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Evapotranspiration of Cotton, *Apocynum pictum*, and *Zyzyphus jujuba* in the Tarim Basin, Xinjiang, China

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Abstract

Evapotranspiration is a crucial component of the water balance of ecosystems and landscapes, especially under arid climates. In the Tarim Basin, China, there is an increasing competition for water between irrigated agriculture, mainly cotton, and natural ecosystems, which results in periods of water shortage. Such water shortages also impact on cotton. Therefore, alternative crops have been searched for, which eventually withstand such periodical water shortages better than irrigated cotton, notably *Zyzyphus jujuba* and *Apocynum pictum*. The fruit tree *Z. jujuba* has been promoted from the previous decade onward in parts of the Tarim Basin. *A. pictum* is used as medicinal plant and in a small scale as fiber crop. *A. pictum* is a perennial herb, which is part of the natural riparian vegetation along the rivers of the Tarim Basin and which grows without irrigation. Therefore, the objective of this paper is to investigate the crop evapotranspiration (ET_c) of those three plant species over the growing season. In this paper, the Penman-Monteith approach was employed. Daily means of stomatal resistance in June was 118 s/m, 222 s/m, and 927 s/m for cotton, *A. pictum* leafs, and *Z. jujuba*, respectively. In October, those daily mean stomatal resistance climbed to 885 s/m and 742 s/m for cotton and *A. pictum* leafs, respectively. ET_c over the growing season was 514.7 mm for cotton, 217.2 mm for *A. pictum*, and 339 mm for *Z. jujuba*. The K_c value of *Z. jujuba* was in the range of other fruit trees. In this study cotton attained high yields compared to world average yields at a low ET_c. This high water use efficiency was achieved through a shift from flood to drip irrigation, the utilization of plastic mulch, and breeding of cotton varieties.

Keywords

Evapotranspiration, Stomatal Conductance, Stomatal Resistance, Penman-Monteith, Remote Sensing

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1. Introduction

Evapotranspiration is an important component of the water balance of ecosystems and landscapes. Especially under arid climates accurate numbers of evapotranspiration are crucial for water resource management and planning.

Cotton is grown in many drylands of the world, e.g. in Central Asia (Uzbekistan, Turkmenistan, and Northwest China), Turkey, Texas (USA), or Australia [1]. In all those areas, cotton depends on irrigation. The Tarim Basin in Xinjiang, Northwest China, has turned into the world's most important cotton production region with a total annual cotton lint production of 2.1 million t in 2010, *i.e.* 8.85% of the world production [2] [3]. In 2011, the share of the cotton lint production in Xinjiang of the worldwide production climbed to 11% [3] [4]. This increase in cotton production went along with a shift from flood irrigation [5] to drip irrigation [6] and application of plastic mulch [7]. Despite of those production changes, the cotton production resulted in periodical water shortage along the Tarim River, which was the major river of the Tarim Basin [8] [9]. Therefore, alternative crops have been searched for, which eventually withstand such periodical water shortages better than irrigated cotton. Among those alternative crops, the most prominent ones are *Zyzyphus jujuba* and *Apocynum pictum*.

The fruit tree *Z. jujuba* has been promoted from the previous decade onward along the southern rim of the Tarim Basin (personal communication, Xinjiang Forestry Administration). Today, in the oases of Qarqan and Qarklik, *Z. jujuba* has become the major crop and has replaced cotton as source of income to local people. *A. pictum*is harvests as medicinal plant and thus serves as additional income source for people in the Tarim Basin. Medicinal tea from *A. pictum* is traded all over Xinjiang. Furthermore, *A. pictum* yields fibers, which are used for small scale textile production. *A. pictum* is a perennial herb, which is part of the natural riparian vegetation along the rivers of the Tarim Basin [10]. *A. pictum*, as many other plant species of the natural riparian vegetation, is a phreatophyte [11] [12]. Phreatophytes do not need to be irrigated, but establish continuous contact to the groundwater through strongly developed root systems, in order to adapt to the arid climate [13].

