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Evapotranspiration of riparian ecosystems and irrigated cotton agriculture at the middle reaches of the Tarim River, Xinjiang, China

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Abstract
In the steppes, semi-deserts, and deserts of Central Asia the most productive ecosystems are riparian ecosystems like forests and shrublands. Rivers also serve as the water source for irrigation so that the major settlements and oases of the region are located near those rivers. Natural ecosystems and irrigated agriculture compete for space and water along those rivers. Expansion of irrigated agriculture resulted in water shortages along the rivers of Central Asia and degradation of natural ecosystems. The Tarim Basin, in Xinjiang, China, which covers an area of 1.02 million km², is home to a population of about 9.5 million people, and has turned into the world's most important cotton production region with a total annual cotton lint production of 2.1 million tonnes, i.e. 8.85% of the world production, in 2010. The Tarim Basin also harbours 54% (352,200 ha) of the world's riparian Populus euphratica Oliv. forests. The objective of this paper is to determine the actual evapotranspiration (ET_a) of cotton as major crop and of the natural vegetation along the Tarim River. Among the natural vegetation, the focus is on Populus euphratica forests and Tamarix dominated shrub vegetation as the major natural ecosystems. The actual evapotranspiration was determined with the Bowen Ratio approach. Reference evapotranspiration (ET_o) and crop coefficients (K_c) were calculated using the Penman-Monteith-approach. The summed ET_o of the three sites investigated was from 1122 mm to 1280 mm for the growing season. The ET_a sums of cotton, Populus euphratica forest, and Tamarix shrub vegetation were 489 mm, 879 mm, and 410 mm, respectively. K_c of cotton ranged between 0.30 and 0.62, thus much lower than in the FAO guidelines. This can be explained by improved varieties, drip irrigation, and plastic mulch.

Keywords: water consumption, *Populus euphratica*, *Tamarix*, Central Asia, Bowen ratio

1. Introduction

Central Asia, which stretches from the Caspian Sea to Northwest China and Mongolia, is largely covered by steppes, semi-deserts, deserts (the Turanian Deserts), and large mountain areas (Tianshan, Pamirs, and Altay as major mountain ranges). Those mountains are the source areas of the rivers of the region, like the Amu Darya, Syr Darya, Ili, Chu, and Tarim. In the semi-desert and desert regions, those rivers sustain riparian ecosystems, which are the most productive ecosystems in the semi-deserts and deserts of Central Asia [1, 2, 3]. At the same time, those rivers serve as a major water source for irrigation, so the major settlements and oases of the region are located along those rivers, too.

Natural ecosystems and irrigated agriculture compete for space and water in the floodplains along those rivers. In the Aral Sea Basin, i.e. along the Amu Darya and the Syr Darya Rivers, planting of cotton was strongly promoted from the 1960s onward. As a consequence, the Aral Sea and the natural ecosystems there have nearly vanished [4]. In the Tarim Basin, the oases area was enlarged from the 1950s onward leading to the complete desiccation of the Lakes Lop Nor and Taitema, the former end-lakes of the Kenqi and Tarim Rivers, respectively [5]. After the year 2000, the Taitema Lake has been partly restored, as flood pulses have been released into the lower reaches of the Tarim almost every year [6]. Still, in both basins lower reaches of the rivers partly turned into episodic river courses or fell dry completely. Under those conditions, the natural riparian vegetation and the irrigation agriculture, especially along the lower reaches, suffered and suffer water shortage leading to degradation of natural ecosystems [4, 7, 8, 9, 10].

The Tarim Basin, in Xinjiang, China, which covers an area of 1.02 million km^2, is a home to a population of about 9.5 million people and is one of the most arid regions worldwide. It has turned into the world’s most important cotton production region with a total annual cotton lint production of 2.1 million tonnes, i.e. 8.85% of the world production, in 2010 [11]. In 2011, the share of the cotton lint production in Xinjiang of the worldwide production climbed to 11% [12]. Half of the cotton in the Tarim Basin is produced along the Aksu and Tarim Rivers [11, 13]. Most of the cotton plantations in Xinjiang have been converted from flood or furrow irrigation into drip irrigation combined with plastic mulch, which covers the soil around the drip lines as described by Zhou et al. 2012 for Northern Xinjiang [14]. This irrigation technique has reduced the water consumption of cotton compared to the previously used technique of flood and furrow irrigation. Yet, on the other hand, the area under cotton has been expanded from 0.4 million ha in 1990 to 1.4 million ha in 2010 [15], so the downstream region along the Tarim River still suffers from periods of water shortages [16].

The Tarim Basin also harbours 54% (352,200 ha) of the world’s riparian *Populus euphratica* Oliv. forests [17]. Those forests form a mosaic of riparian forests, wetlands, shrub vegetation, as well as small stands of herbaceous vegetation [18] and provide habitat for wildlife [17]. The *Populus euphratica* forests are the only forests in the Tarim Basin. The largest contiguous areas of the *Populus euphratica* forests with associated wetlands and shrub vegetation are located along the Tarim River in the two nature reserves Tarim Shangyou and Tarim Huyanglin, which stretch along the Tarim River in Xayar County and downstream from Yingbaza, respectively (Figure 1).

