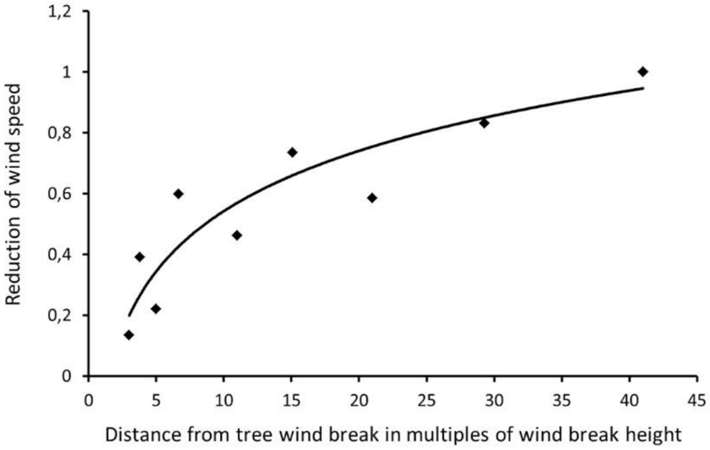

Figure 5. Reduction of wind speed along increasing distance from the multiple row tree wind break with undergrowth. Reduction of wind speed is given as multiple of open field wind speed.

Temperature, air humidity, radiation were only impacted in the close vicinity of the tree wind breaks. The relationships used are given underneath in Table 4. In case of temperature and air humidity, there was only a slight impact closer than 1.5 x tree wind break height. Further away from the tree wind break, the data of the control climate stations were used also to calculate ETo and ETc within the given tree wind break systems.

Table 4. Changes of temperature, air humidity, and radiation under impact of tree wind breaks. H refers to height of tree wind break. Tmin, Tmax, RHmin, and RHmax refer to daily temperature and humidity minima and maxima, respectively, as used for the ETo calculations after [20]. Rs is the daily sum of solar radiation. $T_{min\ wind\ break}$, $T_{max\ wind\ break}$, $RH_{min\ wind\ break}$, $RH_{max\ wind\ break}$, and $Rs_{wind\ break}$ refer to daily temperature and humidity minima and maxima, respectively, and solar radiation as changed by the impact of tree wind breaks.

Tree wind break type	Single row tree wind break	Multiple row tree wind break with undergrowth
Minimum temperature		
Closer than 1.5 x H	$T_{min\ wind\ break} = 1.0007 * T_{min} + 0.4506$	$T_{min\ wind\ break} = 0.8962 * T_{min} + 0.9625$
Further than 1.5 x H	No change	No change
Maximum temperature		
Closer than 1.5 x H	$T_{max\ wind\ break} = 1.008 * T_{max} - 0.1053$	$T_{mAX\ wind\ break} = 0.9522 * T_{max} + 1.5854$

Further than 1.5 x H	No change	No change
Minimum air humidity		
Closer than 1.5 x H	$RH_{min\ wind\ break} = 1.0216 * RH_{min} - 0.0165$	No change
Further than 1.5 x H	No change	No change
Maximum air humidity		
Closer than 1.5 x H	$RH_{max\ wind\ break} = 1.1087 * RH_{max} - 0.0945$	No change
Further than 1.5 x H	No change	No change
Radiation		
Closer than 1 x H (along north-south running tree wind breaks) / Closer than 0.5 x H (north of east-west running tree wind breaks)	$Rs_{wind\ break} = Rs * 0.4493$	$Rs_{wind\ break} = Rs * 0.4493$
Between 1 x H and 4 x H (along north-south running tree wind breaks) / between 0.5 x H and 2 x H (north of east-west running tree wind breaks)	$Rs_{wind\ break} = Rs * 0.9343$	$Rs_{wind\ break} = Rs * 0.9343$

