CENTRAL ASIAN JOURNAL OF WATER RESEARCH (2025) 11(1): 27-46

https://doi.org/10.29258/CAJWR/2025-R1.v11-1/27-46.eng

Central Asian Journal of Water Research

Water consumption of a *Paulownia* plantation in an arid climate in Kyrgyzstan, Central Asia

Niels Thevs [a], Kumar Aliev [b], Clara Baier [c]

[a] Independent Scholar
[b] World Agroforestry, Toktogul Street 141, Bishkek, 720001, Kyrgyzstan
[c] Umweltbundesamt, Wörlitzer Platz 1, Dessau-Roßlau, 06844, Germany

ABSTRACT

Recently, *Paulownia* spec. has been introduced to Central Asia in a number of small plantations. *Paulownia* yields timber of high quality for applications such as furniture, house construction, boat construction, and surf boards, or skis. Thus, *Paulownia* might offer a much-needed raw material for this region and beyond. However, Central Asia is largely occupied by drylands so that *Paulownia* needs irrigation. Against the background of frequent water stress across the region, this study aimed at assessing the water consumption and water productivity of that tree, using a 6-year-old plantation as study site. Trees were planted in May 2017 and cut back to their stumps in 2018. Daily crop evapotranspiration was calculated after the Penman-Monteith approach, whereby the crop coefficients were inherited from actual evapotranspiration values which stemmed from the remote sensing approach S-SEBI. Water consumption per tree was 1741 l, 4461 l, 4500 l, and 4407 l over the growing seasons 2020, 2021, 2022, and 2023, respectively. The water productivity for the stem wood over the whole time-span from planting in 2017 until 2023 was 1.59 g l^{-1} and 5.65 ml l^{-1}. Given the high quality of its timber and its range of high-value applications, it can be concluded that the water consumed by *Paulownia* enables higher value timber and timber products than other trees that grow in comparable areas of Central Asia.

ARTICLE HISTORY

Received: February 20, 2024
Accepted: December 15, 2024
Published: January 16, 2025

KEYWORDS

woody biomass,
renewable raw material,
water consumption,
evapotranspiration, irrigation,
remote sensing

CONTACT Niels Thevs niels.thevs@gmail.com, Bonn, 53115, Germany

Published by Kazakh German University, Almaty/Kazakhstan

1. Introduction

Central Asia, including Kyrgyzstan, is a forest-poor region (Mitchel, 2015; UNECE, 2019; FAO, 2020) which has to import most of its wood demand (FAOSTAT, 2023). Against this background, the countries of that region included plans to promote fast-growing trees in plantations and in agroforestry into recent policy programs, examples being the Green Economy Program in Kyrgyzstan, the recent Strategy to Develop the Agriculture in the Republic of Uzbekistan 2020-2030, or the Kazakhstan-2050 strategy as reviewed by UNECE (2019). Those programs aim at reclaiming unused land for fast-growing tree plantations as well as inserting fast-growing trees into existing agroforestry systems.

Recently, *Paulownia* spec. has been introduced to Central Asia in a number of small plantations (Baier et al., 2021). *Paulownia* yields timber of high quality (Stimm et al., 2013; Bork et al., 2015; Nelis & Mai, 2019; Jakubowski, 2022) for applications such as furniture, house construction, boat construction, and surf boards, or skis. Thus, *Paulownia* might offer a much-needed raw material for this region and beyond. Due to the arid climate across the region, plantations of *Paulownia* require irrigation akin to most of the cropland. At the same time, Central Asia already faces severe water shortages that will be further aggravated in the course of climate change (Reyer et al., 2017).

Against this background, it is critical that new tree species introduced into an arid region – such as *Paulownia* spec. – are assessed as to whether or to what extent they bear the risk of bringing a new significant water consumer to an already water-stressed area. This study, therefore, addressed the following research questions:

- How much is the water consumption of *Paulownia* as plantation tree?
- What is the water productivity (expressed as wood biomass gained per volume of water consumed) of *Paulownia* as plantation tree?
- How do the water consumption and water productivity of *Paulownia* compare to other tree species of the region Central Asia? Does *Paulownia* consume significantly more water than other tree species of that region?

These questions are addressed by investigating the water consumption of the oldest *Paulownia* plantation of Central Asia, which is located at Issyk Kul Lake in Kyrgyzstan. Previous studies had assessed the water consumption by measuring the sap flow in 2019 (Baier et al., 2021) and 2020 (Thevs et al., 2021), whereas this study covers the growing seasons 2018 to 2023 employing a combination of water consumption computing through the Penman-Monteith approach by the FAO (Allen et al., 1998) and remote sensing.

The Penman-Monteith approach is a standard method, which calculates crop and tree evapotranspiration (ET_c), whereby climate data and so-called crop coefficients (K_c) serve as input data. Crop coefficients are published for the major global crops as well as fruit trees from a number of regions. For *Paulownia*, though, there are no crop coefficients available.

Hence, K_c values were calculated based on actual evapotranspiration (ET_a) derived through the remote sensing based Simplified Surface Energy Balance Index (S-SEBI) after Roerink et al. (2000), Sobrino et al. (2005; 2007), as reviewed by Gowda et al. (2007; 2008). Those K_c values fed into the calculation of crop water consumption after Allen et al. (1998) for those time periods during which no satellite images were available. Remote sensing based approaches, such as S-SEBI, were found suitable to assess crop and tree water consumption (Bhattarai et al., 2016).

This study uses the term water consumption as a synonym of evapotranspiration, which is defined as follows: Activities that divert water from its source or water that is no longer available because it has evaporated, been transpired by plants, incorporated into products or crops, consumed by people or livestock, or otherwise removed from the immediate water environment. The term ET_a refers to evapotranspiration of trees and grass vegetation ground cover together assessed through remote sensing, while ET_c refers to results from the calculations based on climate data and crop coefficients. ET_{trees}, finally, refers to the evapotranspiration viz. water consumption of the trees alone.

2. Methods

2.1. Study site

This study refers to the oldest and one of the largest *Paulownia* plantations of Central Asia, which is located on the northern coast of Issyk Kul Lake between the Airport Tamchy and the village Orn'ok (42.60 °N, 76.83 °E) at an elevation of 1636 m a.s.l. (Figure 1). The climate is cold semi-arid according to the Köppen-Geiger classification. Climate data for the study period 2017 to 2023 are shown in Table I for the climate station Cholpon Ata, which is the closest climate station to the study site. The soil is very dense and compacted with a silty to loamy texture, and stones account for 20 % of the total soil volume. There is no humus present, as there was no significant vegetation before this plantation had been established (Baier et al., 2021).