In order to be able to balance the water allocation to cotton and the natural ecosystems, and meet the corresponding water demands, basic information about the water demand of cotton and natural ecosystems is needed. Therefore, in this paper the authors aim at determining the actual evapotranspiration (ET_a) of cotton under the prevalent drip irrigation – plastic mulch irrigation technique, as it is the major crop in the Tarim Basin, as well as at determining the ET_a of the natural vegetation along the Tarim River. Among the natural vegetation, the focus is on *Populus euphratica* forests and *Tamarix* dominated shrub vegetation as the major natural ecosystems.

The actual evapotranspiration of a crop or a patch of vegetation (ET_a) can be determined in the field through: i) calculating a reference ET through climate station data and applying crop coefficients [19], ii) through the Bowen Ratio method e.g. [20] as used by Hou et al. 2010 to determine evapotranspiration of *Populus euphratica* at the Heihe River in Inner Mongolia, China [21], iii) lysimeters e.g. [22], or iv) eddy co-variance measurement devices, e.g. [23, 24]. Thereby, lysimeters and eddy co-variance measurement devices are very costly in comparison to climate stations as needed for the two former approaches.

Therefore, in this study, ET_a is determined through the Bowen Ratio method [20]. Furthermore, ET_a is related to the reference ET (ET_o) of the Penman-Monteith approach [19] through calculation of crop coefficients. This will allow decision makers and those involved in planning to estimate water demand for cotton, *Populus euphratica* forests, and *Tamarix* dominated shrub vegetation in the Tarim Basin and beyond. Such crop coefficients were mainly developed for agricultural crops, but not for the species of the natural vegetation targeted in this study. Crop coefficients for most crops date back to the 19870s or 1980s and thus may not take into account recent breeding progresses [25].

Measurements on water consumption of cotton under drip irrigation combined with plastic mulch are scarce, as this technology only has been adopted in the past 5-10 years. Evapotranspiration of *Populus euphratica* forests and *Tamarix* dominated shrub vegetation were investigated in Qira (Cele) at the southern fringe of the Taklamakan Desert in Xinjiang, China [1], and at the Heihe River in Inner Mongolia, China [21]. Both sites represent *Populus euphratica* forests and *Tamarix* dominated shrub vegetation of a low vegetation cover of 20-30%, while this paper aims at the dense forests and shrub vegetation along the Tarim River, especially those in the protected areas, as described by Thevs et al. 2008 [18].

2. Methods

2.1. Study area

This study was conducted on the three sites: Yingbaza (41.21°N, 84.22°E, elevation 930 m a.s.l.), Iminqak (41.25°N, 84.44°E, elevation 932 m a.s.l.), and Qongaral (41.33°N, 85.57°E, elevation 860 m a.s.l.), all located in the flood plain of the Tarim River and its river branches. Yingbaza and Qongaral are located adjacent to the Tarim Huyanglin Nature Reserve. Iminqak is located in the core zone of that Nature Reserve (Figure 1).

The Tarim River, 1321 km long, forms at the confluence of the three rivers Aksu, Yarkant, and Hotan in Aral City. Today only the Aksu River carries permanently water to the Tarim River, while the Yarkant and Hotan only discharge into the Tarim during flood events. On average, 75% of the annual discharge of the Tarim is delivered by the Aksu River [6]. The headwaters of the Aksu are located north of Aksu City in the Central Tianshan (Figure 1).

There, snow and glacier melt as well as summer rainfall deliver water into the Aksu River's headwaters [5, 26, 27]. Within each year, about 75% of the annual runoff is discharged during July, August, and September, which results in annual summer floods [5, 6]. Thereby, the flood of 2010 was one of the highest during the past five decades so that e.g. the soil surface at the site Iminqak was moist until May 2011.

