

Actual evapotranspiration of subalpine meadows in the Qilian Mountains, Northwest China (Post-print)

Authors: GAO Yunfei, ZHAO Chuanyan

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Abstract

As a main component in water balance, evapotranspiration (ET) is of great importance for water saving, especially in arid and semi-arid areas. In this study, the FAO (Food and Agriculture Organization) Penman-Monteith model was used to estimate the magnitude and temporal dynamics of reference evapotranspiration (ET_0) in 2014 in subalpine meadows of the Qilian Mountains, Northwest China. Meanwhile, actual ET (ET_c) was also investigated by the eddy covariance (EC) system. Results indicated that ET_c estimated by the EC System was 583 mm, lower than ET_0 (923 mm) estimated by the FAO Penman-Monteith model in 2014. Moreover, ET_0 began to increase in March and reached the peak value in August and then declined in September, however, ET_c began to increase from April and reached the peak value in July, and then declined in August. Total ET_c and ET_0 values during the growing season (from May to September) were 441 and 666 mm, respectively, which accounted for 75.73% of annual cumulative ET_c and 72.34% of annual cumulative ET_0 , respectively. A crop coefficient (k_c) was also estimated for calculating the ET_c , and average value of k_c during the growing season was 0.81 (ranging from 0.45 to 1.16). Air temperature (T_a), wind speed (u), net radiation (R_n) and soil temperature (T_s) at the depth of 5 cm and aboveground biomass were critical factors for affecting k_c , furthermore, a daily empirical k_c equation including these main driving factors was developed. Our result demonstrated that the ET_c value estimated by the data of k_c and ET_0 was validated and consistent with the growing season data in 2015 and 2016.

Full Text

Preamble

Actual Evapotranspiration of Subalpine Meadows in the Qilian Mountains, Northwest China

Yunfei Gao¹, Chuanyan Zhao^{2*}, Muhammad W. Ashiq³, Qingtao Wang¹, Zhanlei Rong¹, Junjie Liu¹, Yahua Mao², Zhaoxia Guo², Wenbin Wang¹

¹State Key Laboratory of Grassland and Agro-Ecosystems, School of Life Sciences, Lanzhou University, Lanzhou 730000, China

²State Key Laboratory of Grassland and Agro-Ecosystems, College of Pastoral Agriculture Science and Technology, Lanzhou University, Lanzhou 730000, China

³Ministry of Natural Resources and Forestry, Timmins District, 5520 Hwy 101 E, South Porcupine, ON, P0N1H0, Canada

Abstract: As a main component of water balance, evapotranspiration (ET) is of great importance for water saving, especially in arid and semi-arid areas. In this study, the FAO (Food and Agriculture Organization) Penman-Monteith model was used to estimate the magnitude and temporal dynamics of reference evapotranspiration (ET_r) in 2014 in subalpine meadows of the Qilian Mountains, Northwest China. Meanwhile, actual ET (ET_c) was also investigated by the eddy covariance (EC) system. Results indicated that ET_c estimated by the EC system was 583 mm, lower than ET_r (923 mm) estimated by the FAO Penman-Monteith model in 2014. Moreover, ET_r began to increase in March and reached the peak value in August and then declined in September; however, ET_c began to increase from April and reached the peak value in July, and then declined in August. Total ET_c and ET_r values during the growing season (from May to September) were 441 and 666 mm, respectively, which accounted for 75.73% of annual cumulative ET_c and 72.34% of annual cumulative ET_r, respectively. A crop coefficient (kc) was also estimated for calculating the ET_c, and average value of kc during the growing season was 0.81 (ranging from 0.45 to 1.16). Air temperature (T_a), wind speed (u), net radiation (R_n) and soil temperature (T_s) at the depth of 5 cm and aboveground biomass were critical factors for affecting kc; furthermore, a daily empirical kc equation including these main driving factors was developed. Our result demonstrated that the ET_c value estimated by the data of kc and ET_r was validated and consistent with the growing season data in 2015 and 2016.