Table I. Climate data of the climate station Cholpon Ata from 2017 till 2023 (Weather in the world, 2024)

Year	Temperature [°C]			Wind speed [m/s]		Annual precipitation [mm]
	Average	Min.	Max.	Average	Max.	
2017	9.1	-3	22.7	1	3.2	215
2018	8.7	-7.6	23.3	1.1	3.1	504
2019	9.2	-3.8	22.8	1.1	7.2	574
2020	8.3	-4.9	21.2	1	3.1	714
2021	8.4	-5.9	23.3	1	3.9	176
2022	9.6	-3.6	24.6	1	3	392
2023	9.4	-11.5	23.8	1.2	10.3	298

The plantation consists of four neighboring field plots, of which the first plot was established in early 2017. In 2018, 2019, and 2021, the plantation was expanded by the second, third, and fourth plot, respectively. This study focusses on the oldest plot, for which the most accurate plantation management data were available. That part, which was researched by this study, covers an area of 4.5 ha and comprises 3500 trees, all planted in May 2017. All trees were cut back to the trunk in April 2018 to induce the development of a stronger root system relative to the aboveground biomass. The distance between rows is 4.0 m, the distance between trees within the same row is 3.0 m. All trees belong to the hybrid *Paulownia* tomentosa x fortunei (brand name: Shan Tong). North of this *Paulownia* plot there is a plot with fruit trees, mainly of a local apple variety, which is about half the size of the adjacent *Paulownia* plot.

The trees were irrigated through drip irrigation, whereby each tree row was equipped with a dripline which had emitters every 60 cm. Therefore, a grassy ground cover vegetation developed along the drip lines, which covered more and more area and gained in density year by year until it covered 70% to 80% of the ground in 2022, when the trees increasingly provided shade.

Figure 1. Map of Issyk Kul Lake, including neighboring areas, and locations of the *Paulownia* site (black circle), cold pixels (black diamonds), and hot pixels (white triangles). The dotted lines and inclined numbers refer to the Landsat tiles with their respective path and row numbers.

2.2. Measuring stem volume and biomass production

Tree data – specifically, diameters at 0.05 m, 1.0 m, 1.3 m (diameter at breast height, DBH), and 2.0 m above the ground as well as diameter at the tip of the stem, stem height, and tree height – were recorded at the beginning and the end of the growing seasons 2019 (Baier et al., 2021), 2020 (Thevs et al., 2021), and at the beginning and after the end of the growing season 2023. The trees were pruned so that one or two pairs of opposite branches diverge from the stem near its tip. Stem volumes of the sampled trees were calculated from those data and converted into stem biomass by multiplication with the wood's basic density, which amounts to 0.28 g cm^{-3} for *Paulownia* (Baier et al., 2021). This study focused on stem volumes and biomass, because that part of the tree yields the most valuable timber.

2.3. Calculate tree water consumption

To assess the water consumption of the *Paulownia* plot, first the daily reference evapotranspiration (ET_o) was calculated according to FAO (Allen et al., 1998) for the growing seasons 2017 to 2023 from daily climate data, which were obtained from the climate station Cholpon Ata from the online database Weather in the World, 2024.

These daily ET_o values were calibrated for the *Paulownia* plantation and for the ground cover vegetation inside the plantation (specifically the part that had been planted in 2017). For this calibration two climate stations equipped with sensors for air temperature, air humidity, wind speed, and solar radiation (EM-50 logger from Decagon Devices, US) were placed outside and inside the *Paulownia* plot. The former represents the climate data of the ambient conditions, while the latter represents the micro-climate within the *Paulownia* plot. These climate stations recorded data during the growing season 2019, which was used to calculate that season's daily ET_o for the *Paulownia* plantation and for the ground cover vegetation inside the plantation (Baier et al., 2021). The relationships between the ET_o from Cholpon Ata and the ET_o at the *Paulownia* plantation as well as the ground cover vegetation are shown in Figure 2. The relationship between ET_o at Cholpon Ata and at the *Paulownia* plantation is very strong, as expressed by the high R^2, because the *Paulownia* plantation is located only 20 km from Cholpon Ata and, therefore, in the same geographical setting, specifically the plain adjacent to the northern coast of Lake Issyk Kul. Therefore, the climate at the *Paulownia* plantation and in Cholpon Ata are very similar.

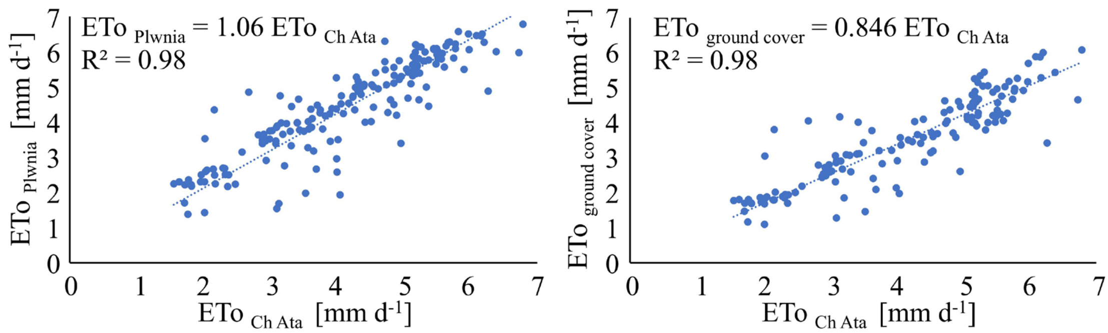

Figure 2. Relationship between ET_o from Cholpon Ata (x-axis) and ETo at the *Paulownia* plantation (left panel) and ET_o for the ground cover vegetation (right panel).

While ET_o refers to a standard grass vegetation, the crop evapotranspiration (ET_c) of a given crop or tree is calculated by multiplying ET_o with a crop coefficient (K_c):

$$ET_c = ET_o K_c \qquad (1)$$

The calculation of ET_o is explained in full detail in Allen et al. (1998). In this study, the terms crop coefficient and crop evapotranspiration are used although the object of this study is a tree.

As K_c values from the literature were not available, for each of the remote sensing based ET_a data points K_c was calculated by ET_a / ET_o. These K_c values were linearly interpolated between ET_a data points, which allowed to calculate an ET_c based on the daily ET_o (Thevs & Nowotny, 2023).

ET_a was assessed using the Simplified Surface Energy Balance Index (S-SEBI) (Roerink et al., 2000; Sobrino et al., 2005; 2007), as explained also by Thevs & Nowotny (2023). Landsat OLI data were used, because their resolution of 100 m x 100 m in the land surface temperature channel (LST) allowed to map the *Paulownia* plot, whereas MODIS with its resolution of 1000 m x 1000 m would be too coarse for the purpose of this study. Thereby, precision and terrain-corrected (L1TP) images were downloaded from the Earth Explorer web site (U.S. Geological Survey, n.d.).The Landsat data were converted into radiance and LST expressed in Kelvin according to USGS (2019).

The S-SEBI model calculates the latent heat flux, i.e. water consumption, as:

$$LE_d = \Lambda_d R_{nd} \quad (2)$$

where LE_d, Λ_d, and R_{nd} refer to the daily latent heat flux sum [MJ d^{-1}], the dimensionless daily evaporative fraction, and the daily net radiation sum [MJ d^{-1}], respectively.