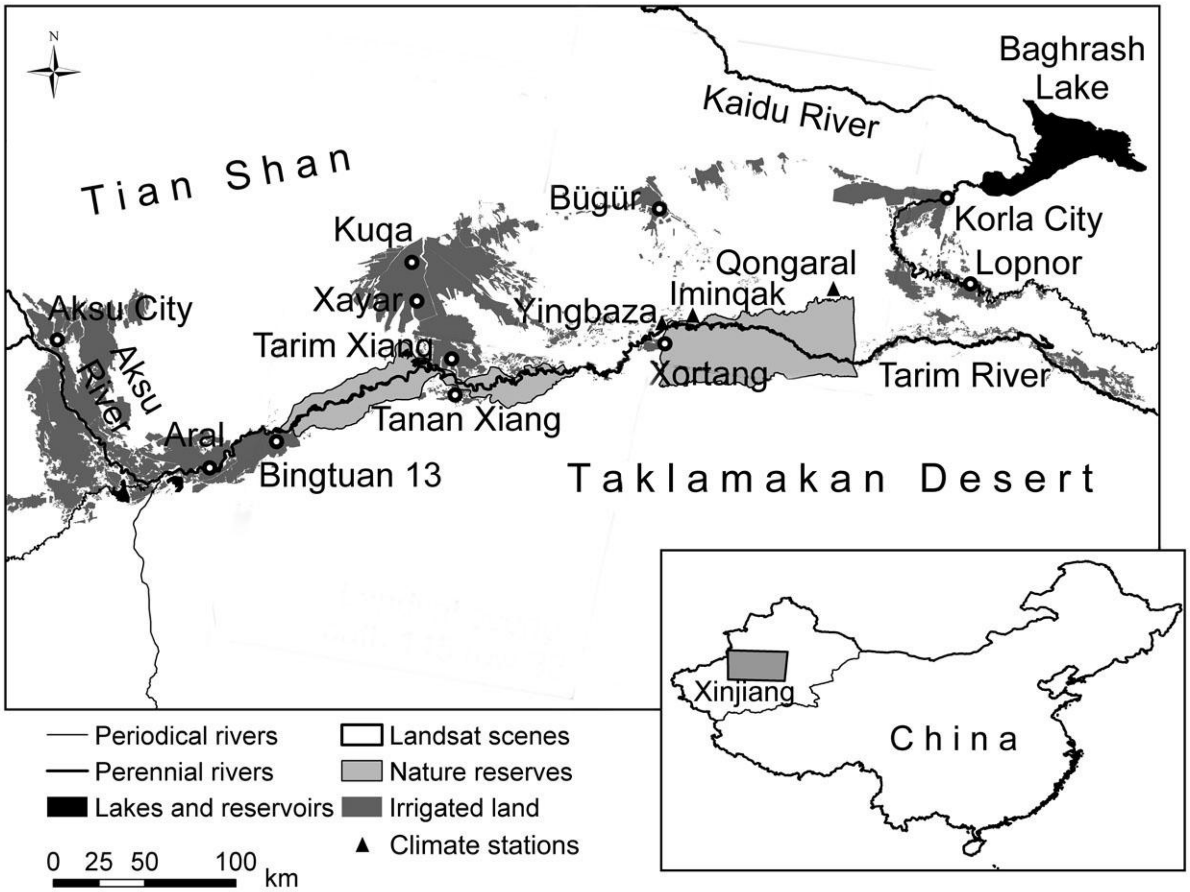

Figure 1. Map of the study area

The climate in the floodplain of the Aksu and Tarim Rivers is extremely arid with an annual precipitation ranging between 30 mm and 70 mm [28]. January mean temperatures are -10°C, while July average temperatures are 26°C (http://www.tutiempo.net/clima/China/CN.html). The natural vegetation along the Tarim River consists of riparian *Populus euphratica* forests, so-called Tugai forests [29, 30], wetlands, shrub vegetation, and areas under perennial herbaceous vegetation [18]. The only forest building species is *Populus euphratica* [31]. The biomass stocks range from 26 t/ha to 44 t/ha for dense forests with total coverage of 50% and more to 18 t/ha to 24 t/ha for forests with total coverage of 10% at the desert margin [3]. The shrub vegetation is dominated by *Tamarix ramosissima* and halophytes on saline sites. *Tamarix ramosissima* is also common as understory vegetation in the Tugai forests [1, 18, 31, 32]. The wetlands are reed beds of *Phragmites autralis*. *Phragmites australis* is distributed on prolonged or periodically submerged sites as well as on non-submerged sites [2]. Areas covered by herbaceous perennial vegetation formed by *Apocynum pictum*, *Glycyrrhiza inflata*, *Karelinia caspica*, or *Alhagi sparsifolia* are distributed island-like within forest or shrub vegetation areas. All those plant species are phreatophytes [32], i.e. those plants cover their water demand from the groundwater. The groundwater levels at the two sites Iminqak and Qongaral are 3 m and 6 m below surface [33], which is well, within the range suitable for *Populus euphratica* and *Tamarix*, respectively [18]. Therefore, there was no water stress for that natural vegetation during the time of this investigation. The plant species grow leafs during April and May so that April can be considered the initial stage and May as the development stage. June and the following months are the mid-stage. Leafs fall in the second half of October.

Within the study area, cotton fields are scattered all along the Tarim River, also inside the nature reserves. There are three farm types: Military Farms (part of the Military Farm 13 lies within the studied area), privately operated large scale farms (distributed around Yingbaza and Xortang) with a total cropland area of 100 to 300 ha, and small scale family operated farms (in Puhui, Tarim Xiang, and Tanan Xiang with a total cropland area of 2 to 7 ha) [15]. Military Farms and privately operated large scale farms use drip irrigation combined with plastic mulch throughout [14], while small scale family operated farms use drip and flood irrigation. Furthermore, the former two farm types often pump groundwater, in order to bridge periods of river water shortage [16, 34].

Depending on water availability, the fields are flooded in autumn or spring, in order to leach salts and build up soil moisture for soil preparation. Soil preparation takes place in March, followed by planting in April. The initial stage lasts until the end of May. Irrigation starts in June corresponding to the onset of the development stage. The mid-stage lasts during July and August. Finally, harvest takes place during September and October [15]. Cotton is grown each year without any rotation [16]. In 2010, the yields of cotton lint of the Xayar and Luntai counties were reported as 1562 kg/ha and 1935 kg/ha, respectively [11]. The cotton site (Yingbaza) was a field of a privately operated large scale farm with access to a groundwater well, so that no significant water shortage was expected.

2.2. Determining ET_o and ET_a

Three climate stations were operated in Iminqak, Qongaral, and Yingbaza in order to calculate ET_a after the Bowen Ratio method and reference ET (ET_o) after the FAO guidelines [19]. Iminqak and Qongaral delivered data during 2011 and 2012, while Yingbaza recorded data only in 2012. Iminqak and Qongaral were established next to the forest ranger station due to logistic reasons, while Yingbaza was placed on a cotton field of 100 m x 50 m with drip irrigation, located 5 km north of the village Yingbaza. The climate station Iminqak was located in a contiguous *Populus euphratica* forest with no other plant species present (Tugai forest with total coverage of 50% and more). The climate station in Qongaral was installed in a Tamarix stand (Tugai forest with total coverage below 50% and >= 25%).