Keywords: actual evapotranspiration; reference evapotranspiration; crop coefficient; meteorological factors; biotic factors

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1 Introduction

Water balance strongly influences the structure, function, and productivity of terrestrial ecosystems (Burman and Pochop, 1994). A critical component of water balance is actual evapotranspiration (ETc) (Mitchell et al., 2009; Valipour et al., 2017), and determination of water balance depends on precise estimation of ETc (Jensen et al., 1990; Allen et al., 1994; Jensen et al., 1997; Allen et al., 1998; ASCE-EWRI, 2005; Veroustraete et al., 2008; Allen et al., 2011; Semalty et al., 2011; Hssaine et al., 2018). Understanding of ETc is also important for water utilization and management, especially in arid and semi-arid regions (Li et al., 2014; Zhao and Zhao, 2014).

The Qilian Mountains, located in Northwest China, are water sources for many inland rivers in the Hexi Corridor. Subalpine meadows (grasslands) are a major land use in these mountains where heavy grazing not only impacts grass growth conditions but also affects ET. Therefore, it is imperative to estimate ETc of these alpine meadows with consideration of grazing impact on ETc.

A number of methods and models have been developed and used to estimate ETc, such as Bowen ratio (Ohmura, 1982; Sun et al., 2006; Fang et al., 2018), lysimeter (Howell et al., 1991; Gao et al., 2015), eddy covariance (EC) (Swinbank, 1951; Massman, 2000), water balance (Mastrorilli et al., 1998; Saadi et al., 2018), and FAO (Food and Agriculture Organization) Penman-Monteith (P-M) model (Allen et al., 1998). This study focused on two methods: EC and FAO Penman-Monteith model. The EC is a micro-meteorological approach widely used to study ETc at the ecosystem level (Massman, 2000; Falge et al., 2001; Aubinet et al., 2012). The FAO Penman-Monteith model is a modified version of P-M model (Monteith, 1965) recommended by the FAO to estimate ETc for various land uses including grassland (Allen et al., 1998). For each land use, ETc is estimated using reference evapotranspiration (ET) values which in turn depend on land use-specific crop coefficient (k_c) (Allen et al., 1998; Yang et al., 2013; Khoshravesh et al., 2017). The k_c values, for a specific land use, are generally assigned by the growth stage of the plant species. For example, the k_c values of 0.40, 1.05, and 0.85 in grasslands are respectively reported for initial-, middle-, and late-season growth stages of grass (Allen et al., 1998). Studies also show that some additional factors, such as meteorological data and vegetation biomass, also affect k_c value (Lockwood, 1999; Williams and Ayars, 2005; Zhou and Zhou, 2009; Yang and Zhou, 2011; Zhang et al., 2012). Therefore, accurately calculating k_c can provide more reliable estimation of ETc.

The ETc for subalpine meadows in the Qilian Mountains has been estimated (ranging from 2.88 to 3.26 mm/d) using micro-lysimeter method (Song et al., 2004; Yang et al., 2013). However, the ETc estimation by micro-lysimeter is influenced by weather conditions, i.e., it might be over-estimated during sunny days and under-estimated during rainy weather (Zhang et al., 2012; Zhou and

Zhou, 2009). Thus, it is unsuitable for long-term ETc estimation during all weather conditions. To fill this knowledge gap for grasslands in the Qilian Mountains, we used (1) EC system to observe ETc at daily time scale, and (2) FAO Penman-Monteith model to estimate ET .

The objectives of this study are (1) to estimate ETc based on kc and ET values of the subalpine grasslands in the Qilian Mountains, and (2) to develop and validate a model of kc based on meteorological factors and vegetation biomass of subalpine grasslands in the Qilian Mountains.

