



# Article Estimation of Evapotranspiration and Crop Coefficient of Chinese Cabbage Using Eddy Covariance in Northwest China

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**Abstract:** Chinese cabbage is a key vegetable crop in northwest China. It is of great significance to study the evapotranspiration (*ET*) and crop coefficient ( $K_c$ ) for agricultural water-saving management in this area. Eddy covariance (EC) was used to measure the *ET* and  $K_c$  of Chinese cabbage in northwest China from 1 May to 16 October 2020, in order to analyze the characteristics of these variables under plastic mulch. The results showed that the average  $K_c$  of the first crop of cabbage was higher in the middle and late stages, with values of 1.08 and 1.09 during the heading and maturity stages, respectively. The average  $K_c$  of the second crop of cabbage was higher in the middle stage, with values of 1.10 and 1.13 during the rosette and heading stages, respectively. The average annual  $K_c$  of Chinese cabbage was 0.81. Although  $K_c$  was higher in the middle and late periods, the water use efficiency was still 28.96 kg·ha<sup>-1</sup>·mm<sup>-1</sup>. The annual *ET* of Chinese cabbage was 505.3 mm. The study revealed the variation pattern of *ET* and  $K_c$  of Chinese cabbage, which provides an important scientific basis for the irrigation management of Chinese cabbage and is of great significance to guide the practice of water-saving vegetable planting.

Keywords: evapotranspiration; crop coefficient; Chinese cabbage; Eddy covariance; water balance

# 1. Introduction

In recent decades, with the continuous population growth and development of the social economy, the demand for water resources has increased rapidly in world. Water resource deficiency, particularly in northwest China, leads to environmental degradation and limits regional economic development and social progress [1,2]. In the arid region of northwest China, about 10% of the area receives agricultural irrigation, and irrigation accounts for the largest part of available water consumption. At present, the area mainly pumps groundwater for irrigation and crop growth. How to improve the agricultural water use efficiency (WUE) has become the focus of scientists around the world [3–9]. Evapotranspiration (*ET*) is a main unknown variable for understanding the ecohydrological system. In arid areas, ET can reach 95% of the water balance [10]. The main form of agricultural water consumption is crop evapotranspiration (*ET*). Therefore, the key to water saving in agriculture is to reduce crop evapotranspiration. The determination of agricultural water management practices, the design of irrigation systems and irrigation regimes, and the calculation of crop yields are all based on accurate ET estimation [11]. A better understanding of ET can help make decisions about irrigation and improve the efficiency of available water [12–15]. The ratio of crop potential evapotranspiration to reference evapotranspiration  $(ET_0)$  is defined as the crop coefficient  $(K_c)$  [11].  $K_c$  is a key parameter for managing agricultural irrigation systems. Thus, studying the evapotranspi-



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**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). ration process and estimating the crop coefficient ( $K_c$ ) are key aspects to improve water use efficiency and save agricultural water in this area.

Previous studies on ET and  $K_c$  have mainly focused on field food crops such as maize and wheat in northwest China. Kang [16] showed that the average seasonal ET and  $K_c$  of maize in northwest China during the last decade were 424.0 mm and 1.04, respectively, according to lysimeter measurements. Li [17] measured the ET and  $K_c$  of spring maize in northwest China in 2007 and studied their characteristics under plastic film mulching. Guo [18] used the eddy covariance (EC) method to study the dynamics of crop coefficient of spring maize with plastic mulch in this region over the past 12 years. Yang [19] studied the effects of drip irrigation technology on soil evaporation (E), crop transpiration (T), and wheat total ET in this area. Studies on vegetable crops are more concentrated in terms of crop coefficient prediction and plant physiology. Pereira [20] predicted crop coefficients from a fraction of ground cover and height, as well as used ground and remote sensing data for background and verification. Pereira [21] also pointed out their practical application to vegetable, field, and fruit crops with a focus on parameterization. Wu [22] investigated the comparative responses to silicon and selenium in relation to different physiological processes in flowering Chinese cabbage under cadmium stress. Sun [23] studied the effect of Piriformospora indica on the drought tolerance of Chinese cabbage leaves.