The objective of this paper is to investigate the crop evapotranspiration of cotton, being the major crop in the Tarim Basin, and the two alternative crops *Z. jujube* and *A. pictum*. A widely applied approach to determining crop and plant evapotranspiration is the reference evapotranspiration approach as described in the FAO Irrigation and Drainage Paper No. 56 [14], which has been compared with other models and proven suitable for dryland conditions in e.g. Iran by [15] [16]. After the Penman-Monteith Equation [14], the evapotranspiration is calculated as follows:

$$ET = \frac{\Delta\left(R_n - G\right) + p_a c_p \left(e_s - e_a\right)/r_a}{\Delta + \gamma\left(1 + \left(r_s/r_a\right)\right)} \quad (1)$$

where

ET: Evapotranspiration (mm/d),
R_n: Net radiation (MJ/m^2 d),
G: soil heat flux (MJ/m^2 d),
p_a: Mean air density at constant pressure (kg/m^3),
c_p: Specific heat of the air (MJ/m^3 ˚C),
e_s: Saturation vapor pressure (kPa),
e_a: Actual vapor pressure (kPa)
Δ: Slope vapor pressure curve (kPa/˚C),
γ: Psychrometric constant (kPa/˚C),
r_s: Bulk surface resistance (s/m),
r_a: Aerodynamic resistance (s/m).

The aerodynamic resistance is calculated after the following equation [14]:

$$r_a = \frac{\ln\left(\left(z_m - d\right)/z_{om}\right)\ln\left(\left(z_h - d\right)/z_{oh}\right)}{k^2 u_z} \quad (2)$$

where

r_a: Aerodynamic resistance (s/m),
z_m: Height of wind measurements (m),
z_h: Height of humidity measurements (m),
d: Zero plane displacement height (m),

z_{om}: Roughness length governing momentum transfer (m),
z_{oh}: Roughness length governing transfer of heat and vapour (m),
k: Von Karman's constant, 0.41,
u_z: Wind speed at height z (m/s).

The bulk surface resistance finally is calculated as follows [14]:

$$r_s = r_l / LAI_{active} \quad (3)$$

where
r_s: bulk stomatal resistance (s/m),
r_l: stomatal resistance of the well illuminated leafs,
LAI_{active}: Illuminated leaf area index.

Equation (1) has been simplified and adjusted to calculate the reference evapotranspiration (ET_0) [14]:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\left(900/(T+273)\right)u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (4)$$

where
ET_0: Reference evapotranspiration (mm/d),
R_n: Net radiation (MJ/m^2 d),
G: soil heat flux (MJ/m^2 d),
T: Air temperature at 2 m height (˚C),
u_2: Wind speed at 2 m height (m/s),
e_s: Saturation vapor pressure (kPa),
e_a: Actual vapor pressure (kPa),
Δ: Slope vapor pressure curve (kPa/˚C),
γ: Psychrometric constant (kPa/˚C).

ET_0 refers to a short grass vegetation of 100% vegetation coverage and 12 cm height, which is not water stressed. Crop evapotranspiration (ET_c) finally is calculated as [14]:

$$ET_c = ET_0 K_c \quad (5)$$

where
ET_c: crop evapotranspiration (mm/d),
ET_0: Reference evapotranspiration (mm/d),
K_c: crop coefficient.

Crop coefficients are given for the world's major crops, including cotton and fruit trees [14]. Thus, there are no crop coefficients for *A. pictum* neither for *Z. jujuba*. The crop coefficients were developed primarily after sources from before 1989 [17]-[21]. Therefore, the crop coefficient given for cotton reflects average cotton cultivation with a low, if any, proportion of drip irrigation. Therefore, in this paper we aim at determining ET_c and crop coefficients of cotton, *A. pictum*, and *Z. jujuba* for representative sites of the Tarim Basin.

2. Study Area

This study focuses on cotton, *A. pictum* and *Z. jujuba*. The ET_c measurements for those three plants were conducted on the sites Yingbaza, Qongaral, and Qarqan, respectively. All three sites are located in the Tarim Basin in South Xinjiang. The Tarim Basin covers an area of 1.02 million km^2, and is home to a population of 9.02 million people. The area of irrigated land has increased all over the Tarim Basin, from 706,000 ha in 1949, over 1,330,000 ha in 1980 and 1,412,000 ha in 1990, in 2010 to 1,600,000 ha [2]. The climate is extremely continental and arid with an annual precipitation ranging between 30 mm and 70 mm [2]. In Korla and Qarqan, January mean temperatures are −10˚C and −7˚C, respectively, while July average temperatures are 26˚C and 24˚C, resüectively (http://www.tutiempo.net/clima/China/CN.html).