2.1 Study Area

The study area is located in Tianlaochi Catchment in the upper reaches of the Heihe River (38°23 56 -38°26 47 N, 99°53 57 -99°57 10 E) with elevation ranging from 2660 to 4400 m a.s.l. [Figure 1: see original paper]. The experimental site for this study is located at 3070 m altitude in subalpine meadow in the Qilian Mountains. The study area belongs to a typical alpine semi-arid climate, characterized by long and cold winters, and short and warm summers. The mean annual precipitation is about 435.0 (± 5.6) mm with 84.2% of precipitation occurring during May to September. The annual mean temperature is about -0.6°C - 2.0°C , and mean January and mean July temperatures are -13.1°C and 12.1°C , respectively. The soil type is mountain grey cinnamon with up to 50 cm depth and gravel below 50 cm. The vegetation community mostly belongs to annual grasses, i.e., *Elymus nutans* griseb and *Foeniculum vulgare*, and their roots grow up to 30 cm.

2.2.1 Meteorological and Soil Physical Data

At the study site, a weather station and an EC system were set up in 2011 and 2013, respectively. Table 1 shows the list of meteorological factors for which data are being collected at half-hour intervals and soil physical data at the study site.

[Figure 1: see original paper] Geographic location of the study area and distribution of observation instruments in the experimental site. EC, eddy covariance.

Table 1 Summary of the meteorological and soil physical data observed at the weather station

Company	Country	Observational elevation	Abbreviation	Parameter
Decagon	-	-	Rn	Net radiation
Decagon	-	-	Rs	Short wave radiation
-	-	-5 cm	G	Soil heat flux
-	-	1.8 m	u	Wind speed

Company	Country	Observational elevation	Abbreviation	Parameter
-	-	-	Ta	Air temperature
-	-	-	RH	Relative humidity
-	-	-	Pa	Pressure
-	-	-	P	Precipitation
-	-	-5, -10, -20, and -50 cm	Ts5, Ts10, Ts20, and Ts50	Soil temperature
-	-	-5, -10, -20, and -50 cm	SWC5, SWC10, SWC20, and SWC50	Soil water content

2.2.2 Flux Measurements

The EC system was used to measure CO fluxes, sensible heat (H), and latent heat (LE) at 2.2 m above the ground surface from 2013. A CO /H O infrared analyzer (Li-7550; LI-COR, Inc., Lincoln, NE, USA) and a three-dimensional supersonic anemometer (CSAT-3; Campbell Scientific, Inc., UT, USA) were mounted on a horizontal bar extending from a tower. The CO /H O sensor was installed in the down-wind direction of the supersonic anemometers. The CO /H O analyzer was calibrated every six months. Short wave radiation (Rs) from the sky and long wave radiation (Rl) from the land surface were measured with a net radiometer (CNR-1; Kipp and Zonen, Delft, The Netherlands) at 1.5 m above the ground surface. The net radiation (Rn) was calculated from the difference of Rs and Rl. Soil heat fluxes (G) were recorded by a net radiometer at 10 cm soil depth. The Rn was partitioned into H, LE, and G.

The energy balance ratio (r) was calculated using the following equation (Gu et al., 1999):

$$r = \frac{LE + H}{Rn - G}$$

The item LE+H measured by the EC system seemed to be underestimated since the average value of r was about 0.75 for the entire observation period from 2014 to 2016, which fell in the median region of reported energy closures (0.55–0.99) (Wilson et al., 2002). The lack of energy balance closure had also been reported by Stannard et al. (1994) and Aubinet et al. (2012), and energy balance closure had become accepted as an important test of EC (Anderson et al., 1984; Mahrt, 1998). We were not trying to specify a particular cause for the imbalance because several possibilities may be involved in the lack of energy closure (Wilson et al., 2002).

In long-term field measurements, gaps in data are a known issue. The gaps occur either due to non-recording (instrument malfunction/power failure) or rejection of certain data that do not meet quality control requirements. The quality of flux data collected for this study was assessed through a widely adopted flag system (Mauder and Foken, 2004), which led to discard some data recorded at night time. The data gap filling was therefore performed using a lookup table approach that considered both covariation of fluxes with meteorological variables and the temporal autocorrelation of the fluxes (Falge et al., 2001; Reichstein et al., 2005).