With regard to water consumption of the tree wind breaks (ET_{trees}), it was found that poplars from the single row wind breaks had the closest relationship with daily average temperature (T_{mean}):

$$ET_{poplars\ single\ row} = 0.5198 * T_{mean} - 3.8827, \tag{3}$$

In contrast, water consumption of trees in the multiple row wind breaks was most closely related to ETo, as:

$$ET_{elm} = 0.22 * ETo, \tag{4}$$

and

$$ET_{trees\ poplar\ multiple\ row} = 1.2075 * ETo, \tag{5}$$

The evapotranspiration of the shrub undergrowth was calculated as follows for elm and poplar multiple row wind breaks:

$$ET_{shrubs} = Coverage_{shrubs} * Kc_{shrubs} * ETo_{shrubs}, \tag{6}$$

with

$Coverage_{shrubs} = 0.8$

$Kc_{shrubs} = 1.05$

For the calculation of ETo_{shrubs}, $Rs_{wind\ break}$ as for close vicinity to tree wind breaks was used and wind speed was set to 0.01 m/s. These assumptions were inherited from a microclimate measurement inside a multiple row shelterbelt by [24].

ETo on the crop fields between the tree wind breaks was substantially reduced by the effect of tree wind breaks. So, under a 50 m x 50 m tree wind break system with single row poplars ETo was reduced by 36%. A 1000 m x 1000 m tree wind break system with single row poplars still yields a reduction of 5% (Tab. 5). The effect of the multiple row tree wind break is more pronounced than the effect of the single row wind breaks, as a 50 m x 50 m tree wind break system with multiple elm and poplar rows reduced ETo by 47% and 55%, respectively. This is in line with the much stronger wind speed reduction by multiple row wind breaks in particular close to the wind breaks (Fig. 4 and 5). The 1000 m x 1000 m tree wind break system with multiple elm rows also yielded an ETo reduction of 5% like the single row wind break (Tab. 5).

Table 5. ETo [mm] of open field conditions and under impact of different wind break types and grid sizes

Tree wind break type	ETo [mm] No tree wind break	Wind break grid sizes 50 m x 50 m	200 m x 200 m	1000 m x 1000 m
Single row poplar Chek	945	607	779	899
Single row poplar Karasay Batyr	995		822	944
Multiple row elm	876	466	701	832
Multiple row poplar	876	397	641	806

Tree wind break water consumption of single row poplars in Chek and Karasay Batyr and multiple row elm and poplar wind breaks was 1558 mm, 1125 mm, 435 mm, and 1300 mm, respectively.

Crop evapotranspiration (ETc) in the Ferghana Valley, Chek, was highest for cotton (904 mm) followed by corn with 838 mm and rice with 812 mm. On the sites in the Chui Valley, Karasay Batyr and Temen Suu, corn had the highest ETc, followed by wheat, potato, and barley (Tab. ###). Thereby, ETc of corn in Karasay Batyr and Temen Suu, 1035 mm and 900 mm, respectively, were higher than ETc of corn in the Ferghana Valley (only 838 mm).

All crop tree wind break systems consumed less water than the corresponding crops without wind break. Thereby, the most pronounced reduction in water consumption was attained by the 50 m x 50 m grid with multiple row elm tree wind breaks, e.g. water consumption of corn was reduced from 900 mm (ETc) to 455 mm, which is a reduction by 49%, including the water consumption of the elm trees and shrub undergrowth in the tree wind breaks (Tab. 6). In contrast, corn and a 50 m x 50 m grid of a multiple row poplar wind break consumed 835 mm (still a reduction by 7%). This water consumption went down to 736 mm (18%) with a grid of 100 m x 100 m (Tab. 6).

Among the poplar tree wind breaks, the single row wind breaks with grid sizes of 100 m x 100 m and 200 m x 200 m resulted in the highest reductions of water consumption, though their effect was less remarkable than that of elm multiple row tree wind breaks. In Karasay Batyr, water consumption of corn without any tree wind break was reduced from 1035 mm (ETc) to 754 mm, i.e. 27% with a wind break grid of 100 m x 100 m, including water consumption of the trees. In the case of cotton, Chek, Ferghana Valley, water consumption was reduced from 904 mm (ETc) to 761 mm, i.e. 16%, also with a wind break grid of 100 m x 100 m, including water consumption of the trees.