The climate stations were equipped with sensors for wind speed, incoming and outgoing radiation (pyranometres CMP3, Kipp & Zonen), ventilated air temperature / humidity sensors in two different heights so that we were able to calculate ET_a with the Bowen Ratio method [20]. One air temperature / humidity sensor was mounted 2 m above soil surface, while the other sensors were mounted 10 m above surface. Electricity supply came from two 12 V car accumulators, which were charged at the nearby ranger station. Data were recorded every 0.1 second and stored by a data logger as 15 min average values.

Daily ET_o was calculated after the Penman-Monteith equation and the related set of formulae as used by the FAO standard [19]:

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \qquad (1)$$

where ET_o reference ET [mm/d]; R_n net radiation [MJ/m² d]; G soil heat flux [MJ/m² d];
T mean daily air temperature at 2 m [°C]; u_2 wind speed at 2 m [m/s]; e_s saturation vapour pressure [kPa]; e_a actual vapour pressure [kPa]; e_s - e_a saturation vapour pressure deficit [kPa]; Δ slope vapour pressure curve [kPa/°C]; γ psychrometric constant [kPa/°C].

T and u_2 were measured by the climate stations. G was set zero for daily ET_o. Relative air humidity measured by the climate stations was used to calculate e_s and e_a [19]. Δ and γ were calculated after [19], too. Incoming solar shortwave radiation R_s and reflected shortwave radiation R_{out} were measured at the climate stations. The extra-terrestrial radiation, albedo, incoming net short wave radiation, and outgoing net longwave radiation, which are needed to calculate R_n in equation 1, were calculated after [19].

Data gaps in the climate station data from Iminqak and Qongaral in 2011 and Yingbaza 2012 were filled based on regressions with climate data from http://www.tutiempo.net/clima/China/CN.html.

Linear regressions were established between daily temperature, air humidity, and wind speed data of our climate stations and the corresponding data of the climate stations Korla and Kuqa (Table 1). Regressions between Korla and Qongaral fit best, while Iminqak and Yingbaza fit best to Kuqa. Data gaps from Iminqak and Qongaral in 2012 were not filled, because the R^2 values were below 0.5 for all regressions. The two climate stations are on elevations of 933 m and 1100 m.

Table 1. Regressions for daily temperature, air humidity, and wind speed between the climate stations Korla and Qongaral, Kuqa and Iminqak, and Kuqa and Yingbaza*

Regression equations	**R^2**
2011	
Regression between Kuqa and Iminqak	
$T_{Iminqak} = 0.9231 * T_{Kuqa} + 3.0884$	0.8511

$T_{max\ Iminqak} = 0.9551 * T_{max\ Kuqa} + 4.8977$	0.8221
$T_{min\ Iminqak} = 1.0745 * T_{min\ Kuqa} – 0.2793$	0.7505
$RH_{Iminqak} = 0.5677 * RH_{Kuqa} +16.021$	0.5563
$u_{Iminqak} = 0.0588 * u_{Kuqa} + 0.5776$	0.1123
Regression between Korla and Qongaral	
$T_{Qongaral} = 1.0855 * T_{Korla} – 3.3333$	0.9881
$T_{max\ Qongaral} = 1.0142 * T_{max\ Korla} + 1.1362$	0.9961
$T_{min\ Qongaral} = 1.1956 * T_{min\ Korla} – 6.4518$	0.9729
$RH_{Qongaral} = 1.0312 * RH_{Korla} + 9.2126$	0.7547
$u_{Qongaral} = 0.2024 * u_{Korla} + 1.4148$	0.4472
2012	
Regression between Kuqa and Yingbaza	
$T_{Yingbaza} = 0.9519 * T_{Kuqa} + 2.3899$	0.8985
$T_{max\ Yingbaza} = 0.9381 * T_{max\ Kuqa} + 3.5202$	0.8975
$T_{min\ Yingbaza} = 1.0553 * T_{min\ Kuqa} + 0.7414$	0.8123
$RH_{Yingbaza} = 0.4469 * RH_{Kuqa} +23.436$	0.1955
$u_{Yingbaza} = 0.1975 * u_{Kuqa} + 0.0644$	0.2278

*The source for climate station data from Korla and Kuqa is: http://www.tutiempo.net/clima/China/CN.html. T is daily average Temperature [°C], T_{max} is daily maximum Temperature [°C], T_{min} is daily minimum Temperature [°C], RH refers to daily mean relative air humidity [%], and u refers to wind speed given in km/h from http://www.tutiempo.net/clima/China/CN.html and converted into m/s.

Daily ET_a was calculated with the Bowen Ratio method. The Bowen Ratio is expressed as:

$$\beta = \gamma\ (T_1 - T_2)/(e_1 - e_2) \tag{2}$$

where β Bowen Ratio; γ psychrometric constant [kPa/°C]; T_1 and T_2 temperature at height 1 and 2 [°C]; e_1 and e_2 vapor pressure at height 1 and 2 [kPa].

$$LE = (R_n + G)/(\beta + 1) \tag{3}$$

where LE latent heat flux [W/m²]; R_n net radiation [W/m²]; G soil heat flux [W/m²]; β Bowen Ratio.