At present, some changes have taken place in the crop planting structure in north-west China. The planting structure in this region has gradually changed from food crops to vegetable crops. Chinese cabbage, a subspecies of *Brassica pekinensis* (Lour.) Rupr., has been widely planted in Northwest China due to its high economic value. A lack of water is still a barrier for growing crops in this area. However, there are few reports about Chinese cabbage *ET* and  $K_c$  based on field observation. Water balance methods, such as the weighing lysimeter, enable direct estimations of *ET* and  $K_c$  [24]. However, the two measurements need to be at least one day apart, and their representativeness is poor. The EC method is regarded as a standard method for measuring *ET*. It can accurately capture *ET* information in a large range within a short period of time (e.g., 10 min) [25]. Therefore, the EC method was adopted in our study to measure the *ET* Chinese cabbage in northwest China. Then,  $K_c$  and other water consumption indices were calculated.

The aims of this experiment were (1) to compare the results of the water balance (WB) method and eddy covariance (EC) measurement of *ET* on Chinese cabbage, (2) to study the daily *ET* and seasonal *ET* variation of Chinese cabbage and its influencing factors, and (3) to analyze the seasonal variation of  $K_c$ .

#### 2. Materials and Methods

#### 2.1. Experimental Site and Design

The research was implemented at the Shiyanghe Experimental Station for Water Saving in Agriculture and Ecology of the China Agricultural University, located in Wuwei City, Gansu Province, northwest China (N  $37^{\circ}52'$ , E  $102^{\circ}50'$ , altitude 1581 m) from 1 May to 16 October 2020. The study area is in a typical temperate continental climate zone. The annual average temperature is 8 °C, the annual accumulated temperature (>0 °C) is 3550 °C, the annual precipitation is 164.4 mm, the average annual pan evaporation is about 2000 mm, the annual number of average sunshine hours is 3000 h, and the frost-free period is 150 days. The average groundwater depth is 25 m, and the data of soil texture are shown in Table 1. The region, suitable for the growth of half-hardy vegetables, is characterized by high altitude, low temperature, long sunshine duration, and suitable light and heat resources. Chinese vegetables, with yellow inner leaves and a short growth cycle, are suitable for growth in the environment of 5–25 °C. The vegetable has the characteristics of high yield and excellent quality.

| Depth (cm) | Soil Texture Dry Bulk Densit |      |  |
|------------|------------------------------|------|--|
| 0–10       | Sandy loam                   | 1.60 |  |
| 10–20      | Silty loam                   | 1.63 |  |
| 20-40      | Silty loam                   | 1.57 |  |
| 40-60      | Silty loam                   | 1.41 |  |
| 60-80      | Silt                         | 1.43 |  |
| 80-100     | Silty loam                   | 1.69 |  |

Table 1. Soil texture of experimental sites.

Our study area spanned 500 m from north to south and 250 m from east to west. The planting density of Chinese cabbage is about 108,000 plants ha<sup>-1</sup>. The row spacing was 40 cm and the planting spacing was 6.7 cm. In this study, the growth period of the first crop of Chinese cabbage was from 17 April to 1 July, and that of the second crop was from 1 August to 16 October. The study area was irrigated 14 times in 2020 on 3 May, 11 May, 19 May, 29 May, 3 June, 13 June, 19 June, 1 August, 12 August, 18 August, 27 August, 5 September, 14 September, and 24 September by drip irrigation with plastic mulch. The total volume of precipitation was 144.4 mm, and the total volume of irrigation water was 293.9 mm throughout the whole study period. The precipitation (P) and irrigation (I) volumes throughout the observation period are shown in Figure 1.



**Figure 1.** The precipitation (P) and irrigation (I) volumes and the diurnal variation in soil water content (SWC) of Chinese cabbage throughout the observation period.

# 2.2. Using Eddy Covariance to Measure and Correct the Measured Value

The eddy covariance system was installed at about 320 m from the northernmost side of the experimental site and 145 m from the westernmost side, adjusting the relative height between the Chinese cabbage canopy and sensors at a constant 2.5 m. Chinese cabbage is the main crop type on experimental site, and the experimental field is large enough to provide an adequate fetch length for EC measurements. The smallest fetch length was 100 m. The mean wind direction was northwest. The eddy covariance system consisted of a temperature and humidity sensor (model HMP45C, Vaisala, Vantaa, Finland), a krypton hygrometer (model KH20, Campbell Scientific, Inc., Logan, UT, USA), and a 3D sonic thermometer/anemometer (model CSAT3, Campbell Scientific, Inc., USA). The HMP45C sensor can measure average temperature and humidity at 10 min intervals. The KH20 sensor and CSAT3 sensor can measure vertical fluctuations in temperature, water vapor density, and wind speed at 0.1 s intervals. All data are transferred to the same data logger (model CR5000, Campbell Scientific Inc, 100 USA), generating 10 min of statistical data (average, variance, and covariance). Continuous observations were conducted from 1 May to 16 October 2020.