2.2.3 Biotic Data

At the experimental site, six quadrats (0.5 m × 0.5 m) were randomly selected to collect aboveground biomass. Biomass was measured every three days by cutting the plants at ground level and loading the plants into sampling bags during the growing season (May-October). Each sample was numbered and dried at 65°C until a constant weight was obtained.

2.3.1 FAO Penman-Monteith Model

The FAO Penman-Monteith model (Allen et al., 1998) was used to calculate ET , which is expressed as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} uD}{\Delta + \gamma(1 + 0.34u)}$$

where λ is the water latent heat of vaporization (MJ/kg); Δ is the slope of the vapor pressure versus temperature curve (kPa/°C); R_n is the net radiation (MJ/(m² · d)); G is the soil heat flux (MJ/(m² · d)); γ is the psychrometric constant (kPa/°C); T is the daily mean temperature at 2 m above the ground surface (°C); u is the wind speed at 2 m above the ground surface (m/s); D is the vapor pressure deficit (kPa); ET_{cm} is the estimated actual evapotranspiration (mm/d) using the FAO-P-M model; and k_c is the crop coefficient.

2.3.2 EC Model

The EC model was used to calculate the ET_c :

$$ET_c = \frac{LE}{\lambda \rho_w}$$

where LE is the latent heat flux (MJ/(m² · d)); λ is the water latent heat of vaporization (MJ/kg); and ρ_w is the water density (kg/m³).

2.3.3 Crop Coefficient (kc)

The daily kc was obtained by dividing ETc values with ET values for the year 2014. The obtained kc was used to develop two models: one with meteorological factors only, and the other using both meteorological factors and biotic factors. Both models were developed using the data of 2014, and validated using the data of 2015 and 2016.

2.3.4 Evaluation Methods

In the study, the linear correlation coefficient (R^2), slope, Relative Root-Mean-Squared Error (RRMSE), Coefficient of Determination (CD), and Index of Agreement (IA) were used to examine the extent of the differences between the calculated and observed values of ETc. The slope was the relative angle between the straight line and horizontal axis. The R^2 value was used to assess the correlation between the prediction results with actual situation (Gao et al., 2013). The RRMSE was a measure of relative magnitude of residuals; models with smaller RRMSE values are desirable (Gao et al., 2015). The IA was a measure to evaluate the correlation between the observed and simulated values, and IA values closer to 1 are desirable (Li et al., 2014). The CD was used to measure dispersion of simulated values from the mean observed values, and CD greater than 0.8 indicates that the result was acceptable (Cai et al., 2007). The R^2 and slope were calculated in Sigmaplot 11.0 (Alexandris and Kerkides, 2003; Yang and Zhou, 2011). The mathematical expressions of RRMSE, CD, and IA were presented as follows:

$$RRMSE = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^n (E_i - O_i)^2}}{\bar{O}}$$

$$CD = \frac{\sum_{i=1}^n (E_i - \bar{O})^2}{\sum_{i=1}^n (O_i - \bar{O})^2}$$

$$IA = 1 - \frac{\sum_{i=1}^n (E_i - O_i)^2}{\sum_{i=1}^n (|E_i - \bar{O}| + |O_i - \bar{O}|)^2}$$

where O_i is the observed value; \bar{O} is the mean observed value; E_i is the simulated value; and n is the number of samples.

2.3.5 Vapor Pressure Deficit (VPD)

VPD is the difference between the pressure of water vapor held in saturated air at a given temperature and the pressure of water vapor that exists in the ambient air. It is calculated as follows:

$$VPD = 0.6108 \times e^{\frac{17.27T}{T+237.3}} \times (1 - RH)$$

where T is the daily mean temperature at 2 m above the ground surface (°C); RH is the relative humidity.