R_n was calculated for 15 min time steps corresponding to the data recording of the three climate stations after the corresponding equations given in [19]. The authors did not install

soil heat flux sensors, because it could be not guaranteed for disturbance a free soil heat flux measurement due to activities of neighbouring people. Therefore, $G = 0.1 R_n$ was assumed as suggested by the FAO guidelines [19]. The 15 min LE were converted into ET_a for 15 min time steps and summed up to daily climate station ET_a.
ET_o of the FAO guidelines is converted into crop evapotranspiration by multiplying ET_o with either a single crop coefficient (K_c) or a dual crop coefficient ($K_{cb} + K_e$), which are listed by [19]. Thereby, K_c comprises transpiration from the crops and evaporation from the soil surface, while the dual crop coefficient separates a coefficient for transpiration (K_{cb}) and for evaporation from the soil surface (K_e). K_{cb} values were calculated as:

$$K_{cb} = ET_a / ET_o \quad (4)$$

In this study K_{cb} coefficients were used, because the evaporation via the soil surface can be neglected during most time of the growing season. In the case of the natural vegetation, the groundwater is too deep to connect with the soil surface and in case of cotton the soil is covered by plastic mulch.

3. Results

The relevant climate data for the calculation of ET_o are given in Table 2 as monthly averages.
Air temperature and radiation were lower in 2012 compared to 2011, e.g. the July average air temperature was 25.2°C in 2012 (in Yingbaza), but 27.0°C and 27.4°C in 2011 (in Iminqak and Qongaral, respectively). The wind speed differed considerably between Iminqak and Qongaral with 0.6 m/s to 0.74 m/s and 1.79 m/s to 2.02.m/s, respectively (Table 2). Accordingly, ET_o in July was 1.1 mm/d higher in Qongaral than in Iminqak (Table 2). Qongaral also showed the highest ET_o sum, 1280 mm of all three sites (Table 3). In Yingbaza the wind speed was higher than 1.3 m/s in most months of the growing season, i.e. also considerably higher than in Iminqak. Despite the lower air temperature and radiation in Yingbaza in 2012, the ET_o in July was 6.3 mm/d, thus only 0.5 mm/d lower than Iminqak in 2011. ET_a was highest in the forest site, i.e. Iminqak (ET_a in July 5.3 mm/d), followed by the cotton field in Yingbaza (ET_a in July 3.6 mm/d), and the shrub vegetation at Qongaral with ET_a in July of 2.3 mm/d (Table 2). Though, the ET_a of the cotton field in April and May, 1.5 mm/d and 1.8 mm/d, respectively, was lower than the ET_a of those two months in the shrub vegetation at Qongaral (1.7 mm/d and 1.9 mm/d, respectively).

Table 2. Monthly data of air temperature (air temp.), relative air humidity (RH), wind speed, incoming solar radiation (R_s), net radiation (R_n), ET_o, and ET_a at the climate stations Iminqak (2011), Qongaral (2011), and Yingbaza (2012)*

Month	**Air temp. [°C]**	**RH [%]**	**wind speed [m/s]**	**R_s [MJ/m² d]**	**R_n [MJ/m² d]**	**ET_o [mm]**	**ET_a [mm]**
Iminqak 2011							
April	18.5	32.4	0.74	23.8	15.0	4.9	2.9
May	21.2	39.4	0.68	27.5	18.4	5.9	4.0
June	25.2	39.1	0.69	29.0	19.9	6.8	5.0
July	27.0	37.3	0.71	28.1	19.2	6.8	5.3
August	25.9	41.4	0.70	25.1	16.7	5.9	4.2
September	21.5	43.3	0.64	20.3	12.6	4.2	3.7
October	14.4	46.6	0.60	15.0	8.0	2.5	2.2
Qongaral 2011							
April	16.7	33.2	2.02	24.0	15.0	5.5	1.7
May	19.7	40.2	1.98	27.7	18.4	6.5	1.9
June	25.2	44.0	1.94	29.2	20.1	7.6	2.3
July	27.4	39.6	1.96	28.4	19.3	7.9	2.3
August	26.3	42.2	1.96	25.3	16.8	6.9	2.4
September	20.2	40.4	1.86	20.5	12.4	5.1	1.9
October	11.5	52.1	1.79	15.1	8.0	2.8	1.1
Yingbaza 2012							
April	18.0	33.4	1.51	20.1	11.9	5.1	1.5
May	20.5	37.8	1.43	22.1	13.7	5.8	1.8
June				21.8	14.3		
July	25.2	46.5	1.43	23.4	15.1	6.3	3.6
August	24.8	42.8	1.36	20.9	13.2	6.0	3.7
September	21.4	53.5	0.20	17.8	9.8	3.3	
October	10.1	39.7	1.09	14.2	5.9	2.5	0.8

*All climate parameters for 2 m above soil surface

The monthly sums of ET_o and ET_a (Table 3) follow the patterns of the monthly averages from Table 2. The highest ET_a sum, with 879 mm for the whole growing season, was found in the forest in Iminqak, followed by the cotton field with an ET_a of 489 mm, and an ET_a of the shrub vegetation in Qongaral of 410 mm. Correspondingly, K_{cb} was highest for the forest throughout the growing season (Table 3), ranging between 0.59 in April and 0.88 in October

2011. During April and May, K_{cb} of cotton (0.30) were as low as for the shrub vegetation. Afterwards, the K_{cb} of cotton steeply increased to 0.62 in August. In the shrub vegetation, climate station Qongaral, the monthly K_{cb} values were quite uniform throughout the vegetation period (Table 3).