Table 6. This is a table. Tables should be placed in the main text near to the first time they are cited.

Crop and tree wind break type	ET [mm] No tree wind break (ETc)	ET of crops and trees of tree wind break systems of grid size [m] 50	100	200	400	500	750	1000
Single row wind break, poplars, Chek								
corn	838	754	718	728	756	766	785	791
cotton	904	788	761	777	811	823	844	852
rice	812	743	702	708	733	743	760	767

Single row wind break, poplars, Karasay Batyr								
barley	611		497	496	510	515	523	529
corn	1035		754	787	830	844	865	882
potato	699		549	556	576	582	593	602
wheat	753		582	594	618	625	638	648
Multiple row wind break, elm, Temen Suu								
barley	572	370	409	461	504	516	530	542
corn	900	455	565	672	762	786	813	839
potato	648	388	443	508	563	578	594	610
wheat	701	402	469	543	605	622	641	659
Multiple row wind break, poplar, Temen Suu								
barley	572	763	599	561	546	547	551	555
corn	900	835	736	752	785	799	820	840
potato	648	777	628	603	600	604	612	620
wheat	701	789	651	635	640	646	657	667

4. Discussion

Authors should discuss the results and how they can be interpreted in perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

ETc values in this study are in the range of further studies, e.g. water consumption of corn with values between 741 mm and 841 mm measured in Texas with a lysimeter under sprinkler irrigation [27]. Wheat ETc calculated from climate data from Almaty [34] was the same as wheat ETc under open field conditions of this study. Annual corn water consumption in the Heihe Basin in NW China was 668 mm [28]. This value is lower than ETc of corn under all assumptions in this study, because corn in the Heihe Basin was grown under plastic mulch, which considerably reduced evaporation from the soil surface during the initial crop development stage. Cotton ETc in this study, 904 mm (Tab. 6), was slightly higher than 807 mm as measured with a lysimeter near Tashkent [29]. In this study, the daily average water consumption of the single row poplar tree wind break in the Ferghana Valley was 7.3 mm or 45 l per tree in average [25], which is in the range of the result by [30] for *Populus fremontii* in Arizona, but lower than the findings of [31], who measured 16.6 to 137.9 l per day and tree for a fast growing columnar hybrid of *Populus nigra*. Water consumption of poplars, in particular the single row wind break, was higher in this study than e.g. [32], who found 1.7 mm to 5.6 mm for *Populus gansuensis* in NW China and [33] who measured 3 l to 24 l per day for *Populus alba* var *pyramidalis* in NW China as well. This difference possibly can be explained by the very small crown area of the poplar trees and through the single row wind break arrangement and an upwind fetch of more than 1 km, which exposes the trees more to the dry ambient air compared to a plantation or denser wind break system.

In contrast to Thevs et al. [34], all tree wind break systems here consume less water than crops without tree wind breaks. This difference can be explained, as in Thevs et al. [34] firstly the assumptions regarding wind speed reduction by tree wind breaks were more conservative than the wind speed reductions found in this study and secondly multiple row poplar tree wind breaks were investigated with poplars significantly older and of higher DBH than the poplars considered in this study.

Reduction of ETo under shelterbelts in this study was between 5% and 55% and between 18% and 27% for 200 m x 200 m grids of single row and multiple row tree wind breaks. These values are in the range of the reduction of crop water consumption as suggested by the literature from Soviet Union times [8,9,15], but higher that of [12].