If the daily net radiation (R_{nd}) is converted into evapotranspiration, i.e. potential evapotranspiration (ET_{pot}), ET_a can be calculated as follows (Sobrina et al., 2005; 2007):

$$ET_a = \Lambda ET_{pot} \quad (3)$$

Thereby, the evaporative fraction (Λ) is the share of ET_{pot} which is actually realized as ET_a. Hence, over well-watered vegetation, such as wetlands, Λ ≈ 1 and $ET_a \approx ET_{pot}$. There, the land surface temperature (LST) is low, because the energy of the incoming radiation is consumed by the ongoing evapotranspiration. In contrast, Λ and ET_a are zero at places without any vegetation or other moisture. Here, LST is high, because the energy of the incoming radiation goes into the sensible heat flux. Between these two extremes, a linear relationship between LST and Λ is assumed (Roerink et al., 2000). The calculation of Λ rests on so-called cold pixels, where Λ ≈ 1, and hot pixels, where Λ ≈ 0, which must be selected from the given satellite image.

The evaporative fraction Λ is calculated as follows:

$$\Lambda = \frac{(T_H - T_x)}{(T_H - T_C)} \quad (4)$$

where T_H and T_C refer to the average LST of the hot pixels and cold pixels of a given satellite image, respectively, while T_x refers to the LST of the pixel, for which Λ is calculated. Cold pixels must show a low LST due to their high evapotranspiration and not due to simply being cold objects, e.g. deeper water bodies. Hot pixels must not exhibit any evapotranspiration and are, therefore, selected in areas without vegetation. However, non-vegetated areas may have a wide range of LST due to their surface characteristics (such as surface color or structure) or geographical location. From that range of non-vegetated areas, the pixels with the lowest LST must be selected as hot pixels to avoid that Λ will be over-estimated (Waters et al., 2002; Sena et al., 2007). The cold and hot pixels were selected manually for each Landsat image, in order to avoid errors by cloud cover or land cover changes, for example by grazing.

ET_{pot} [mm d^{-1}] is calculated using the following set of formulae (5-8):

$$ET_{pot} = \frac{R_{nd}}{L_{water}\,\rho_{water}} \qquad (5)$$

where ρ_{water} is the density of water (1005 g l^{-1}), while R_{nd} [MJ m^{-2} d^{-1}] refers to the daily net radiation (cf. equation 7).

L_{water}, the latent heat of vaporization of water [MJ g^{-1}] is calculated using the following equation:

$$L_{water}=10^{6}\ (2500.8-2.36\ (LST-273.15)) \qquad (6)$$

Thereby, *LST* is the land surface temperature in Kelvin.

Equation 7 calculates the daily net radiation *Rnd* [MJ m^{-2} d^{-1}]:

$$R_{nd}=R_{s}\ (1-a)-110\ tr \qquad (7)$$

where α refers to the albedo and tr to the transmissivity. The albedo was calculated from each Landsat image according to Liang (2000).

R_s is the daily solar radiation [MJ m^{-2} d^{-1}] and is calculated as follows:

$$R_{s}=trR_{a} \qquad (8)$$

where tr is the transmissivity. Ra, the extraterrestrial radiation [MJ m^{-2} d^{-1}], was calculated after the respective equations from the Penman-Monteith approach that had been mentioned above to calculate ET_o (Allen et al., 1998). The transmissivity is the fraction of Ra that eventually penetrates the atmosphere down to the earth's surface. For each date of each Landsat image the transmissivity was taken from the respective ET_o calculations.

The water consumption was mapped from Landsat OLI (Landsat 8 and 9) images, path/row 149/30, 149/31, and 150/30 during the growing seasons 2018 through 2023 (Supplement 1). On each satellite image, clouds were masked out manually. The so-called cold pixels were placed manually into reed beds at the western and eastern coast of lake Issyk Kul, while the so-called hot pixels were placed into areas without vegetation adjacent to cropland. All handling of the satellite images, other geo-data, and the calculations of water consumption (or evapotranspiration) were done in Q-GIS (version 3.16.7).

The resulting ET_a and ET_c data included the water consumption of the trees and the grassy ground cover vegetation summed together ($ET_{c\ plot}$). To calculate the water consumption, ET, of the trees alone, ET_c of the ground cover vegetation was assessed and subtracted from ET_c of the trees and the ground cover vegetation summed together. For the growing seasons 2018, 2019, and 2020, the water consumption (ET_c) of that ground cover vegetation was calculated after Allen et al. (1998) based on the relationship shown in Figure 2 and observations of the coverage of that vegetation. For 2021, 2022, and 2023, ET_{trees} was calculated as ET_{trees} = 0.79 ET_c plot. The factor 0.79 was adopted from Allen & Pereira (2009) for Citrus plantations with a tree crown coverage of 50-60%, because those Citrus plantations had similar K_c values are revealed in this study.

3. Results

3.1. Tree data and woody biomass

At the end of the growing season 2023, the stem biomass and stem volume reached 25.3 kg per tree and 0.09 m^3 per tree, respectively (Table II). This corresponds to a stem biomass of 21 t ha^{-1}. While the stem biomass increased by 3.8 t ha^{-1} (by 76%) during the growing season of 2020, increased by 4.3 t ha^{-1}, which corresponds to only 26%, during the growing season 2023.

Table II. Tree data from 2019 (Baier et al., 2021) 2020 (Thevs et al., 2021), June 2023, and December 2023

Tree parameter	30 Apr 2019	21 Oct 2019	26 May 2020	19 Oct 2020	17 Jun 2023	25 Dec 2023
Tree height [m]	2.73	4.43	4.24	5.39		8
DBH [cm]	5.0	7.9	7.7	10.4	15.3	17.5
Stem volume per tree [m^3]	0.006	0.016	0,022	0.039	0.072	0.09
Stem biomass per tree [kg]	1.53	4.3	6.2	10.9	20	25.3

Table II. Cont.

Stem volume per area [m^3 ha^{-1}]	5	13.3	18.3	32.5	60	75.9
Stem biomass per area [kg ha^{-1}]	1274	3582	5165	9080	16667	21084

3.2. Water consumption

The daily ET_a values as revealed by remote sensing show a clear seasonal pattern with the annual maxima in June or July of each year. The maximum daily ET_a values of the plot established in 2017 only exceed 3 mm d^{-1} in 2019, increase to 4.6 mm d^{-1} in 2021, and remain between 4 mm d^{-1} and 5 mm d^{-1} during the following years (Figure 3). The maximum daily ET_a values of the plot established in 2018 exceed 3 mm d-1 a year later, in 2020, but remain between 4 mm d^{-1} and 5 mm d^{-1} from 2021 till 2023. The maximum daily ET_a values of the plot established in 2019 only exceed 4 mm d-1 during the growing season 2023. The daily ET_a values of the plot established in 2021 never exceed 2 mm d^{-1} during the study period of this study. The fruit trees never exceed an ET_a of 3.5 mm d^{-1}. Correspondingly, the K_c values of the fruit trees ranged between 0.4 and 0.5 during mid-stage.