Table 3. Monthly ET_o, monthly ET_a sums [mm], and K_{cb} at the climate stations Iminqak, Qongaral, and Yingbaza

Month	**Iminqak**			**Qongaral**			**Yingbaza**		
	ET_o	**ET_a**	**K_{cb}**	**ET_o**	**ET_a**	**K_{cb}**	**ET_o**	**ET_a**	**K_{cb}**
2011									
April	151	88	0.59	166	50	0.30			
May	188	128	0.68	201	60	0.30			
June	210	160	0.76	223	67	0.30			
July	222	177	0.80	240	70	0.29			
August	206	145	0.70	211	70	0.33			
September	128	112	0.87	151	58	0.38			
October	78	68	0.88	87	33	0.38			
Sum	1182	879	0.74	1280	410	0.32			
2012									
April							153	46	0.30
May							188	57	0.30
June							196	81	0.41
July							201	114	0.57
August							177	109	0.62
September							125	55	0.44
October							82	27	0.32
Sum							1122	489	0.44

4. Discussion

ET_a of the *Populus euphratica* forest at the climate station Iminqak, 879 mm, was lower than ET_a of *Populus euphratica* plantations at the Amu Darya River in Uzbekistan, 1030 mm, as reported by [35]. This difference might be explained through the high groundwater level of 0.9 m to 2 m under the sites of Khamzina et al. 2009 and the presumably high tree density, with which the trees had been planted. An ET_a of 447 mm was reported by Hou et al. 2010 for *Populus euphratica* forests with a vegetation coverage of around 25% from Ejina, Inner Mongolia, which is lower than ET_a of *Populus euphratica* forest in this study. This difference is due to the lower vegetation coverage of Hou et al. 2010 compared to the site of this study.

The K_{cb} of the *Populus euphratica* forest from June to September were in the same range as $K_{cb\ mid}$ stage values for Almond and fruit trees without ground cover [19]. The crop coefficients of the *Populus euphratica* forest before June and for October were higher than the $K_{cb\ ini}$ and $K_{cb\ end}$ values for Almond and fruit trees without ground cover [19], respectively. During the initial stage there was still soil moisture available from the previous year, which explains the high crop coefficient at Iminqak. Thus we only can refer to K_{cb} for the mid and end stage. These rather high K_{cb} values reflect that *Populus euphratica* is adapted to the arid climate by exploiting the groundwater rather than being a water saving plant.

The ET_a of shrub vegetation for the whole growing season (410 mm) is higher than corresponding ET_a values for sparse *Populus euphratica* forests and *Tamarix* shrub vegetation of 192 mm to 392 mm and 92 mm to 180 mm, respectively, measured by Thomas et al. 2006 in Xinjiang, China. This corresponds to higher vegetation coverage at the Qongaral climate station compared to the sites of Thomas et al. 2006.

The ET_a of cotton (climate station Yingbaza), 489 mm, was slightly lower than ET_a of cotton measured through stomatal conductance and leaf area index at Yingbaza, which was 525 mm [36]. ET_a of cotton of this study was also lower than the results of Zheleznyh and Risbekov 1987, but is in the range of Ibragimov 2007, who found an ET_a of 432 to 615 mm in a field experiment under drip irrigation and 642 to 739 mm under furrow irrigation in Uzbekistan. Also, the climate station ET_a of cotton correspond with ET_a of cotton measured and determined with the S-SEBI model by Costa dos Santos et al. 2010 in Brazil.

The pattern of the K_{cb} coefficients of cotton in this study, i.e. low K_{cb} at the beginning of the growing season and steep increase during crop development during summer (Table 3), is the same as the K_{cb} values listed in the FAO guidelines for calculation of evapotranspiration [19]. However, the K_{cb} values of this study during beginning of the growing season are higher than the $K_{cb\ ini}$ of the FAO guidelines. This can be explained by the soil moisture from the flooding during autumn/spring, which results in evaporation from the soil surface not covered by plastic mulch. During July and August (mid-stage), K_{cb} are lower compared to $K_{cb\ mid}$ from the FAO guidelines [19]. While Allen et al.1998 list a K_{cb} of 1.10 to 1.15 for the mid-stage, K_{cb} of cotton in this study were only 0.57 for July and 0.62 for August. These K_{cb} values correspond with the K_c values measured through stomatal conductance and leaf area index at Yingbaza [36]. These differences between K_{cb} values of this study and K_{cb} values of Allen et al.1998 can be explained through improved cotton varieties and different crop management. The K_{cb} values listed by Allen et al. 1998 date back from the 1970s and 1980s. In the meantime, more water saving varieties have been developed [25].

The regressions used to fill data gaps (Table 1) have high R^2 for temperature, but low R^2 for wind speed. This indicates that wind is a local feature, which can be explained by winds driven by the specific local thermal. For a large scale and area-wise assessment of evapotranspiration and water consumption based on climate data, it seems not possible to interpolate wind speed from existing climate stations. R^2 of regressions between Korla and Qongara are higher throughout compared to the corresponding R^2 between Kuqa, Iminqak, and Yingbaza, respectively. This can be explained by the shorter distance between Korla and

Qongaral compared to the distances betwee Kuqa and Iminqak and Yingbaza, respectively. Furthermore, Korla and Qongaral are located on a similar elevation and in a similar landscape.