The most pronounced reductions of ETo just of the field plots were found with the multiple row wind breaks at small grid sizes, e.g. 50 m x 50 m and 100 m x 100 m. This is explained by the wind speed reduction by these multiple row wind breaks, which is much more significant in close distances to the wind break compared to the single row wind breaks (Fig. 4 and 5). In the large grid sizes, 500 m x 500 m and more, the effect to reduce water consumption is similar between the single row and the multiple row wind breaks. Though, the high water consumption of poplars over compensates the reduction of crop water consumption through the multiple row wind breaks. In particular the 50 m x 50 m grid of the poplar multiple row wind break consumes so much water that the overall water consumption of barley, potato, or wheat combined with such a multiple row poplar wind break system is higher than water consumption of the crops without a wind break (Tab. 6). The multiple row poplar wind breaks attain an overall reduction of water consumption at grid sizes of 400 m x 400 m and larger, with the strongest reduction at grid sizes of 400 m x 400 m and 500 m x 500 m (785 mm and 799 mm, respectively, compared to ETc of corn of 900 mm as shown in Tab. 6). This coincides with grid sizes which were most widely used during Soviet Union times [8,9,15,7]. The single row poplar wind break resulted in a higher reduction of the overall water consumption, as the water consumption of corn in Karasay Batyr was reduced from ETc of 1035 mm to an overall water consumption of 754 mm with a 100 m x 100 m grid. Thus, the single row poplar wind breaks attain a higher reduction in overall water consumption compared to the multiple row poplar wind breaks, because there are fewer trees per area in the agricultural landscape.

5. Conclusions

In this study the effect of tree wind breaks on water consumption in irrigated agriculture for Kyrgyzstan and adjacent areas was studied. Thereby, single row wind breaks from poplars and multiple row wind breaks from elm and poplar were studied, as these are the only remaining tree wind breaks types in the study region. Overall, the effect of reducing the total water consumption in irrigated agriculture is largest by multiple row elm wind breaks, followed by single row poplar wind breaks, and smallest by multiple row poplar wind breaks. Yet, elm grows much slower than poplar so that from an economic perspective poplars might be more attractive for farmers. Furthermore, single row wind breaks might by much easier to be integrated into the agrarian landscape, as they consume less space.

Author Contributions: Conceptualization, methodology, writing—original draft preparation and review and editing, Niels Thevs; investigation, data curation, and formal analysis, Alina Gombert and Eva Strenge; visualization and writing—review and editing, Kumar Aliev and Begaiym Emileva

Funding: This study was undertaken with support from the Federal Ministry of Economic Cooperation and Development of Germany (BMZ), through the Advisory Service on Agricultural Research for Development (BEAF) under Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), Germany. BMZ funded a research grant of 100,000 EUR and a six-month internship for Eva Strenge, in order to collect sap flow data. Niels Thevs' position as an integrated expert at the World Agroforestry Center as well as the sapflow equipment and the climate stations were co-funded by BMZ as part of the Center for International Migration and Development (CIM) program.

Acknowledgments: We thank the land owners and village administrations in the study sites for their support and permission to work on their land.

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

References

1. CACILM and ADB (Central Asian Countries Initiative for Land Management and Asian Development Bank). Central Asia Atlas of Natural Resources. CACILM and ADB: Manila, Philippines, **2010**. http://www.adb.org/sites/default/files/publication/27508/central-asia-atlas.pdf.