Yingbaza (41˚12'22" N 84˚13'16" E) is a village in Bügür County, about 200 km southwest of Korla at the middle reaches of the Tarim River. The study site Yingbaza is a cotton field 5 km north of the village Yingbaza. The field plot has a size of 100 m × 80 m. Cotton is planted under plastic mulch combined with drip irrigation as described by [22]. Thereby, at both sides of each drip line one row of cotton seeds are planted. The two rows of cotton and the drip line are covered with one sheet of plastic foil as plastic mulch. Cotton is planted during April and harvested during September and October. The yields are around 1.5 t/ha lint cotton.

Qongaral (41˚18'27" N 85˚33'32" E) is located in Korla City at the Layi River, a branch of the Tarim River in its inland delta (**Figure 1**). *A. pictum* forms natural mono-species stands along the Layi River. There, *A. pictum* grows up to a height of 1 m with an above ground biomass of 0.6 to 0.92 t/ha. The groundwater level fluctuates around 5 m. *A. pictum*is occasionally grazed by sheep and goats. The *A. pictum* stands are bordered by Tamarix shrub vegetation (unpublished data).

Qarqan (38˚08'49" N 85˚29'47" E) is an oasis town at the southern rim of the Tarim Basin (**Figure 1**). It is one of the first oasis towns which started to promote cultivating *Z. jujuba* ten years ago. The investigated site is an orchard surrounded by *Populusalba* tree rows as shelterbelt. The trees are planted in rows, which were 4 m apart from each other. Tree spacing within rows is 2 m. The tree height is 3 m. The soil is partly covered with grass vegetation, which is occasionally grazed by sheep and goats.

3. Methods

At each of the three sites, ET_0 and ET_c were determined based on field measurements. Equation (5) was solved for K_c so that K_c was calculated based on ET_0 and ET_c.

At each site, a mobile climate station was installed from the morning until the evening during the days of measurement (**Table 1**). This mobile climate station consisted of an air temperature/air humidity sensor (PASSRHT

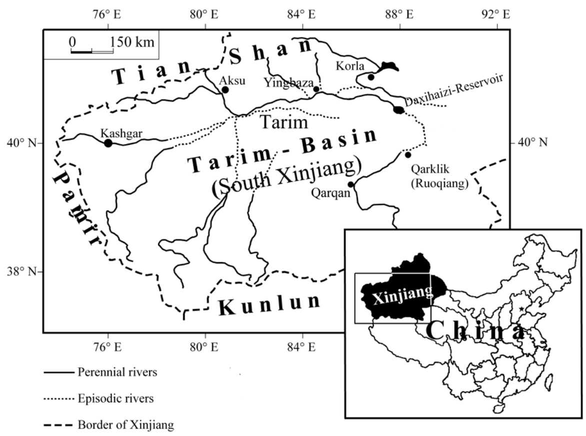

Figure 1. Map of the Tarim Basin with the investigation sites.

Table 1. Climate station and crop data at days of measurement of stomatal conductance. For the climate station data average values of hourly mean values are given. Only for solar radiation the sum of radiation per hour during the time of measurement is given. For *A. pictum*, two LAI values are given: LAI leafs/LAI stems.

Crop and date	Temp. (˚C)	Relative air humidity (%)	Wind speed (m/s)	Solar radiation (MJ/m^2)	Albedo	Crop height (m)	*LAI active*
Cotton							
Jun-15	25.6	36	4.2	15.2	0.23	0.2	0.04
Jul-13	30.2	31	2.3	25.9	0.19	1	0.46
Aug-18	32.1	30	1.7	24	0.21	1	1.75
Oct-20	13.7	13	1.8	16.6	0.23	1	1.5
A. pictum							
May-24	26.4	20	1.7	20.3	0.21	0.7	0.09/0.04
Jun-12	28.7	27	2.6	9.5	0.23	0.84	0.13/0.06
Jul-11	34.3	22	1.1	24.1	0.22	1	0.13/0.06
Aug-24	30.7	28	1.6	22.8	0.21	1	0.13/0.06
Oct-18	15.9	17	2.2	15.4	0.21	1	0.11/0.06
Z. jujuba							
Jun-17	30.9	31	0.13	27.4	0.19	3	0.42
Jul-15	29.4	40	0.09	20.8	0.15	3	0.46
Aug-20	30.9	30	0.22	14.8	0.15	3	0.46