5. Conclusion

In this study, crop coefficients (K_{cb}) were elaborated for cotton, *Populus euphratica* forest and Tamarix shrub vegetation for sites at the Tarim River. These K_{cb} coefficients are as follows: $K_{cb\ mid}$ and $K_{cb\ end}$ for cotton 0.57-0.62 and 0.32, respectively. $K_{cb\ mid}$ and $K_{cb\ end}$ for *Populus euphratica* forest 0.7-0.8 and 0.88, respectively. K_{cb} throughout the growing season for Tamarix was 0.3-0.38.

Drip irrigation and plastic foil (plastic mulch) considerably improved water use efficiency in cotton cultivation in Xinjiang, China. However, plastic is only partially collected, so more and more plastic remnants accumulate in the soil, which might decrease root space in the future. Natural ecosystems, e.g. *Populus euphratica* forests, on the other hand are huge water consumers. The ecosystem services provided by those natural ecosystems are crucial, though their costs in terms of water need to be considered during planning and allocation of water resources.

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7. References

1. Thomas, F.M., Foetzki, A., Arndt, S.K., Bruelheide, H., Gries, D., Zeng, F.J., Zhang, X.M., 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.
2. Thevs, N., Zerbe, S., Gahlert, F., Mijit, M., Succow, M. (2007): Productivity of reed (Phragmites australis Trin. ex. Staud.) in continental-arid NW China in relation to soil, groundwater, and land-use. Journal of Applied Botany and Food Quality 81: 62-68.
3. Thevs, N., Buras, A., Zerbe, S., Kühnel, E., Abdusalih, N., Ovezberdyyeva, A. (2012): Structure and wood biomass of near-natural floodplain forests along the Central Asian rivers Tarim and Amu Darya. Forestry 81: 193-202.
4. Glantz, M.H. (1999): Creeping Environmental Problems and Sustainable Development of the Aral Sea Basin, Cambridge University Press, Cambridge.
5. Song, Y.D., Fan, Z.L., Lei, Z.D., Zhang, F.W. (2000): Research on Water Resources and Ecology of Tarim River, China. Xinjiang Peoples Press, Urumqi, China. (in Chinese).

6. Tang, D.S., Deng, M.J. (2010): On the Management of Water Rights in the Tarim River Basin. China Water Power Press, Beijing (in Chinese).
7. Hoppe, T. (1992): Chinesische Agrarpolitik und Uygurische Agrarkultur im Widerstreit. Das sozio-kulturelle Umfeld von Bodenversalzungen und -alkalisierungen im nördlichen Tarim-Becken (Xinjiang). Institut für Asienkunde, Hamburg.
8. Spoor, M. (1993): Transition to Market Economies in Former Soviet Central Asia: Dependency, Cotton, and Water. URL http://repub.eur.nl/res/pub/18862/wp160.pdf.
9. Treshkin, S.Y. (2001): The Tugai Forests of Floodplain of the Amudarya River: Ecology, Dynamics and their Conservation. In: Breckle, S.W., Veste, M., and Wucherer, W. (eds.): Sustainable Land Use in Deserts, 95-102. Springer, Heidelberg.
10. Zhu, Z.P., Giordano, M., Cai, X.M., Molden, D., Hong, S.C., Zhang, H.Y., Lian, Y., Li, H., Zhang, X.C., Zhang, X.H., Xue, Y.P. (2003): Yellow River Comprehensive Assessment: Basin Features and Issues. IWMI and YRCC. http://www.iwmi.cgiar.org/Publications/Working_Papers/working/WOR57.pdf (accessed 2013-12-30).
11. Xinjiang Statistics Bureau (2011): Xinjiang Statistical Yearbook of 2010. China Statistics Press, Beijing.
12. USDA (2012): China - Peoples Republic of Cotton and Products Annual. GAIN Report Number: CH12031. http://www.thefarmsite.com/reports/contents/chinacotmay12.pdf (accessed 2013-12-30).
13. Feike, T., Mamitimin, Y., Li, L., Abdusalih, N., Doluschitz, R. (2015): Development of agricultural land and water use and its driving forces in the Aksu-Tarim Basin, P.R. China. Environmental Earth Science 73(2): 517-531.
14. Zhou, S.Q., Wang, J., Liu, J.X., Yang, J.H., Xu, Y. and Li, J.H. (2012): Evapotranspiration of a drip-Irrigated, film-mulched cotton field in Northern Xinjiang, China. Hydrological Processes, 26: 1169-1178.
15. Peng, H.Y., Thevs, N., Beckmann, V., Abdusalih, N. (2016): Economic performance of cotton and fruit plantations in arid regions: observation from the Tarim River Basin, NW China. Asian Journal of Agricultural Extension, Economics & Sociology, 8(3): 1-15.
16. Thevs, N. (2011): Water scarcity and allocation in the Tarim Basin: decision structures and adaptations on the local level. Journal of Current Chinese Affairs 3: 113-137.
17. UNESCO and World Heritage Convention (2016): Taklimakan Desert—Populus euphratica Forests. Tentative List of World Heritage Site Nominations. http://whc.unesco.org/en/tentativelists/5532/. (accessed 2016-12-30)
18. Thevs, N., Zerbe, S., Peper, J., Succow, M. (2008): Vegetation and vegetation dynamics in the Tarim River floodplain of continental-arid Xinjiang, NW China. Phytocoenologia 38: 65-84.