2. Reyer, C.P.O., Otto, I.M., Adams, S., Albrecht, T., Baarsch, F., Cartsburg, M., Eden, A., Ludi, E., Marcus, R., Mengel, M., Mosello, B., Robinson, A., Schleussner, C.-F., Serdeczny, O., Stagl, J. Climate change impacts in Central Asia and their implications for development. *Regional Environmental Change*, **2015**, doi 10.1007/s10113-015-0893-z.
3. Karthe, D. Environmental Changes in Central and East Asian Drylands and their Effects on Large Central and East Asian Lakes and their Effects on Major River-Lake Systems. *Quaternary International*, **2017**, doi: 10.1016/j.quaint.2017.01.041.
4. Unger-Shayesteh, K.; Vorogushyn, S.; Farinotti, D.; Gafurov, A.; Duethmann, D.; Mandychev, A.; Merz, B. What do we know about past changes in the water cycle of Central Asian headwaters? A review. *Global and Planetary Changes*. **2013**, 110, 4–25.
5. Feike, T.; Mamitimin, Y.; Li, L.; Abdusalih, N.; Doluschitz, R. Development of agricultural land and water use and its driving forces in the Aksu-Tarim Basin, P.R. China. *Environ. Earth Sci*. **2014**, http://dx.doi.org/10.1007/s12665-014-3108-x.
6. Rumbaur, C.; Thevs, N.; Disse, M.; Ahlheim, M.; Brieden, A.; Cyffka, B.; Duettmann, D.; Feike, T.; Frör, O.; Gärtner, P.; Halik, Ü.; Hinnenthal, M.; Keilholz, P.; Kleinschmid, B.; Krysanova, V.; Kuba, M.; Mader, S.; Menz, C.; Othmanli, H.; Pelz, S.; Schroeder, M.; Siew, T.F.; Stender, V.; Stahr, K.; Thomas, F.M.; Welp, M.; Wortmann, M.; Zhao, X.; Chen, X.; Jiang, T.; Luo, J.; Yimit, H.; Yu, R.D.; Zhang, X.M.; Zhao, C.Y. Sustainable management of river oases along the Tarim River (SuMaRiO) in Northwest China under conditions of climate change. *Earth Syst. Dyn*. **2015**, 6, 83e107.
7. Schroeder, W. R.; Kort, J. Shelterbelts in the Soviet Union. *Journal of Soil and Water Conservation*. **1989**, 44, 130–134. Available online at http://www.jswconline.org/content/44/2/130.full.pdf.
8. UNECE/FAO. Forest Landscape Restoration in the Caucasus and Central Asia. Geneva Timber and Forest Discussion Paper, 72. ECE/TIM/DP/72. Forestry and Timber Section, Geneva, Switzerland, **2019**. http://www.unece.org/fileadmin/DAM/timber/publications/DP-72-flr-cca-en.pdf. Accessed 18-June-2019.
9. Albenskii, A.V.; Kalashnikov, A.F.; Ozolin, G.P.; Nikitin, P.L.; Surmach, G.P.; Kulik, N.F.; Senkevich, A.A.; Kasyanov, F.M.; Pavlovskii, E.S.; Roslyakov, N.V. Agroforestry Melioration. Lesnaya promyshlennost. Moscow. **1972**.
10. Vasilyev, M.E. Melioration through Forests and Harvest. Kainar. Almaty. **1980**.
11. Puri, S.; Bangarwa, K. S. Effects of trees on the yield of irrigated wheat crop in semi-arid regions. In *Agroforestry Systems*. **1992**, 20, 229–241. DOI: 10.1007/BF00053141.
12. Perry, C.H.; Woodall, C.W.; Liknes, G.C.; Schoeneberger, M.M. Filling the gap: improving estimates of working tree resources in agricultural landscapes. *Agroforestry Systems*. **2009**, 75, 91-101.
13. Alemu, M.M. Ecological Benefits of Trees as Windbreaks and Shelterbelts. *International Journal of Ecosystem* **2016**, 6, 10-13. DOI 10.5923/j.ije.20160601.02.
14. Dokuchaev Scientific Research Institute of Agriculture. Agroforestry Melioration of Vegetable Cultures and Potato. Voronesh Publishing House, Voronesh. **1961**.
15. Stepanov, A.M. Agroforestry Melioration in Irrigated Lands. Agropromizdat, Moscow. **1987**.
16. Susa, N.I. Agroforestry Melioration. Governmental Publishing House for Agriculture. Moscov. 1959.
17. Kort, J. Benefits of windbreaks to field and forage crops. *Agriculture, Ecosystems & Environment*. **1988**, 22-23, 165-190.
18. Zheng, X.; Zhu, J.; Xing, Z. Assessment of the effects of shelterbelts on crop yields at the regional scale in Northeast China. *Agricultural Systems*. **2016**, 143, 49–60. DOI: 10.1016/j.agsy.2015.12.008.
19. Stigter, C.J; Mohammed, A. E.; Nasr, A., Nawal, K.; Onyewotu, L.O.Z; Oteng'i, S.B.B.; Kainkwa, R.M.R. Agroforestry solutions to some African wind problems. *Journal of Wind Engineering and Industrial Aerodynamics*. **2002**, 90, 1101–1114. DOI: 10.1016/S0167-6105(02)00224-6.
20. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. Crop evapotranspiration - Guidelines for computing crop water requirements. FAO Irrigation and drainage paper 56. FAO: Rome, **1998**.
21. Granier, A. Une nouvelle méthode pour la mesure du flux de sève brute dans le tronc des arbres. *Annales des Sciences forestières EDP Sciences*. **1985**, 42-2, 193-200.
22. Zotarelli, L.; Dukes, M.D.; Romero, C.C.; Migliaccio, K.W.; Morgan, K.T. Step by step calculation of the Penman-Monteith Evapotranspiration (FAO-56 Method). Inst. Food Agric. Sci. Univ. Fla. **2010.**
23. Thevs, N.; Strenge, E.; Aliev, K.; Eraaliev, M.; Lang, P.; Baibagysov, A.; Xu, J.C. Tree shelterbelts as an element to improve water resource management in Central Asia. *Water.* **2017**, 9, 842-852, doi:10.3390/w9110842.