The latent heat flux and sensible heat flux were calculated using the eddy correlation method [25].

$$\lambda ET = \rho_a \lambda \overline{w'q'},\tag{1}$$

$$H = C_v \rho_a \overline{w'T'},\tag{2}$$

where  $\lambda ET$  and H are the latent and sensible heat flux (W·m<sup>-2</sup>),  $\overline{w'q'}$  is the covariance between fluctuations of vertical wind speed w' (m·s<sup>-1</sup>) and humidity q' (kg·kg<sup>-1</sup>),  $\overline{w'T'}$  is the covariance between fluctuations of w' and sonic temperature T' (K),  $\rho_a$  is the air density (kg·m<sup>-3</sup>),  $C_p$  is the specific heat of dry air at constant pressure (J·kg<sup>-1</sup>·K<sup>-1</sup>),  $\lambda$  is the latent heat of water vaporization (J·kg<sup>-1</sup>), and ET is the crop evapotranspiration (kg·m<sup>-2</sup>·s<sup>-1</sup>).

In this study, the original data measured by EC at 10 Hz were recalculated by Eddpro software (version 4.0, LI-COR Inc., Lincoln, NE, USA) to obtain the average latent heat flux, sensible heat flux, and momentum flux at time intervals of 30 min. The original data observed using the EC method were modified according to the Guide for Observation of Eddy Correlation Flux [26–29]. The following two interpolation methods were used to obtain the missing data in this study: (1) the linear interpolation method when the missing period was within 0-2 h; (2) the diurnal average method when the missing period was between 2 and 24 h.

#### 2.3. Other Measurements

A net radiometer (model NR-LITE, Kipp & Zonen, Delft, The Netherlands), which was set at a relative height of 1.5 m above the canopy, was applied to measure the net radiation (*Rn*). Before the experiment, a net pyrgeometer (model CG2, Kipp & Zonen, Delft, The Netherlands) and a high-precision albedometer (model CM7B, Kipp & Zonen, Delft, The Netherlands) were used to calibrate the radiometer.

A soil heat flux plate (model HFP0, Hukseflux, The Netherlands) was set at a soil depth of 50 mm below the surface. Surface soil heat flux was calculated by correcting the value at 50 mm for the heat storage above the sensors, determined by the change in soil temperature above the heat flux sensors. The temperature above the soil heat flux plate was measured by four pairs of thermocouples (model 105T, Campbell Scientific, USA) located directly above the soil heat flux plate at depths of 20 mm and 40 mm. All sensors were sampled every 5 s, and the average values for soil heat flux and net radiation every 30 min were collected and calculated in CR5000. Observations were conducted continuously from 1 May to 16 October 2020.

Soil volumetric water content was monitored by soil moisture sensors (model CS616, Campbell Scientific, USA), and soil temperature was monitored by soil temperature sensors (model 109L, Campbell Scientific, USA). Soil temperature was monitored from 1 May to 16 October 2020 at soil depths of 20 cm, 40 cm, 60 cm, and 80 cm. Soil volumetric water content was monitored from 1 May to 17 July 2020 at soil depths of 20 cm, 40 cm, 60 cm, and 100 cm. It was also monitored from 17 July to 16 October 2020 at soil depths of 20 cm, 40 cm, 60 cm, and 80 cm. At the same time of monitoring, soil samples were collected regularly in the observation area at depths of 10 cm, 20 cm, 40 cm, 60 cm, 80 cm, and 100 cm. The soil moisture content of each layer was measured by the drying method to calibrate the data measured by the instrument. The diurnal variation in soil water content (SWC) during the whole observation period is shown in Figure 1.