from UMS, Munich), wind speed sensor (Davis anemometer), and two pyranometers (GLOBAL-pyra 03 from Delta Ohm), which measured incoming solar radiation and reflected radiation. Air temperature, air humidity, and wind speed were recorded as minutely averages by a data logger (EM50 from UMS, Munich). The radiations were recorded by a data logger (GP1 from UMS, Munich) and aggregated to minutely averages, too. The conversions of air humidity and air temperature into saturation vapor pressure deficit as well as the calculation of the net radiation based on the incoming solar radiation and reflected radiation followed the FAO guidelines by [14]. These climate data and their conversion results were used for the ET_0 and ET_c calculations. Soil heat flux was assumed as 0.1 * R_n as suggested by [14].

While the climate station was operated, the stomatal resistance was measured hourly with a porometer (SC-1, Decagon). On each site, three plants were selected randomly, from which three leafs each at the top, in the middle, and at the lower part of the crown were measured every hour.

4. Results

The air temperature, air humidity, and radiation (**Table 1**) were in the same range at all three sites. Only the wind speed was much lower in the *Z. jujuba* orchard (below 0.25 m/s) compared to the cotton field and the *A. pictum* stand investigated. At the latter two sites the wind speed frequently was above 1.5 m/s. LAI_{active} differed considerably between the three plant species. *Z. jujuba*, being a tree, had an LAI_{active} between 0.42 and 0.46 throughout the measurement period (**Table 1**). The LAI_{active} of *A. pictum* leafs and stems did not exceed 0.13 and 0.06 respectively, throughout the growing season. The LAI_{active} of cotton was 0.04 during the initial stage until the measurement in mid-June. Afterwards, it increased sharply up to 1.75 in August (**Table 1**).

The stomatal resistance of cotton and *A. pictum* leafs increased during the growing season. Cotton leafs additionally showed an increasing stomatal resistance from measurements in the morning to measurements in the afternoon/evening. This trend was most pronounced during the measurements in August and October. In contrast, *Z. jujuba* did not show such a clear trend. Though, in June and July the stomatal resistances of *Z. jujuba* increased from 764 s/m and 348 s/m in the morning to 1446 s/m and 833 s/m between 12:00 and 13:00 local time, respectively. At 18:00 local time, the stomatal resistances of *Z. jujuba* were 539 s/m in June and 708 s/m in July (**Figure 2**).

While the stomatal resistance of cotton in June (daily average of June 15^{th} was 118 s/m) was lower than the corresponding values of *A. pictum* leafs, stems, and *Z. jujuba* (daily averages of the measurements in June were 222 s/m, 470 s/m, and 927 s/m, respectively), cotton attained higher daily mean stomatal resistances (885 s/m) than *A. pictum* leafs (742 s/m) and *A. pictum* stems (419 s/m) in October (**Figure 2**).