24. Strenge, E. Sap flow characteristics of *Populus alba* and *Ulmus minor* in shelterbelt systems in Central Asia and their interaction with the local- microclimate. Master Thesis. University of Trier. **2017**.
25. Gombert, A. J. Estimating water consumption of poplar shelterbelt based on sap flow. Bachelor Thesis. Rhine-Waal University of Applied Sciences, Faculty of Life Sciences. **2018.**
26. Strenge, E.; Thevs, N.; Aliev, K.; Eraaliev, M.; Lang, P.; Baibagysov, A. Water consumption of *Populus alba* trees in tree shelterbelt systems in Central Asia. *Central Asian Journal for Water Resources*. **2018,** 4, 48-62. https://www.water-ca.org/api/v1/articles/5955-water-consumption-of-populus-alba-trees-in-tree shelterbelt-systems-in-central-asia.pdf.
27. Howell, T.A.; Tolk, J.A.; Schneider, A.D.; Evett, S.R. Evapotranspiration, yield, and water use efficiency of corn hybrids differing in maturity. *Agron J*. **1998**, 90, 3–9. doi:10.2134/agronj1998.00021962009000010002x.
28. Hochmuth, H.; Thevs, N.; He, P. Water allocation and water consumption of irrigation agriculture and natural vegetation in the Heihe River watershed, NW China. *Environmental Earth Sciences*. **2014**, DOI 10.1007/s12665-014-3773-9.
29. Zheleznyh, V.; Risbekov, Y.U. Analysis of experimental investigations on lizimeters comparatively with data on cotton field. **1987**. http://www.cawater-info.net/bk/water_land_resources_use/english/iptrid/uz_34.pdf.
30. Schaeffer, S. M.; Williams, D. G. Transpiration of desert riparian forest canopies estimated from sap flux. **1998**. http://www.tucson.ars.ag.gov/salsa/archive/publications/ams_preprints/schaeffer.PDF.
31. Muller, E.; Lambs, L. Daily variations of water use with vapor pressure deficit in a plantation of I214 poplars. *Water*. **2009**, 1, 32–42.
32. Chang, X.; Zhao, W.; Zhang, Z.; Su, Y. Sap flow and tree conductance of shelter-belt in arid region of China. *Agricultural and Forest Meteorology*. **2006**, 138, 132–141. DOI: 10.1016/j.agrformet.2006.04.003.
33. Xu, X.; Tong, L.; Li, F.; Kang, S.; Qu, Y. Sap flow of irrigated *Populus alba var. pyramidalis* and its relationship with environmental factors and leaf area index in an arid region of Northwest China. *Journal of Forest Research*. **2011**. 16, 144–152. DOI: 10.1007/s10310-010-0220-y.
34. Thevs, N.; Nurtazin, S.; Beckmann, V.; Salmurzauly, R.; Akimalieva, A. Water consumption of agriculture and natural ecosystems along the Ili River in China and Kazakhstan. *Water*. **2017**, 9, 207-221; doi:10.3390/w9030207.