White plastic mulch with a width of 1.2 m was applied in the field, and the spacing of each application was 0.4 m. Six weighing micro-evaporation barrels were applied to measure soil evaporation ( $E_S$ ) under the film and bare soil [30]. During the growth period of Chinese cabbage, four plants were selected to measure the growth indicators (plant height, canopy height, leaf length, leaf width, and number of leaves) every week. Lastly,  $K_c$  was calculated according to FAO 56, i.e., the ratio of the  $ET(ET_{EC})$  measured by the EC method to the reference  $ET(ET_0)$  calculated by the Penman–Monteith formula [11].

#### 2.4. Applying the Water Balance Method to Estimate ET

The water balance (WB) method based on mass conservation is a simple method to estimate *ET* [24,31,32], which can be expressed by Equation (5).

$$P + I + Q_g - ET - D = \Delta W, \tag{3}$$

where *P* is the precipitation, *I* is the irrigation,  $Q_g$  is the contribution from the water table, *ET* is the actual *ET*, *D* is the deep drainage, and  $\Delta W$  is the change in water storage in the 0–100 cm soil layer, which can be calculated as

$$\Delta W = W_{t_2} - W_{t_1},\tag{4}$$

where  $W_{t_1}$  and  $W_{t_2}$  are the average water storage in the 0–100 cm soil layer at time  $t_1$  and  $t_2$ , respectively.

We ignored deep drainage in drip irrigation. The buried depth of the groundwater level is more than 40–50 m; thus, the contribution of the water table ( $Q_g$ ) could also be ignored. Thus, Equation (3) can be simplified as

$$ET_{WB} = P + I - \Delta W. \tag{5}$$

## 2.5. Water Use Efficiency Calculation

Water use efficiency based on cumulative evapotranspiration is calculated as

$$WUE = \frac{Y}{ET},\tag{6}$$

where *Y* is the yield (kg·ha<sup>-1</sup>), and *ET* is the cumulative evapotranspiration (mm).

# 2.6. Data Analysis Method

Excel data analysis software was used to carry out polynomial fitting analysis on *ET*,  $E_s$ , and  $K_c$  in the observation area, and regression analysis was conducted on *ET* and its influencing factors. The statistical index used was the determination coefficient ( $R^2$ ).

$$R^{2} = \left[\frac{\sum_{i=1}^{N} (O_{i} - \overline{O}) (P_{i} - \overline{P})}{\sqrt{\sum_{i=1}^{N} (O_{i} - \overline{O})^{2}} \sqrt{\sum_{i=1}^{N} (P_{i} - \overline{P})^{2}}}\right]^{2},$$
(7)

where  $O_i$  is the measured value,  $P_i$  is the fitted value,  $\overline{O}$  is the average of the measured value, and  $\overline{P}$  is the average of the fitted value.

# 3. Results and Discussion

# 3.1. The Examination of ET Measured by Eddy Covariance

The water balance method is generally regarded as an accurate method for calculating *ET* over a long period of time [25]. In our study, the results from the water balance method were used to test whether the *ET* measured by the eddy covariance method was reliable. Figure 2 shows that the weekly  $ET_{EC}$  and  $ET_{WB}$  were consistent at different growth stages  $(ET_{EC} = 0.94ET_{WB}, R^2 = 0.59, n = 19)$ .



**Figure 2.** Comparison of weekly *ET* of Chinese cabbage from eddy covariance measurement and water balance method.

As can be seen from Table 2, the total  $ET_{EC}$  and  $ET_{WB}$  throughout the growth period of the first crop were 275.6 mm and 236.3 mm, respectively. The ratio of  $ET_{EC}$  to  $ET_{WB}$  at the seedling stage, rosette stage, heading stage, and maturity stage were 0.48, 3.66, 1.05, and 1.34, respectively, and the ratio throughout the growth period was 1.17. The total  $ET_{EC}$ and  $ET_{WB}$  of the second crop were 229.7 mm and 192.8 mm throughout the growth period, respectively. The ratio of  $ET_{EC}$  to  $ET_{WB}$  at the seedling stage, rosette stage, heading stage, and maturity stage were 2.84, 0.91, 1.38, and 0.74, respectively, and the ratio throughout the growth period was 1.19. These results showed that the  $ET_{EC}$  was in good agreement with  $ET_{WB}$ , especially throughout the growth period. This proves that the EC method could accurately measure the Chinese cabbage's ET in the study area.