19. 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. FAO, Rome.
20. Malek, E., Bingham, G.E. (1993): Comparison of the Bowen ratio-energy balance and the water balance methods for the measurement of evapotranspiration. Journal of Hydrology 146: 209-220.
21. 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.
22. Zheleznyh, V., Risbekov, Yu. (1987): Analysis of experimental investigations on lizimeters compratively with data on cotton field. http://www.cawater-info.net/bk/water_land_resources_use/english/iptrid/uz_34.pdf (assessed 2013-08-28).
23. Cleverly, J.R., Dahm, C.N., Thibault, J.R., Gilroy, D.J., Allred Coonrod, J.E. (2002): Seasonal estimates of actual evapotranspiration from Tamarix ramosissima stands using three- dimensional eddy covariance. Journal of Arid Environments 52: 181e197.
24. Scott, R.L., Cable, W.L., Huxman, T.E., Nagler, P.L., Hernandez, M., Goodrich, D.C. (2008): Multiyear riparian evapotranspiration and groundwater use for a semiarid watershed. Journal of Arid Environment 72: 1232e1246.
25. Lee, J.A., Fang, D.D. (2015): Cotton as a World Crop: Origin, History, and Current Status. Alliance of Crop, Soil, and Environmental Science Societies. doi:10.2134/agronmonogr57.2013.0019.
26. Chou, T. (1960): The problem of channel shifting of the middle reaches of the Tarim River in Southern-Sinkiang. In: Murzayev, E.M., Chou, L. (Eds.): Natural conditions of Sinkiang. Chinese Academy of Sciences, Peking, Prirodnyye usloviya Sin'tsziana NAUK, Moscow, pp. 87-133 (in English).
27. Giese, E., Mamatkanov, D.M., Wang, R. (2005): *Wasserressourcen und deren Nutzung im Flussbecken des Tarim (Autonome Region Xinjiang / VR China).* Zentrum für Internationale Entwicklungs- und Umweltforschung /ZEU), Universität Giessen, Giessen, Germany.
28. Liu, M.G. (1997): Atlas of Physical Geography of China. China Map Press. Beijing.
29. Tian, Y.Z. (1991): Tokai on the delta at the lower reach of the Keriya River - a natural vegetation complex reflecting ecological degradation. In: Jäkel, D. (eds.): Reports on the "1986 Sino-German Kunlun-shan Taklamaklan Expedition". Gesellschaft für Erdkunde zu Berlin, Berlin, pp. 99-112.
30. Ogar, N. P. (2003) Vegetation of river valleys. In: Rachkovskaya, E.I., Volkova, E.A., Khramtsov, V.N. (eds.): Botanical geography of Kazakhstan and middle Asia (Desert region). Komarov Botanical Institute of Russian Academy of Sciences, Saint Petersburg, Institute of Botany and Phytointroduction of Ministry of Education and Science of Republic Kazakhstan, Almaty, Institute of Botany of Academy of Sciences of Republic Uzbekistan, Tashkent, pp. 313-339. (in English).

31. Wang, S.J., Chen, B.H., Li, H.Q. (1996): Euphrates Poplar Forest. China Environmental Science Press. Beijing. (in English).
32. Gries, D., Zeng, F., Foetzki, A., Arndt, S.K., Bruelheide, H., Thomas, F.M., Zhang, X.M., Runge, M. (2003): Growth and water relation of *Tamarix ramosissima* and *Populus euphratica* on Taklamakan desert dunes in relation to depth to a permanent water table. Plant Cell and Environment 26: 725-736.
33. Keilholz, P., Disse, M., Halik, Ü. (2015): Effects of Land Use and Climate Change on Groundwater and Ecosystems at the Middle Reaches of the Tarim River Using the MIKE SHE Integrated Hydrological Model. Water 7: 3040-3056.
34. Thevs, N., Zerbe, S., Peng, H.Y., Rouzi, A., Abdusalih, N. (2015): Water allocation and water consumption of irrigation agriculture and natural vegetation in the Aksu and Tarim river basin, Xinjiang, China. Journal of Arid Environments 112A: 87-97.
35. 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. Agricultural and Forest Meteorology 149: 1865-1874.
36. Thevs, N., Rouzi, N. (2015): Evapotranspiration of Cotton, *Apocynum pictum*, and *Zyzyphus jujuba* in the Tarim Basin, Xinjiang, China. Journal of Water Resource and Protection 7: 1001-1009. (http://dx.doi.org/10.4236/jwarp.2015.713081).
37. Ibragimov, N., Evett, S.R., Esanbekov, Y., Kamilov, B.S., Mirzaev, L., Lamers, J.P.A. (2007): Water use efficiency of irrigated cotton in Uzbekistan under drip and furrow irrigation. Agricultural Water Management 90: 112-120.
38. Costa dos Santos, C.A., Bezerra, B.G., da Silva, B.B., Rao, T.V.R. (2010): Assessment of daily actual evapotranspiration with SEBAL and S-SEBI algorithms in cotton crop. Revista Brasileira de Meteorologia. http://dx.doi.org/10.1590/S0102-77862010000300010.