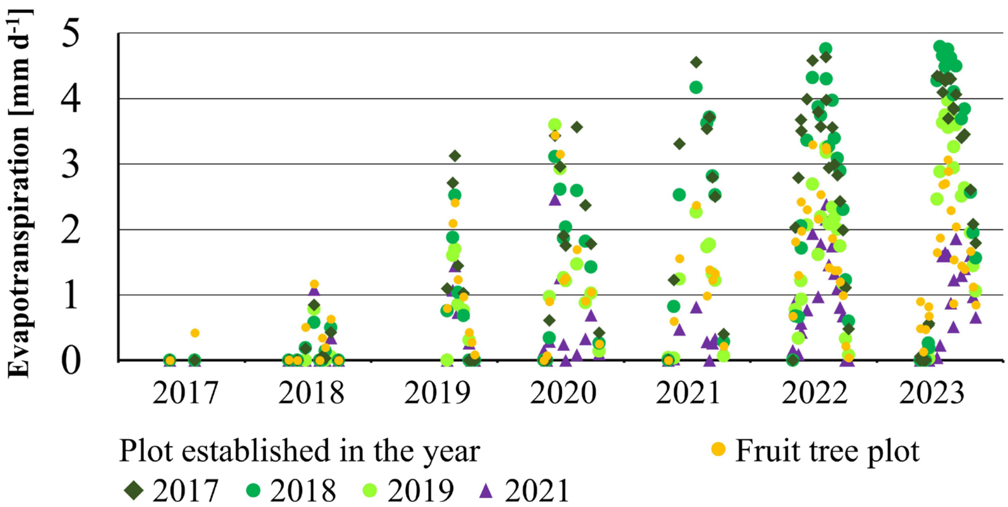

Figure 3. ET_a of the four plots and the fruit tree plot (trees and grass ground cover) from 2017 through 2023.

Analogous to ET_a, the K_c values of the plot that had been established in 2017 remained low (below 0.2) during the growing season 2018, jumped to a maximum of 0.65 the following growing season, and reached values between 0.8 and 1 during the growing seasons 2021-2023 (Figure 4), though the K_c values ranged between 0.6 and 0.8 for most of the time during the growing seasons 2021-2023. Within each growing season, K_c remained close to zero during May and only increased substantially during June, while it dropped sharply at the end of the growing seasons, when irrigation ceased.

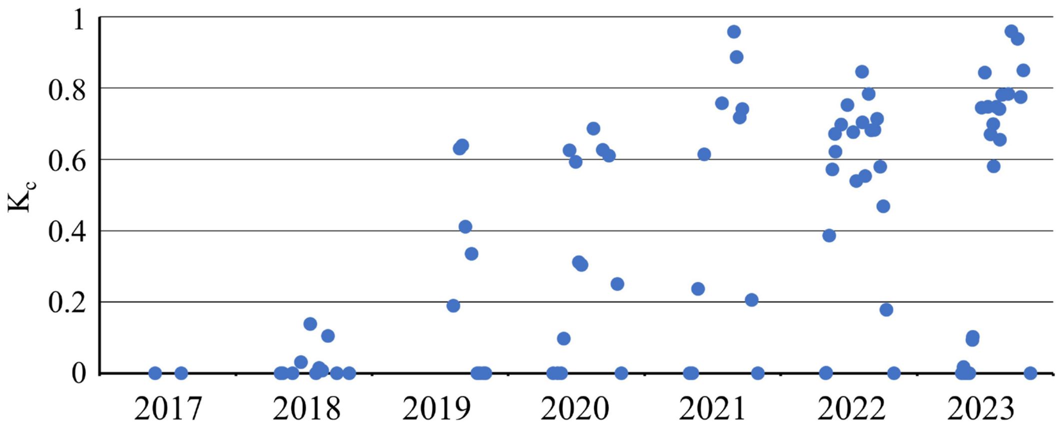

Figure 4. K_c values over the growing seasons 2017-2023 of the plot established in 2017 (*Paulownia* and grassy understory vegetation pooled together)

While ET_o from 2017 to 2023 remained in a range between 720 mm and 787 mm over the growing seasons, the ET_a of trees and grass ground cover vegetation as derived from remote sensing increased from 29 mm in 2018 to 470 mm in 2021 and remained around 470 mm afterwards (Table III). ET_c of the ground cover vegetation increased from 69 mm in 2018 to 160 mm in 2020. Afterwards, as the trees developed larger crowns, ET_c of the ground cover vegetation remained between 98 mm and 100 mm over the growing seasons 2021 to 2023. In 2018, the calculated ET_c of the ground cover vegetation exceeds ET_a of trees and ground cover so that no further tree water consumption was calculated for this year (Table III).

The water consumption expressed for single trees of the plot established in 2017 reached values of 4407 l to 4500 l over the whole growing seasons 2021, 2022, and 2023 (Table II). The growing season 2019 was only covered by satellite images from beginning of August so that the tree water consumption of 425 l reflects only the three months August, September, and October.

Table III. ET_o, total ET_a of the *Paulownia* plantation plot planted 2017, ET_a of the *Paulownia* trees, total water consumption per tree, average daily water consumption per tree, and maximum daily water consumption per tree over the growing seasons 2017-2023. Note: In 2019, total ET_a of the *Paulownia* plantation plot planted 2017, ET_c of ground cover grass vegetation, ET of the *Paulownia* trees, total water consumption per tree, average daily water consumption per tree, and maximum daily water consumption per tree were only recorded for August, September, and October, as highlighted by the asterix.

Year	ET_o [mm]	ET_a of trees and ground cover [mm]	ET_c of ground cover [mm]	ET of *Paulownia* trees [mm]	ET per tree [l] over total season	Daily ET per tree [l d^{-1}], average over growing season	Daily ET per tree [l d^{-1}], maximum over growing season
2017	760						
2018	768	29	69				
2019	781	96*	61*	35*	425*	4.6*	25.9*
2020	720	304	160	145	1741	9.5	31.6
2021	774	470	99	372	4461	24.4	47.6
2022	787	474	100	375	4500	24.6	45.7
2023	801	465	98	367	4407	24.1	49.7

The increase in tree water consumption along with the tree development becomes more pronounced when adding water consumption data from 2017 and 2018, as shown in Table IV. The average water consumption per tree (and sapling in 2017) was estimated at 1 l d^{-1}, which amounts to 184 l over the growing season from 1st of May to 31st of October for 2017 and 2018 each, when *Paulownia* emerged from the ground, as it was planted in 2017 and regrew from the stump in 2018. Baier et al. (2021) had measured tree water consumption through sap flow measurements and reported an average tree water consumption of 452 l over the whole growing season. From 2019 (sap flow measurement) to 2020, the tree water consumption (derived by remote sensing) jumped to 1741 l per tree over the growing season. The sum of the water consumption per tree from planting to the end of the growing season 2023 is 15929 l.

3.3. Water productivity

The water productivity calculated for the end of the growing season 2023 was 1.59 g l^{-1} and 5.65 ml l^{-1}. Note that this water productivity refers to the stem wood and excludes branches. If calculated for the end of the growing seasons 2020 and

2019, the water productivities would have been 4.26 g l^{-1} and 3.38 g l^{-1}, respectively. The former corresponds to 15.2 ml l^{-1}. The latter is calculated with the data from Baier et al. (2021). This decrease of water productivity over time, from 2020 to 2023, is also reflected in Figure 5, which shows that the accumulated water consumption increased faster after 2020 compared to the stem biomass increment.

Table IV. Water consumption of *Paulownia* trees from 2017 till 2023 from literature values and remote sensing data.