**Table 2.** *ET* of Chinese cabbage from water balance method, as well as *ET* and  $K_c$  from eddy covariance measurement, over the whole growth period.

| Crop           | Growth Stage       | Period                  | Days | Cumulative <i>ET</i><br>(mm) |           | Daily Average<br>ET (mm∙Day <sup>-1</sup> ) |           | Average K <sub>c</sub>  |                |
|----------------|--------------------|-------------------------|------|------------------------------|-----------|---|-----------|---|----------------|
|                |                    |                         |      | ET <sub>WB</sub>             | $ET_{EC}$ | $ET_{WB}$                                   | $ET_{EC}$ | Average 57.8<br>60.8<br>113.4<br>323.5<br>135.6<br>39.7<br>31.69<br>79.6<br>286.5 | K <sub>c</sub> |
| First crop     | Seedling           | 1–19 May                | 18   | 66.8                         | 32.3      | 3.7   | 1.8       | 91.5  | 0.35           |
|                | Rosette            | 20–31 May               | 12   | 14.7                         | 53.9      | 1.2   | 4.5       | 57.8  | 0.93           |
|                | Heading            | 1–10 June               | 10   | 62.6                         | 66.0      | 6.3   | 6.6       | 60.8  | 1.08           |
|                | Maturity           | 11 June–1 July          | 21   | 92.1                         | 123.5     | 4.4   | 5.9       | 113.4   | 1.09           |
|                | Whole growth stage | 1 May–1 July            | 61   | 236.3                        | 275.6     | 3.9   | 4.5       | 323.5   | 0.85           |
| Second<br>crop | Seedling           | 1–31 August             | 30   | 29.5                         | 83.8      | 1.0   | 2.8       | 135.6   | 0.62           |
|                | Rosette            | 1–10 September          | 10   | 48.1                         | 43.7      | 4.8   | 4.4       | 39.7  | 1.10           |
|                | Heading            | 11–18 September         | 8    | 25.8                         | 35.7      | 3.2   | 4.5       | 31.69   | 1.13           |
|                | Maturity           | 19 September–16 October | 28   | 89.4                         | 66.6      | 3.2   | 2.4       | 79.6  | 0.84           |
|                | Whole growth stage | 1 August–16 October     | 76   | 192.8                        | 229.7     | 2.5   | 3.0       | 286.5   | 0.80           |

## 3.2. Diurnal and Seasonal Variations of Chinese Cabbage's ET and Influencing Factors

Figure 3a,b show the daily evapotranspiration change of two crops at different growth stages, which presented a tendency to rise first and then to fall. The maximum daily *ET* at the seedling stage, rosette stage, heading stage, and maturity stage of the first crop was 0.12 mm·h<sup>-1</sup>, 0.17 mm·h<sup>-1</sup>, 0.22 mm·h<sup>-1</sup>, and 0.27 mm·h<sup>-1</sup>, respectively, and the corresponding times were 1:00, 12:00, 2:00, and 1:00 p.m., respectively. The maximum daily *ET* at the seedling stage, rosette stage, heading stage, and maturity stages of the second crop was 0.21 mm·h<sup>-1</sup>, 0.22 mm·h<sup>-1</sup>, 0.22 mm·h<sup>-1</sup>, and 0.22 mm·h<sup>-1</sup>, respectively, and the corresponding times were all 1:00 p.m. This may have been caused by the change in sunshine duration and solar radiation during the different periods. It was observed that *ET* at night was approximately zero at different stages, with the exception (below zero) of the



first crop seedling period, which may have been due to the large temperature difference between day and night in early summer and the condensation of water vapor at night.

**Figure 3.** (a) Diurnal *ET* variation of Chinese cabbage at different growth stages of the first crop; (b) diurnal *ET* variation of Chinese cabbage at different growth stages of the second crop.