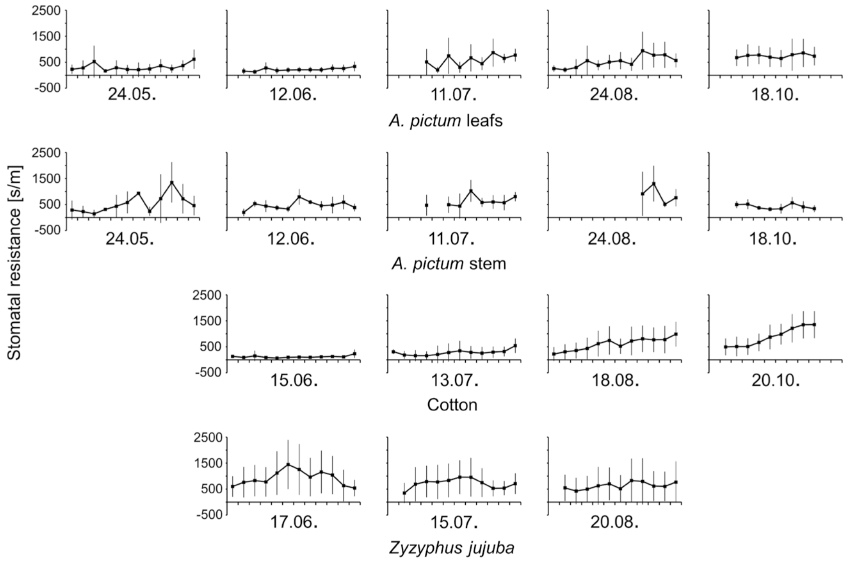

Figure 2. Hourly mean values and standard deviation of the stomatal resistance (s/m) during the days of measurement. All x-axes refer to a time span of 07:00 to 19:00 Xinjiang time, *i.e.* geographical time, which is equivalent to 09:00 to 21:00 Bejing time.

Corresponding to the low LAI_{active} in June, the hourly ET_c of cotton was lower than that of *A. pictum* and *Z. jujuba* (**Figure 3**). During the July measurements, the hourly ET_c of cotton exceeded the ET_c of the other two plant species. Cotton and *Z. jujuba* showed a peak of the ET_c around noon, while *A. pictum* showed such a peak only during the measurements in May, July, and October (**Figure 3**).

The ET_0 values in the *A. pictum* stand and the cotton field were in the same range throughout the growing season (**Table 2**), e.g. between 6.1 mm/d and 8.1 mm/d from June to August, while the ET_0 of the *Z. jujuba* orchard was less than half of those values, *i.e.* 2.8 mm/d to 3.5 mm/d from June to August. This result corresponds with the considerably lower wind speed in the *Z. jujuba* orchard compared to the other two sites.

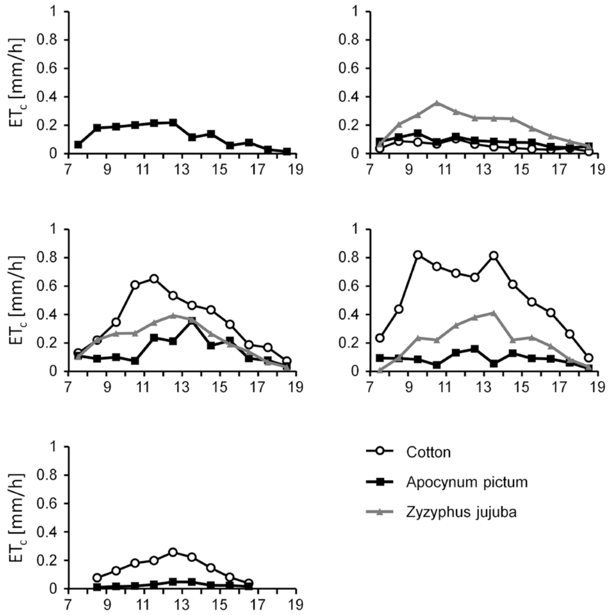

Figure 3. Hourly ET_c during the days of measurement of cotton, *A. pictum*, and *Z. jujuba*. The time at the x-axis is the local geographical time (Xinjiang time), which is two hours later than Beijing time.

Table 2. Daily ET_0 (mm), ET_c (mm), and K_c of cotton, *Apocynum pictum*, and *Zyzyphus jujuba* during the months May to October 2012.

Month	May	June	July	August	October	Total growing season
Crop						
Cotton						
ET_0 (mm)		7.3	8.1	7.9	2.5	
ET_c (mm)		0.6	4.1	6.3	1.3	524.7
K_c		0.09	0.51	0.79	0.52	
Date		Jun-15	Jul-13	Aug-18	Oct-20	
A. pictum						
ET_0 (mm)	6.2	7.8	7.3	6.3	3.2	
ET_c (mm)	1.5	1	1.8	1	0.3	217.2
K_c	0.24	0.13	0.26	0.16	0.1	
Date	May-24	Jun-12	Jul-11	Aug-24	Oct-18	
Z. jujuba						
ET_0 (mm)		3.5	2.9	2.8		
ET_c (mm)		2.4	2.7	2.4		339
K_c		0.67	0.91	0.85		
Date		Jun-17	Jul-15	Aug-20		