Year	Water consumption per tree [l] (sap flow) from Baier et al. (2021)	Water consumption per tree [l] remote sensing	Assumption based on data from (Andivia et al., 2013)
2017			184
2018			184
2019	452		
2020		1741	
2021		4461	
2022		4500	
2023		4407	

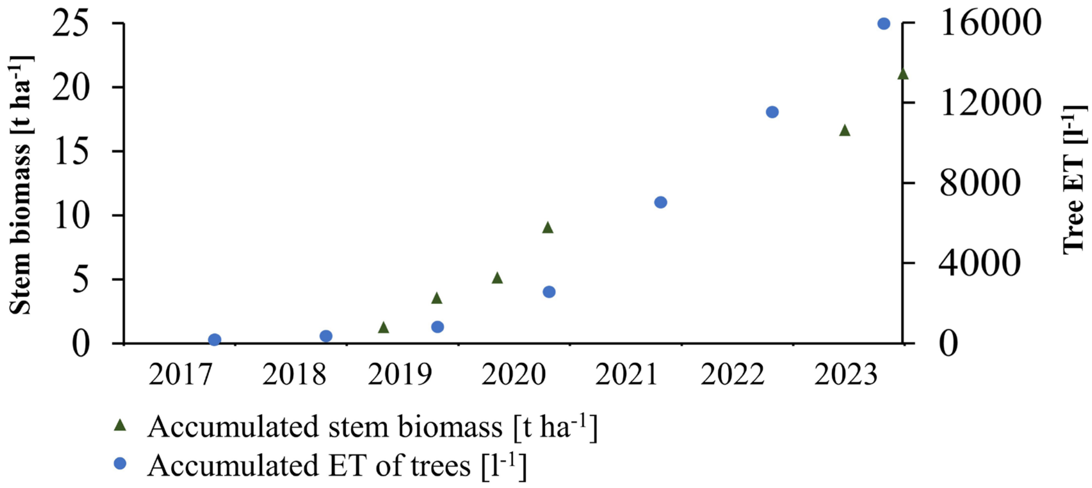

Figure 5. Stem biomass [t ha^{-1}] and tree water consumption [l per tree] accumulated over the growing seasons 2017-2023.

4. Discussion

On average, 10-year-old *Paulownia* trees reach a DBH of 35 to 40 cm and a volume of 0.3 to 0.5 m^3 (Stimm et al., 2013), which would be equivalent to an average annual DBH increment of 3.5 to 4.0 cm and an average annual volume increment of 30 to 50 l. Willwock (2019) studied growth rates of *Paulownia* trees in

Bishkek, Kyrgyzstan, and measured an annual DBH and volume increment of 4.9 to 6.6 cm and 30 to 40 l, respectively. García-Morote et al. (2014) attained a biomass of 2.14 t ha^{-1} to 4.5 t ha^{-1} after a one-year planting experiment, which also exceeds the biomass found in this study after the first year. That experiment was irrigated with 380 mm over the growing season, which is closer to the water consumption (ET_a) of 2020 (the third year after cutting back the trees) than 2018 (the first year after cutting back the trees). All those readings are well above the DBH, volume, or biomass increment observed in this study on *Paulownia* trees. This can be explained by a relatively short growing season and cool summer temperatures compared to e.g. Bishkek (Jakubowski, 2022). A plantation in Bulgaria yielded a biomass of 3.5 t ha^{-1} after two years (Jakubowski, 2022), which is very close to the 3582 kg ha^{-1} (Table II) measured on the plot in Kyrgyzstan at the end of the growing season 2019, i.e. its second year after being cut back.

The K_c values of the plantation established in 2017 are in the same range as K_c values for Citrus fruit tree plantations with ground cover vegetation as listed in Allen et al. (1998) and Allen & Pereira (2009). They are, however, lower than those of fruit tree species with ground cover vegetation, such as apricots or apples – which attain K_c values of up to 1.15 and 1.2, respectively, during mid-season (Allen et al., 1998) – or those of walnuts with a crown coverage of 50%, which attain K_c values of up to 1.10 during mid-season (Allen & Pereira, 2009). Looking at timber-bearing trees, Allen et al. (1998) list conifers with K_c values of 1.0 throughout the growing season, while Thevs et al. (2017) found a K_c value of 1.43 for mid-season for poplar trees in an irrigated agroforestry system in Kazakhstan. Guidi et al. (2008) measured K_c values of 1.71-4.28 and 1.97-5.30 for two-year-old poplar and willow short rotation plantations, respectively, near Pisa in Italy. In a *Populus euphratica* forest in Ejina, Inner Mongolia, China, a K_c value of 0.62 was measured during the second half of June, which is in the same range as the K_c values which this study found for *Paulownia*. However, *P. euphratica* does not yield timber of good quality (Hou et al., 2010).

Wullschleger et al. (1998) compiled a list of tree species with their maximum daily water consumption, which ranged from 24 kg d^{-1} to 94 kg d^{-1} for those trees with a diameter between 15 cm and 20 cm. This diameter range corresponds to the average diameter of the *Paulownia* trees planted in 2017 during the growing season of 2023 and the daily maximum water consumption of the *Paulownia* trees was 49.7 l, which is in the range mentioned above. *Cecropia longipes* (diameter 20 cm), which is a tree with large leaves similar to *Paulownia* had a maximum daily water consumption of 47 kg d^{-1}. The highest maximum daily water consumption of 94 kg d^{-1} was reported for *Eucalyptus grandis*.

On the plot that had been established in 2017, Baier et al. (2021) had measured the water consumption of *Paulownia* trees through sapflow measurements during the whole growing season 2019, which resulted in an average tree water consumption of 452 l per tree over the whole growing season. In this study, the water consumption of *Paulownia* summed up to 425 l per tree over the three months August, September, and October. If satellite images had been available throughout the whole growing season 2019, this study would have revealed a higher tree water consumption than Baier et al. (2021), though less than two-fold of Baier et al.'s (2021), because the water consumption of the trees is very low during May and only increases during June, while it drops sharply during late September and October. The difference between the two studies can be partly explained by an underestimation of water consumption by the sap flow method (Steppe et al., 2010; Fuchs et al., 2017; Flo et al., 2019).

From the growing season 2019 to 2020 and further to 2021, the tree water consumption increased sharply (cf. Table IV), which can be explained by a huge increase in tree diameters. Wullschleger et al. (1998) showed that the daily water consumption per eucalyptus tree (*Eucalyptus grandis* × *urophylla*) increased from less than 5 kg d^{-1} to about 30 kg d^{-1} along with an increase in stem diameter from 10 cm to 20 cm. A further increase of stem diameter resulted in a tree water consumption of nearly 150 kg d^{-1}. A similar relationship between stem diameter of eucalyptus and water consumption was found by Forrester (2015). As a comparison, young eucalyptus (1.5 to 7 years old) in South Africa showed daily water consumptions per tree from 15 l d^{-1} up to 64 l d^{-1} (Albaugh et al., 2013), which is well above the tree water consumptions found in this study. In this study, the water consumption per tree was 4407 l over the growing season 2023, which corresponds to 24.1 l d^{-1} (Table III and IV). A review on the water consumption of willows (Salix spec.) by Frédette et al. (2019) revealed an average of 4.6 mm d-1, which is above the highest ET_a of this study (Table III). In contrast to the growing seasons previous to 2021, the water consumption per tree remained in the same range from 2021 through 2023 (Table II and III). This change in water consumption is in line with the change in relative growth exhibited by the *Paulownia* trees: For instance, the trees' average DBH more than doubled from the end of the growing season 2019 to the end of the following growing season 2020. In contrast, it only increased by 68% during the following three growing seasons until the end of 2023 (Table II). In addition, the canopy area remained similar during the growing seasons 2021 to 2023, whereas it had increased substantially before (own field observations). These two findings may explain the steep increase in water consumption until 2021 compared to the plateau observed since then.