As can be seen from Figure 4a,b, the variation in *ET* throughout the growth period of the two crops showed a cubic parabolic trend with the relative growing day (first crop:  $ET = -12.53RGD^3 + 9.66RGD^2 + 7.56RGD + 0.57$ ,  $R^2 = 0.67$ ; second crop:  $ET = -9.39RGD^3 + 0.51RGD^2 + 7.61RGD + 1.40$ ,  $R^2 = 0.63$ ). The daily *ET* gradually increased from the seedling stage to the heading stage but decreased after the heading stage. The maximum value of *ET* in the first crop was 8.91 mm·day<sup>-1</sup> at the heading stage (4 June), and the minimum value of *ET* in the first crop was 0.67 mm·day<sup>-1</sup> at the seedling stage (3 May). In the second crop, the maximum value of *ET* was 5.45 mm·day<sup>-1</sup> at the maturity stage (11 September), and the minimum value of *ET* was 0.16 mm·day<sup>-1</sup> at the maturity stage (17 October), which may have been mainly due to the late harvesting of the mature Chinese cabbage.

Figure 5a,b also showed a parabolic trend of daily  $E_s$  with relative growing day throughout the growth period of the two crops (first crop:  $E_s = 7.45RGD^2 - 12.42RGD + 5.72$ ,  $R^2 = 0.34$ ; second crop:  $E_s = 75.72RGD^2 - 82.12RGD + 22.56$ ,  $R^2 = 0.35$ ).  $E_s$  decreased from the seedling to late rosette stage and increased in the late growth stage. This change was mainly caused by the fact that the enlarged leaf area covered the ground. In the later stage, the increase in  $E_s$  was due to the senescence of green leaves and the decomposition of plastic film.

As can be seen from Table 2, the total  $ET_{EC}$  of the first crop at the seedling, rosette, heading, and maturity stages was 32.3 mm, 53.9 mm, 66.0 mm, and 123.5 mm, respectively, and the corresponding average daily  $ET_{EC}$  was 1.8 mm·day<sup>-1</sup>, 4.5 mm·day<sup>-1</sup>, 6.6 mm·day<sup>-1</sup>, and 5.9 mm·day<sup>-1</sup>, respectively. Throughout the growth period, the amount of total ET was 275.6 mm, and the daily average ET was 4.5 mm·day<sup>-1</sup>. The total  $ET_{EC}$  of the second crop at the seedling stage, rosette stage, heading stage, and maturity stage was 83.8 mm, 43.7 mm, 35.7 mm, and 66.6 mm, respectively, and the corresponding daily average  $ET_{EC}$  was 2.8 mm·day<sup>-1</sup>, 4.4 mm·day<sup>-1</sup>, 4.5 mm·day<sup>-1</sup>, and 2.4 mm·day<sup>-1</sup>, respectively. Throughout the growth period, the total ET was 229.7 mm, and the daily average ET was 3.0 mm·day<sup>-1</sup>.



**Figure 4.** (a) Seasonal *ET* variation of Chinese cabbage throughout the growing period of the first crop. Relative growing days (RGDs) refer to the normalized growing days, e.g., "1" represents 61 days after sowing; (b) seasonal *ET* variation of Chinese cabbage throughout the growing period of the second crop.



**Figure 5.** (a) Seasonal  $E_s$  variation throughout growing period of the first crop; (b) seasonal  $E_s$  variation throughout growing period of the second crop.

Guo [18] showed that the annual average *ET* of spring maize was 481.7 mm. The study of Yang [19] estimated that the annual average *ET* of wheat in this area was 430.0 mm. In this study, the annual *ET* of Chinese cabbage was 505.3 mm, only 23.6 mm higher than that of maize, and 75.3 mm higher than that of wheat. Furthermore, the water use efficiency (WUE) of Chinese cabbage was  $28.96 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{mm}^{-1}$ , which is higher than the previous result of  $25.2 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{mm}^{-1}$  for spring maize [17]. The water consumption of field vegetable crops is not much higher than that of field food crops, although the water use efficiency of field vegetable crops is higher than that of food crops. Therefore, a change in the planting structure in this area would not cause a significant increase in agricultural irrigation water consumption.