Corresponding to the LAI development, the ET_c of cotton was the lowest of the three plant species in June (0.6 mm/d), but increased sharply until August reaching 6.3 mm/d. Accordingly, the K_c values also increased sharply from 0.09 in June to 0.79 in August. The K_c values of *A. pictum* fluctuated between 0.13 and 0.26 from May to August and decreased to 0.1 in October (**Table 2**). The corresponding ET_c values ranged between 1 mm/d and 1.8 mm/d from May to August and dropped to 0.3 mm/d. The ET_c of *Z. jujuba* was between 2.4 mm/d and 2.7 mm/d during the time period from June to August. So, it showed the highest ET_c during spring and was between the ET_c of cotton and *A. pictum* from June onwards. The estimated ET_c of the whole growing season for cotton, *A. pictum*, and *Z. jujuba* were 524.7 mm, 217.2 mm, and 339 mm, respectively (**Table 2**).

5. Discussion

The daily ET_0 determined for cotton and *A. pictum* (**Table 2**) is similar to ET_0 reported by [23] for Ejina in the Heihe river basin in Inner Mongolia, China, which has a similar climate as the Tarim Basin. The ET_c over the growing season of cotton (**Table 2**) is below corresponding values given by [1] or [24], but similar to [25] and in the same range as the norms for water consumption from Soviet times (*i.e.* 550 - 600 mm) [26] and values given by [27] for Turkmenistan.

The crop coefficients of cotton after [24] are: $K_{c\ ini}$ = 0.35, $K_{c\ mid}$ = 1.15 - 1.2, and $K_{c\ end}$ = 0.5 - 0.7. The K_c values of cotton of this study follow this pattern, as there is an increase from K_c in June to K_c in July and August followed by a decrease to K_c in October (**Table 2**). Though, the K_c values of this study are lower than those of [14] throughout the growing season. Especially the K_c of June, during the initial stage of cotton, of 0.09 is much lower than the corresponding $K_{c\ ini}$ of 0.35 listed by [24]. This difference can be explained through the application of plastic mulch combined with drip irrigation, because the plastic mulch covers all soil, which is wetted during irrigation from the drip lines so that evaporation from the soil surface is inhibited. The drip irrigation may also explain the differences of further K_c values of this study compared to the K_c listed by [14] as well as the low ET_c in general.

Z. jujuba showed K_c values in the range of the *Rosaceae* fruit trees listed by the FAO irrigation and Drainage Paper 56 [14]. The low hourly and seasonal ET_c of *Z. jujuba* compared to cotton (**Figure 3** and **Table 2**) is due to the low ET_0 of *Z. jujuba* (**Table 2**). The low ET_0 in the *Z. jujuba* orchard is explained by the wind speed, which is much lower than on the cotton field and the *A. pictum* stand. The orchard is embedded into a narrow web of shelterbelt tree lines, which reduce the wind speed, while there is no obstacle, e.g. vegetation, for wind at the investigated cotton field and the *A. pictum* site.

The ET_c over the growing season of *A. pictum* is in the same range as the water use of *Alhagi sparsifolia* and *Tamarix ramosissima*. *Alhagi sparsifolia* and *Tamarix ramosissima* are plant species of the natural riparian vegetation along the rivers of the Tarim Basin like *A. pictum* [28]. The K_c values of *A. pictum* are lower than all crop coefficients listed by [14]. This is due to the low LAI_{active}, which corresponds with the anatomy of *A. pictum* and the low vegetation coverage of that natural vegetation. *A. pictum*, though, is part of the natural riparian vegetation of the Tarim Basin and thus is adapted to the arid climate there, it does not have a higher stomatal resistance than the other two crops investigated. *A. pictum* is adapted to the arid climate by establishing contact to the groundwater being a phreatophyte [11] [12]. Therefore, *A. pictum* survives under the arid climate by securing the water supply rather than saving water as other desert plants. So, if *A. pictum* grew with higher vegetation coverage (*i.e.* higher plant density) or the *A. pictum* plants grew larger, then the ET_c and K_c would increase.

In this study cotton attained a high yield compared to world average yields [3] at a rather low ET_c. In Turkmenistan at similar ET_c rates cotton yields and thus the water use efficiency is significantly lower [25]. This high water use efficiency was achieved through a shift from flood to drip irrigation, the utilization of plastic mulch, and breeding of cotton varieties. The issue of garbage pollution through drip line and plastic mulch as well as their recycling is beyond the scope of this paper.

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