Water productivities were measured by Thomas et al. (2006) for a number of phreatophytic plant species, which cover their water demand from the groundwater in arid lands, in the Qira River plain at the margin of the Taklmakan Desert, Xinjiang, China. The tree species *Populus euphratica* showed water productivities of 2.12 g l^{-1} to 2.78 g l^{-1}. The herbaceous species *Alhagi sparsifolia* showed water productivities of 2.99 g l^{-1} to 5.18 g l^{-1}. Those water productivities are in the range of *Paulownia's* water productivity as found in this study.

Russian Olive (*Elaeagnus angustifolia*) on a site in Khorezm, Uzbekistan, was reported to consume 16 to 23 l d^{-1} per tree (Khamzina et al., 2009), which is a bit lower than the tree water consumption of *Paulownia* during its fifth, sixth, and seventh year after tree planting. The timber quality of *E. angustifolia* and P. euphratica wood, however, is clearly inferior to *Paulownia* wood in terms of quality. Thus, *P. euphratica* wood is mostly used as firewood, while *Paulownia* offers high-quality timber (Nelis & Mai, 2019; Bork et al., 2015; Stimm et al., 2013). Other water productivities for trees beyond the sapling stage from the literature were 1.5-3 gC kg^{-1} water for Pine plantations and native forests in N-Argentina (Cristiano et al., 2020) and 1.72-2.45 g l^{-1} for *Populus deltoides* in N-Carolina (Maier et al., 2019), which both are slightly above the water productivity of *Paulownia* in this study when considering the biomass accumulation over the seven years from 2017 to 2023. Water productivities for two-year-old poplars in Mississippi, USA, ranged from 2.9 to 6.6 g biomass l^{-1} (Renninger et al., 2021), which also is slightly higher than the water productivity of *Paulownia* during its early growth. The higher water productivities of these latter three studies can be partly explained by a longer growing season compared to the Issyk Kul region, considering that Jakubowski (2022) reviewed that the length of the growing season impacts growth rates of *Paulownia*.

Along with its widespread adoption as an ornamental or timber tree, concerns were voiced that *Paulownia* species might be an invasive tree species, e.g. as described by Snow (2015) for the U.S. In Austria, *Paulownia* tomentosa has been listed as an invasive species (Essl, 2007), while the Czech Republic gave it a status of an alien species that needs constant monitoring (Pergl et al., 2016). A country-wide mapping across Austria (Essl, 2007) revealed that *Paulownia* tomentosa behaved as a pioneer species that mainly colonized disturbed urban habitats, because its seeds are very light-demanding to germinate, while it rarely colonized near-natural habitats, such as forest clearings and riparian shrublands. Invasiveness of *P. tomentosa* was found under humid climate conditions, which provide sufficient soil moisture for the germination, sapling survival, and tree establishment. In Central Asia, such humid climate conditions are confined to few areas on higher elevations and along rivers, whereas natural forests or shrubland will outcompete *Paulownia* saplings. Those areas are also used as pastures. Given that *Paulownia* saplings are very susceptible to herbivory, livestock will most likely feed on any *Paulownia* specimen that reach the sapling stage (Longbrake, 2001). Therefore, *Paulownia* is not considered an invasive species in the context of this study.

In this study, the S-SEBI approach was employed to supplement the Penman-Monteith approach instead of assessing daily ET_a by synthetic daily LST images that could have been created through a fusion of Landsat and MODIS LST layers, as done by Weng et al. (2014), Hazaymeh et al. (2015), Zhao et al. (2020), or Salehi et al. (2021). The study area at Issyk Kul Lake faces partial cloud cover during many days of the growing season. Hence, the Landsat images which cover the study site and met the conditions of no cloud cover over the study site represented clear sky and sunny conditions, which resulted in higher ET_a and ET_c than under cloudy conditions. Therefore, synthetic LST layers, which eventually are based on those cloud-free Landsat pixels, may include a bias towards sunny conditions. The calculation of the Landsat ET_a depends on the so-called cold and hot pixels, which have to be selected manually because cloud cover, changing water levels, or grazing may render such pixels wrong so that they have to excluded from further processing. Daily synthetic layers possibly overlook such errors.

During the growing season 2018, ET_c of the ground cover vegetation was higher than ET_a of trees and ground cover vegetation. This is in line with findings that the remote sensing approach employed in this study cannot accurately assess low rates of water consumption (Stannard, 1993), as are typical for sparse vegetation, which has been reviewed by (Li et al., 2021). This inaccuracy may add to the explanation presented above as to why the sapflow data by Baier et al. (2021) and the remote sensing data of this study on the water consumption of *Paulownia* during the season 2019 differ. To appropriately assess such conditions of sparse vegetation or early stages of vegetation development, further calibration of this remote sensing approach is needed.

5. Conclusion

The water consumption and water productivity of *Paulownia* over a time span of seven years, starting with planting, are comparable to other tree species that grow under dryland conditions in neighboring regions of Central Asia – despite the fact that *Paulownia* is a fast-growing tree. This study, however, did not include the branches, instead focusing on the stem volume and biomass, which delivers the high-quality wood for which *Paulownia* is often planted. If we consider the biomass of the branches and their potential use for biorefinery or as a source of bioenergy, the water productivity reported by this study is a conservative number. Given the superior quality of its timber compared to poplar, elm, or Russian Olive, which are widely distributed across Central Asia, and its range of high-value applications, it can be concluded that the water consumed by *Paulownia* enables higher-value timber and timber products than other regionally used trees at a comparable level of water consumption.

If *Paulownia* was planted on large newly reclaimed areas, it would strain the available water resources, just as any other crop that would be expanded onto previously uncultivated land. However, if *Paulownia* was planted instead of other trees, it would not put more pressure onto existing water resources than those trees. The Issyk Kul region has a long tradition of producing fruit, in particular apples, but also apricots. As can be seen from the K_c values discussed above, the water consumption of such fruit orchards is similar to the water consumption of *Paulownia*. A detailed economic analysis of the profits from a *Paulownia* plantation versus fruit orchards is still lacking, because *Paulownia* plantation examined in this study has not been harvested and therefore has not yielded any revenue yet. Once this one and newer plantations are harvested, such an economic analysis needs to be done urgently. Notably though, Kyrgyzstan has been a net exporter of e.g. apricots for the past 20 years, while it needs to import nearly all its timber (FAOSTAT, 2023). Therefore, the introduction of fast-growing trees, such as *Paulownia*, in plantations or agroforestry systems can address the domestic demand for timber and reduce import dependencies.