Crop *ET* is related to many factors, such as crop growth, surface characteristics, and meteorological factors. To clarify the influencing factors of Chinese cabbage's *ET* in the study area, Table 3 lists the relationship of net radiation  $(W \cdot m^{-2})$ –*ET* and temperature (°C)–*ET* for two crops of Chinese cabbage. Daily *ET* had a linear relationship with  $R_n$  (first crop:  $R^2 = 0.53$ ; second crop:  $R^2 = 0.47$ ) and an exponential relationship with  $T_a$  (first crop:  $R^2 = 0.34$ ; second crop:  $R^2 = 0.14$ ). Table 3 also shows the results of multiple linear regression between *ET* and these factors (first crop: *ET* =  $0.03R_n + 0.19T_a - 2.81$ ,  $R^2 = 0.6$ ; second crop:  $ET = 0.03R_n - 0.04T_a + 0.82$ ,  $R^2 = 0.48$ ). Law [33] pointed out that Rn was the main influencing factor on *ET*, which is consistent with our conclusion. Temperature had no significant effect on *ET* of Chinese cabbage in the study area. In addition, the multiple regression equation established in the study can be used as an experiential formula to calculate *ET* in this area.

| First Crop                  | <b>Regression Equation</b>      | <i>R</i> <sup>2</sup> | n   |
|-----------------------------|---------------------------------|-----------------------|-----|
| Net radiation ( <i>Rn</i> ) | $ET = 0.03R_n - 0.30$           | 0.53                  | 61  |
| Air temperature $(T_a)$     | $ET = 0.57 e^{0.10Ta}$          | 0.34                  | 61  |
| Multiple linear regression  | $ET = 0.03R_n + 0.20T_a - 2.81$ | 0.60                  | 61  |
| Second Crop                 | <b>Regression Equation</b>      | <i>R</i> <sup>2</sup> | п   |
| Net radiation ( <i>Rn</i> ) | $ET = 0.0247R_n + 0.4988$       | 0.47                  | 77  |
| Air temperature $(T_a)$     | $ET = 1.1975 e^{0.0468Ta}$      | 0.14                  | 77  |
| Multiple linear regression  | $ET = 0.03R_n - 0.04T_a + 0.82$ | 0.48                  | 77  |
| Whole Crop                  | <b>Regression Equation</b>      | <i>R</i> <sup>2</sup> | n   |
| Net radiation ( <i>Rn</i> ) | $ET = 0.03R_n - 0.01$           | 0.47                  | 168 |
| Air temperature $(T_a)$     | $ET = 1.63 e^{0.03Ta}$          | 0.03                  | 168 |
| Multiple linear regression  | $ET = 0.03R_n - 0.06T_a + 0.74$ | 0.48                  | 168 |

Table 3. Regression analysis between daily *ET* and its influencing factors.

# 3.3. Seasonal Variation of Chinese Cabbage's Kc and Its Influencing Factors

Figure 6a,b show that the  $K_c$  of the two crops throughout the growing period exhibited a cubic parabolic trend with the change in relative growing days (first crop:  $K_c = -1.42RGD^3$  $+ 0.46RGD^2 + 1.83RGD + 0.11$ ,  $R^2 = 0.87$ , n = 62; second crop:  $K_c = -4.65RGD^3 + 3.71RGD^2 +$ 0.76RGD + 0.35,  $R^2 = 0.86$ , n = 77). The daily  $K_c$  of the first crop showed an increasing trend from the seedling to heading stage and a small decreasing trend after the heading stage. The maximum value of  $K_c$  was 1.19 at the heading stage (8 June), and the minimum value of  $K_c$  was 0.15 at the seedling stage (1 May). The maximum  $K_c$  on 8 June was probably caused by continuous rainfall on 7 and 8 June. The daily  $K_c$  was higher in the middle and late periods, ranging from 0.93 to 1.19. The daily  $K_c$  of the second crop showed an increasing trend from the seedling stage to heading stage and a gradual decreasing trend after maturity stage. The maximum value of  $K_c$  was 1.24 at the rosette stage (7 September) and the minimum value of  $K_c$  was 0.07 at the maturity stage (16 October). The daily  $K_c$  was higher in the rosette and heading periods, ranging from 0.98 to 1.24.



**Figure 6.** (a) Seasonal  $K_c$  variations of Chinese cabbage throughout the growing period of the first crop; (b) seasonal  $K_c$  variations of Chinese cabbage throughout the growing period of the second crop.