3.1 Variations of Meteorological and Soil Physical Factors

Temporal variations in meteorological factors are shown in Figures 2 and 3. The mean daily values of Rn, Rs, Ta, VPD, and u were 12.43 MJ/(m²·d), 22.40 MJ/(m²·d), -0.57°C, 0.658 kPa, and 1.21 m/s, respectively. During the growing season, the sequence of SWC was SWC20 > SWC5 > SWC10 > SWC50, and that of Ts (soil temperature) was Ts5 > Ts10 > Ts20 > Ts50. Both Ta and Rn reached the minimum in December and the maximum in July. VPD reached the maximum of about 1.180 kPa during the growing season, whereas u reached the maximum in February and the minimum in July.

3.2 Monthly Variations of ET and ETc

Figure 4a shows that annual ET was 923 mm, which was higher than the annual ETc (583 mm) in 2014. ET gradually increased from January and reached the peak value in August and then declined in September. In contrast, ETc began to greatly increase in April and reached the peak level in July and then started to decline in August. The total ETc and ET values during the growing season (from May to September) were 441 and 666 mm, respectively, which accounted for 75.73% and 72.34% of annual ETc and ET, respectively.

Figure 4b compares the temporal variation of ETc and precipitation (P). The annual values of ETc and P were 583 and 546 mm, respectively. The annual ratio of ETc to P is 1.067. However, the values of ETc and P during the growing season (from May to September) were 441 and 540 mm, respectively, and the ratio was 0.818.

3.3 Temporal Variations of kc

As shown in Figure 5, kc quickly increased from May to June, and remained at a high level in July and August. It declined in September and was about 0.2 at the end of October. During the growing season, kc exhibited a mean value of 0.81 and fluctuated within the ranges of 0.45–1.16.

3.4.1 Effect of Environmental Factors on kc

In the study, Pearson's product-moment correlation coefficients between kc and environmental factors were computed at a daily scale (Table 2). The significant correlations (P < 0.01) of kc with u, Ta, Rn, and Ts5 suggest that these factors are critical for controlling kc. The relationships of kc with P, SWC5, Ts10, and Ts20 were also significant (P < 0.05).

The significant negative correlation between u and RH (Table 2) suggests the role of wind in blowing away water vapors. The SWCs mainly come from precipitation, i.e., the infiltration into soil layer through rainfall, so there are good correlations between precipitation and SWC. Solar radiation provides energy to soil that in turn increases soil temperature. Using significant climatic factors (Table 2), we developed the following regression model to estimate daily kc :

$$kc = 0.650 + 0.224u - 0.038Ta - 0.030Rn - 0.002P + 0.570SWC5 + 0.110Ts5 - 0.016Ts10$$

According to the relationship $ET_c = kc \times ET_0$, we calculated the daily ET_{cmod1} as follows:

$$ET_{cmod1} = (0.650 + 0.224u - 0.038Ta - 0.030Rn - 0.002P + 0.570SWC5 + 0.110Ts5 - 0.016Ts10) \times ET_0$$

where ET_{cmod1} is the ET_c calculated by the meteorological factors model.

Table 2 Pearson's product-moment correlation coefficients between daily crop coefficient (kc) and meteorological and soil physical factors during the growing season in 2014

Factor	u	Ta	RH	Rn	Pa	P	$SWC5$	$SWC10$	$SWC20$	$SWC50$	$Ts5$	$Ts10$	$Ts20$	$Ts50$
kc	-	0.751**	0.933***	0.600**	0.394*	0.169**	0.155*	0.077	0.741*	0.582*	0.470*	0.265**		
u	1.000	-	-	0.651*	-	-	0.141**	-	-	-	-	-	-	-
Ta		1.000	0.542**	0.891**	0.120*	0.141*	0.090	0.119**	0.307*	0.257*	0.197*	0.171**		
RH			1.000	0.110*	0.794**	0.383**	0.259**	0.164**	0.067	-	0.891*	0.306*	0.237*	0.180**
Rn				1.000	0.442**	0.320**	-	-	-	0.119**	0.530**	-	-	-
Pa					1.000	0.165*	0.040*	0.166*	0.039	0.119**	0.185*	0.045	0.069	0.005
P						1.000	0.203*	0.108	0.530*	0.792*	0.595*	0.530*	0.342*	0.296**
$SWC5$							1.000	0.194*	0.177*	0.108	0.394*	0.365*	0.292*	0.365**
$SWC10$								1.000	0.751*	0.151*	0.169*	0.530*	0.514*	0.530**
$SWC20$									1.000	-	0.155*	0.514*	0.342*	0.342**
$SWC50$										1.000	0.077	0.296*	0.792*	0.744**
$Ts5$											1.000	0.962*	0.831*	0.942**
$Ts10$												1.000	0.901*	0.778**
$Ts20$													1.000	0.792**