References

Albaugh, J.M., Dye, P.J., & King, J.S. (2013). Eucalyptus beyond Its Native Range: Environmental Issues In Exotic Bioenergy Plantations, *International Journal of Forestry Research*. https://doi.org/10.1155/2013/852540

Allen, R.G., Pereira, L.S., Raes, D., & Smith, M. (1998). Crop evapotranspiration - Guidelines for computing crop water requirements, *FAO Irrigation and drainage paper* 56, Rome, FAO

Allen, R.G. & Pereira, L.S. (2009). Estimating crop coefficients from fraction of ground cover and height. I*rrigation Science*, 28, 17–34. https://doi.org/10.1007/s00271-009-0182-z

Andivia, E., Fernández, M., Alaejos, J., & Tapias, R. (2013). Consumo de aguade distintas especies leñosas utilizables como cultivos energéticos. 6° *Congreso Forestal Español*. https://www.congresoforestal.es/actas/doc/6CFE/6CFE01-122.pdf. Accessed 21 June 2020

Baier, C., Thevs, N., Villwock, D., Emileva, B., & Fischer, S. (2021). Water productivity of Paulownia tomentosa x fortunei (Shan Tong) in a plantation at Lake Issyk-Kul, Kyrgyzstan, *Central Asia. Trees*, 35, 1627-1637. https://doi.org/10.1007/s00468-021-02141-8

Bhattarai, N., Shaw, S.B., Quackenbush, L.J., Im, J., & Niraula, R. (2016). Evaluating five remote sensing based single-source surface energy balance models for estimating daily evapotranspiration in a humid subtropical climate. *International Journal of Applied Earth Observation and Geoinformation*, 49, 75-86

Bork, J., Walter, E., Mosandl, R., & Stimm, B. (2015). Paulownia—vorläufige Ergebnisse zu Möglichkeiten und Grenzen des Anbaus im Wald. *Forstarchiv,* 86, 102–106. https://doi.org/10.4432/0300-4112-86-102

Cristiano, P.M., Diaz Villla, M.V.E., De Diego, M.S., Lacoretz, M.V., Madanes, N., & Goldstein, G. (2020). Carbon assimilation, water consumption and water use efficiency under different land use types in subtropical ecosystems: from native forests to pine plantations. *Agricultural and Forest Meteorology,* 291, 108094. https://doi.org/10.1016/j.agrformet.2020.108094

Essl, F. (2007). From ornamental to detrimental? The incipient invasion of Central Europe by Paulownia tomentosa. *Preslia*, 79, 377–389

FAO (2020). Global Forest Resources Assessment. *Country Reports* 2020. http://www.fao.org/forest-resources-assessment/fra-2020/country-reports/en/. Accessed 10 June 2023

FAOSTAT (2023). https://www.fao.org/faostat/en/#home. Accessed 05 Jun 2023

Flo, V., Martinez-Vilalta, J., Steppe, K., Schuldt, B., & Poyatos, R. (2019). A synthesis of bias and uncertainty in sap flow methods. *Agriculture and Forest Meteorology,* 271, 362–374. https://doi.org/10.1016/j.agrformet. 2019.03.012

Forrester, D.J. (2015). Transpiration and water-use efficiency in mixed-species forests versus monocultures: effects of tree size, stand density and season. *Tree Physiology*, 35, 289–304. https://doi.org/10.1093/treephys/tpv011

Frédette, C., Labrecque, M., Comeau, Y., & Brisson, J. (2019). Willows for environmental projects: A literature review of results on evapotranspiration rate and its driving factors across the genus Salix. *Journal of Environment Management*, 246, 526-537. https://doi.org/10.1016/j.jenvman.2019.06.010

Fuchs, S., Leuschner, C., Link, R., Coners, H., & Schuldt, B. (2017). Calibration and comparison of thermal dissipation, heat ratio and heat field deformation sap flow probes for diffuse-porous trees. *Agriculture and Forest Meteorology,* 244–245, 151–161. https://doi.org/10.1016/j.agrformet.2017.04.003

García-Morote, F.A., López-Serrano, F.R., Martínez-García, E., Andrés-Abellán, M., Dadi, T., Candel, D., Rubio, E., & Lucas-Borja, M.E. (2014). Stem Biomass Production of Paulownia elongata × P. fortunei under Low Irrigation in a Semi-Arid Environment. *Forests*, 5, 2505-2520; doi:https://doi.org/10.3390/f5102505

Gowda, P.H., Chavez, J.L., Colaizzi, P.D., Evett, S.R., Howell, T.A., & Tolk, J.A. (2008). ET mapping for agricultural water management: present status and challenges. *Irrigation Science,* 26, 223-237

Gowda, P.H., Chavez, J.L., Colaizzi, P.D., Evett, S.R., Howell, T.A., & Tolk, J.A. (2007). Remote sensing based energy balance algorithms for mapping ET: current status and future challenges. *American Society of Agricultural and Biological Engineers*, 50, 1639-1644

Guidi, W., Piccioni, E., & Bonari, E. (2008). Evapotranspiration and crop coefficient of poplar and willow short-rotation coppice used as vegetation filter. *Bioresource Technology*, 99, 4832-4840

Hazaymeh, K. & Hassan, Q.K. (2015). Fusion of MODIS and Landsat-8 Surface Temperature Images: A New Approach. *PLOS ONE*, 10. e0117755. doi:https://doi.org/10.1371/journal.pone.0117755

Hou, L.G., Xiao, H.L., Si, J.H., Xiao, S.C., Zhou, M.X., & Yang, Y.G. (2010). Evapotranspiration and crop coefficient of Populus euphratica Oliv forest during the growing season in the extreme arid region northwest China. *Agricultural Water Management*, 97, 351-356

Jakubowski, M. (2022). Cultivation Potential and Uses of Paulownia Wood: A Review. Forests, 13, 668. https://doi.org/10.3390/f13050668

Khamzina, A., Sommer, R., Lamers, J.P.A., & Vlek, P.L.G. (2009). Transpiration and early growth of tree plantations established on degraded cropland over shallow saline groundwater table in northwest Uzbekistan. *Agriculture and Forest Meteorology,* 149, 1865–1874. https://doi.org/10.1016/j.agrformet.2009.06.015

Li, C., Li, Z., Gao, Z., & Sun, B. (2021). Estimation of Evapotranspiration in Sparse Vegetation Areas by Applying an Optimized Two-Source Model. *Remote Sensing*, 13, 1344 https://doi.org/10.3390/rs13071344

Liang, S.L. (2000). Narrowband to broadband conversions of land surface albedo I Algorithms. *Remote Sensing of the Environment*, 76, 213-238.