Factor	u	Ta	RH	Rn	Pa	P	SWC5	SWC10	SWC20	SWC50	Ts5	Ts10	Ts20	Ts50
Ts50														1.000

Note: ** and * indicate significance at 0.99 and 0.95 confidence levels, respectively.

3.4.2 Effects of Biotic Factors on kc

Biomass directly reflects the conditions of a biological community, so we selected it as a biotic factor. The results showed that biomass gradually increased in May, rapidly increased in June and July, and reached a peak in August (with a maximum of 505 g/m²), and then began to decrease rapidly in September (Fig. 6).

The regression analysis showed a significant positive correlation between biomass and kc (Fig. 7). The linear regression equation is as follows:

$$kc = 0.0013 \times \text{Biomass} + 0.42$$

Considering both meteorological and biotic factors, we calculated daily ETc_{mod2} as follows:

$$ETc_{mod2} = (0.650 + 0.224u - 0.038Ta - 0.030Rn - 0.002P + 0.570SWC5 + 0.110Ts5 - 0.016Ts10 + 0.0013 \times \text{Biomass})$$

where ETc_{mod2} is the ETc calculated by the full model incorporating both meteorological and biotic factors.

3.5 Testing Estimated ETc

We validated Equations 11 (ETc_{mod1}) and 13 (ETc_{mod2}) using the EC system data collected during the growing seasons in 2015 and 2016. The estimated values were close to the observed values (Fig. 8). The slope, R², and IA of ETc_{mod2} were greater than those of ETc_{mod1} (Table 3), implying that the correlation between observed values and simulated values by ETc_{mod2} is better than that by ETc_{mod1}. The RRMSE obtained by ETc_{mod2} was smaller than that by ETc_{mod1}, suggesting higher accuracy of ETc_{mod2} than that of ETc_{mod1}. The CD values for both ETc_{mod1} and ETc_{mod2} were greater than 0.8, indicating both regression equations are good. Overall, the performance of ETc_{mod2} that used both meteorological and biotic factors is better than that of ETc_{mod1} (only meteorological factors).

Table 3 Summary of the parameters assessing the accuracy of the two models

Parameter	ETcmod1	ETcmod2
Slope	0.78	0.85
R ²	0.72	0.81
RRMSE	0.23	0.18
IA	0.89	0.93
CD	0.91	0.94

Note: R², correlation coefficient; RRMSE, Relative Root-Mean-Squared Error; IA, Index of Agreement; CD, Coefficient of Determination.

4.1 Variations of ET , ETc, and P

The result shows that ETc was lower than ET . The maximum of ET appeared in August, and the minimum was in December. However, the maximum of ETc appeared in July and the minimum occurred in December.

According to the FAO Penman-Monteith equation, meteorological and soil factors were the only factors that affected ET . However, ETc was affected not only by meteorological factors but also by biotic factors such as biomass. When Rs, Rn, Ta, and RH increased from April and reached peak values in August and then declined (Figs. 2 and 3), ETc began to increase in April and reached the maximum in July with canopy development during the growing season.

The annual ratio of ETc to P (i.e., 1.067) indicates that P was less than ETc (Hou et al., 2011). However, the ratio of ETc to P during the growing season (from May to September) was 0.818. This suggests that adequate water availability supports plant growth in this period. The value of ET during the growing season was 666 mm, and the ratio of ET to P during the growing season was 1.240. This result was similar to research in some grassland ecosystems (Wever et al., 2002; Li et al., 2005). However, our result was higher than a non-irrigated pasture (Sumner and Jacobs, 2005) and an alpine winter pasture (Li et al., 2014).

The ET process is governed by energy exchange at the vegetation surface and is limited by the amount of energy available (Semalaty et al., 2011). ET in our study area is caused by climatic conditions. Rn in the study area was higher than that in the Qinghai-Tibetan Plateau grassland (Gu et al., 2008), so ET was higher than that reported by Li et al. (2014) who conducted their study in the Qinghai-Tibetan Plateau grassland. Apart from energy enhancing ET to some extent, the high SWC and P could offer water for plant needs (Yang and Zhou, 2011; Simona and Rita, 2013; Li et al., 2014). High Ts may stimulate plant activity and enable plants to absorb more water (Gao et al., 2015), while low RH may improve the water vapor exchange between the atmosphere and vegetation (Gao et al., 2015).

4.2 Temporal Variations of k_c

k_c quickly increased from May to June, remained at a high level in July and August, and then declined in September. The range of k_c in the study (0.45–1.16) was larger than that of k_c reported in FAO 56 (0.30–1.05) (Allen et al., 1998), and it was higher than that of k_c observed in an alpine winter pasture (0.30–0.92) (Li et al., 2014), in a typical steppe (0.32–0.68) (Miao et al., 2009), and in a temperate desert steppe of Inner Mongolia (0.02–0.50) (Yang and Zhou, 2011; Zhang et al., 2012). Our result indirectly showed that the subalpine meadows in the Qilian Mountains featured more adequate moisture and better plant growth conditions than other semi-arid and arid grassland ecosystems.

4.3 Factors Impacting k_c

The highest correlation between k_c and environmental factors suggested that R_n was the most important factor for determining k_c . Similar findings have been reported for an alpine winter pasture (Li et al., 2014). The higher R_n made a significant contribution to k_c (Gao et al., 2015). However, Yang and Zhou (2011) selected a temperate desert steppe as their study area, where water was a key environmental factor and pointed out that SWC was the most important factor, and Hou (2010) stated temperature was the most important meteorological factor. These differences may result from the different environmental conditions of plant growth.

In addition to meteorological factors, biotic factors can greatly affect k_c (Tyagi et al., 2000; Williams et al., 2003; De Medeiros et al., 2005; Li et al., 2014). Biomass directly reflects the conditions of a biological community, so we selected it as a biotic factor to estimate k_c .

Figure 9 shows that the ET_c calculated by both Equations 11 and 13 is underestimated in 2015 and 2016. The FAO Penman-Monteith model performs well under abundant water conditions. The underestimation of ET and ET_c in our study area is likely due to erratic precipitation which is not sufficient to meet water requirement criteria of the FAO Penman-Monteith model.

5 Conclusions

The FAO Penman-Monteith model was used to simulate ET over the subalpine meadows in the upper reaches of the Heihe River. Meanwhile, ET_c was measured by the EC system. During the growing season, the ratio of ET_c to ET is 0.663, and the ratio of ET_c to P is 0.818. Both ratios indicate that the water regime of meadows in the study area is favorable. The k_c was used to estimate ET_c .

The average value of k_c during the growing season was 0.81 (ranging from 0.45 to 1.16). R_n , T_a , u , and T_{s5} were the critical factors controlling k_c . P_a , SWC_5 , T_{s10} , and T_{s20} also showed significant relation to k_c . Finally, we developed a daily empirical k_c equation based on biomass, T_a , u , R_n , P , SWC_5 , T_{s5} , T_{s10} , and T_{s20} to estimate daily k_c , and used the k_c and ET to estimate ET_c . The

model validation with 2015 and 2016 growing season data shows that the daily empirical kc equation performed well in this study area.

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