Longbrake, A.C.W. (2001). Ecology and Invasive Potential of Paulownia tomentosa (Scrophulariaceae) in a Hardwood Forest Landscape. *PhD Dissertation*. College of Arts and Sciences of Ohio University

Maier, C.A., Burley, J., Cook, R., Ghezehei, S.B., Hazel, D.W., & Nichols, E.G. (2019). Tree Water Use, Water Use Efficiency, and Carbon Isotope Discrimination in Relation to Growth

Potential in Populus deltoides and Hybrids under Field Conditions. *Forests*, 10, 993. doi: https://doi.org/10.3390/f10110993

Mitchell, A.M. (2015). Kyrgyz Republic—Communities, Forests, and Pastures. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/550371468263989781/kyrgyz-republic-communities-forests-and-pastures. Accessed 15 June 2023

Nelis, P.A. & Mai, C. (2019). Improved strength properties of three-layered particleboards with different core and surface layers based on Kiri wood (Paulownia spp.). *European Journal of Wood Products*, 77, 761–769. https://doi.org/10.1007/s00107-019-01442-7

Pergl, J., Sádlo, J., Petrusek, A., Laštuuvka, Z., Musil, J., Perglova, I., Šanda, R., Šefrová, H., Šíma, J., Vohralik, V. (2016). Black, Grey and Watch Lists of Alien Species in the Czech Republic Based on Environmental Impacts and Management Strategy. *NeoBiota*, 28, 1

Renninger, H.J., Steward, L.F., & Rousseau, R.J. (2021). Water Use, Efficiency, and Stomatal Sensitivity in Eastern Cottonwood and Hybrid Poplar Varietals on Contrasting Sites in the Southeastern United States. *Frontiers in Forests and Global Change*. https://doi.org/10.3389/ffgc.2021.704799

Reyer, C.P.O., Rigaud, K.K., Fernandes, E., Hare, W., Serdeczny, O., & Schellnhuber, H.J. (2017). Turn down the heat: regional climate change impacts on development. *Regional Environmental Change*, 17, 1563–1568. https://doi.org/10.1007/s10113-017-1187-4

Roerink, G.J., Su, B., & Menenti, M. (2000). S-SEBI A simple remote sensing algorithm to estimate the surface energy balance. *Physics and Chemistry of the Earth*, B 25, 147–157

Salehi, H., Shamsoddini, A., Mirlatifi, S.M., Mirgol, B., & Nazari, M. (2021). Spatial and Temporal Resolution Improvement of Actual Evapotranspiration Maps Using Landsat and MODIS Data Fusion. *Frontiers of Environmental Sciences,* 9, 795287. doi: 10.3389/fenvs.2021.795287

Senay, G.B., Budde, M., Verdin, J.P., & Melesse, A.M. (2007). A Coupled Remote Sensing and Simplified Surface Energy Balance Approach to Estimate Actual Evapotranspiration from Irrigated Fields. *Sensors,* 7, 979-1000

Snow, W.A. (2015). Ornamental, Crop, or Invasive? The History of the Empress Tree (Paulownia) in the USA. *Forests Trees amd Livelihoods*, 24, 85–96

Sobrino, J.A., Gómez, M., Jiménez-Muñoz, J.C., & Olioso, A. (2007). Application of a simple algorithm to estimate daily evapotranspiration from NOAA–AVHRR images for the Iberian Peninsula. *Remote Sensing of the Environment*, 110, 139-148

Sobrino, J.A., Gómez, M., Jiménez-Muñoz, J.C., Olioso, A., & Chehbouni, G. (2005). A simple algorithm to estimate evapotranspiration from DAIS data: Application to the DAISEX campaigns Original Research Article. *Journal of Hydrolology*, 315, 117-125

Stannard, D.I. (1993). Comparison of Penman-Monteith, Shuttleworth-Wallace, and Modified Priestley-Taylor Evapotranspiration Models for wildland vegetation in semiarid rangeland. *Water Resources Research*, 29, 1379-1392

Steppe, K., de Pauw, D.J.M., Doody, T.M., & Teskey, R.O. (2010). A comparison of sap flux density using thermal dissipation, heat pulse velocity and heat field deformation methods. *Agriculture and Forest Meteorology,* 150, 1046–1056. https://doi.org/10.1016/j.agrformet.2010.04.004

Stimm, B., Stiegler, J., Genser, C., Wittkopf, S., & Mosandl, R. (2013). Paulownia— Hoffnungsträger aus Fernost? Eine schnellwachsende Baumart aus China in Bayern auf dem Prüfstand. *LWF Aktuell,* 96, 18–21

Thevs, N. & Nowotny, R. (2023). Water consumption of industrial hemp (Cannabis sativa L.) during dry growing seasons (2018-2022) in NE Germany. *Journal of Cultivated Plants*, 75, 173-184. DOI: 10.5073/JfK.2023.07-08.01

Thevs, N., Baier, C., & Aliev, K. (2021). Water Productivity of Poplar and Paulownia on Two Sites in Kyrgyzstan, Central Asia. *Journal of Water Resource and Protection*, 13, 293-308. https://doi.org/10.4236/jwarp.2021.134018

Thomas, F.M., Foetzki, A., Arndt, S.K., Bruelheide, H., Gries, D., Li, X., Zeng, F., Zhang, X., & Runge, M. (2006). Water use by perennial plants in the transition zone between river oasis and desert in NW China. *Basic and Applied Ecology,* 7, 253-267. https://doi.org/10.1016/j.baae.2005.07.008

UNECE (2019). Forest Landscape Restoration in the Caucasus and Central Asia - Challenges and Opportunities. Background study for the Ministerial Roundtable on Forest Landscape Restoration in the Caucasus and Central Asia (21–22 June 2018, Astana, Kazakhstan). http://www.unece.org/fileadmin/DAM/timber/Forest_Policy/Capacity_building/FLR_CCA_challenges___opportunities_081018-ENG-edited.pdf. Accessed 10 May 2023

U.S. Geological Survey. (n.d.). Earth Explorer. Retrieved June 20, 2023, from https://earthexplorer.usgs.gov/

USGS (2019). Landsat 8 (L8) Data Users Handbook, Department of the Interior, U.S. Geological Survey, LSDS-1574 Version 5.0. Sioux Falls, South Dakota, EROS. https://www.usgs.gov/landsat-missions/landsat-8-data-users-handbook Accessed 16 Jan 2023

Villwock, D. (2019). Water productivity of Poplar and Paulownia as fast-growing trees in Central Asia, *Master Thesis,* University of Hohenheim

Waters, R., Allen, R.G., Tasumi, M., Trezza, R., & Bastiaanssen, W.G.W. (2002). SEBAL Surface Energy Balance Algorithms for Land – Idaho Implementation – Advanced Training and Users Manual, University of Idaho, USA

Weather in the world. (June 23, 2023). https://rp5.ru/Weather_in_the_world

Weng, Q., Fu, P., & Gao, F. (2014). Generating daily land surface temperature at Landsat resolution by fusing Landsat and MODIS data. *Remote Sensing of the Environment*, 145, 55-67. https://doi.org/10.1016/j.rse.2014.02.003

Wullschleger, S.D., Menzer, F.C., & Vertessy, R.A. (1998). A review of whole-plant water use studies in trees. *Tree Physiology,* 18, 499-512

Zhao, G., Zhang, Y., Tan, J., Li, C., & Ren, Y. (2020). A Data Fusion Modeling Framework for Retrieval of Land Surface Temperature from Landsat-8 and MODIS Data. *Sensors*, 20, 4337. https://doi.org/10.3390/s20154337