As can be seen from Table 2, the daily average  $K_c$  of the first crop of Chinese cabbage at the seedling stage, rosette stage, heading stage, and maturity stages was 0.35, 0.93, 1.08, and 1.09, respectively, and the daily average  $K_c$  throughout the growth period was 0.85. The average daily  $K_c$  of the second crop at the seedling stage, rosette stage, heading stage, and maturity stage was 0.62, 1.10, 1.13, and 0.84, respectively, and the daily average  $K_c$ throughout the growth period was 0.80.  $K_c$  of the first crop in the seedling stage was far smaller than that of the second crop. That situation may have come from the fact that the period just after sowing was missed, because the first crop was sowed on 17 April, but the observation started on 1 May. There was no significant difference in  $K_c$  value between the two crops at the rosette and the heading stages. At the maturity stage before harvest, the  $K_c$  value of the first crop of Chinese cabbage was still high, which might have been due to the antiaging effect of plastic film mulching on Chinese cabbage. The  $K_c$  of Chinese cabbage was a bit small in the second crop, which may have been due to the late harvest of the second crop of Chinese cabbage for cost saving, which led to  $K_c$  dropping rapidly. Guo [18] showed that the average  $K_c$  of spring maize was 0.88. The average  $K_c$  of Chinese cabbage was 0.81, which was 0.07 lower than that of maize. A previous study found that  $K_c$  mainly depends on crops growth, but is also affected by soil moisture [34]. All these influencing factors may underlie the complex changes in  $K_c$ .

Table 4 shows that irrigation (I) greatly improved  $K_c$ .  $K_c$  of the first crop of Chinese cabbage changed from 0.16 to 0.45, from 0.37 to 0.40, from 0.61 to 0.83, from 0.78 to 1.04, from 1.10 to 1.14, and from 1.12 to 1.10 on the days after the first, second, third, fourth, fifth, and sixth irrigations, respectively. Unlike the irrigation at the five other timepoints, the  $K_c$  value decreased after the sixth irrigation, which may have been related to the small irrigation amount at the maturity stage. For the second crop, the  $K_c$  value increased from 0.13 to 0.56, from 0.56 to 0.60, from 0.58 to 0.47, from 0.80 to 0.99, from 1.02 to 1.19, and from 1.11 to 1.17 on the days after the first, second, third, fourth, fifth, and sixth irrigations, respectively. The value remained basically unchanged after the seventh irrigation.

| First Crop     | Irrigation     | 3rd DBI * | 2nd DBI | 1st DBI | Irrigation Day | 1st DAI <sup>#</sup> | 2nd DAI | 3rd DAI |
|----------------|----------------|-----------|---------|---------|----------------|----------------------|---------|---------|
|                | 1st irrigation |           | 0.15    | 0.22    | 0.16           | 0.45                 | 0.40    | 0.42    |
|                | 2nd irrigation | 0.41      | 0.29    | 0.24    | 0.37           | 0.40                 | 0.46    | 0.45    |
| K <sub>c</sub> | 3rd irrigation | 0.32      | 0.37    | 0.59    | 0.61           | 0.83                 | 0.79    | 0.84    |
|                | 4th irrigation | 1.06      | 1.04    | 1.00    | 0.78           | 1.04                 | 1.05    | 1.03    |
|                | 5th irrigation | 1.05      | 1.03    | 1.09    | 1.10           | 1.14                 | 1.23    | 1.22    |
|                | 6th irrigation | 0.96      | 1.12    | 1.15    | 1.12           | 1.10                 | 0.92    | 1.10    |
| Second Crop    | Irrigation     | 3rd DBI   | 2nd DBI | 1st DBI | Irrigation Day | 1st DAI              | 2nd DAI | 3rd DAI |
|                | 1st irrigation | 0.10      | 0.12    | 0.23    | 0.13           | 0.56                 | 0.47    | 0.48    |
| Kc             | 2nd irrigation | 0.38      | 0.40    | 0.29    | 0.56           | 0.60                 | 0.55    | 0.43    |
|                | 3rd irrigation | 0.43      | 0.56    | 0.77    | 0.58           | 0.47                 | 0.72    | 0.55    |
|                | 4th irrigation | 0.86      | 0.80    | 0.84    | 0.80           | 0.99                 | 0.77    | 1.00    |
|                | 5th irrigation | 1.05      | 1.00    | 1.02    | 1.12           | 1.09                 | 1.24    | 1.11    |
|                | 6th irrigation | 1.21      | 0.98    | 1.11    | 1.17           | 1.15                 | 1.13    | 1.14    |
|                | 7th irrigation | 0.88      | 1.01    | 1 1 1   | 1 09           | 1.08                 | 1 10    | 1.00    |

**Table 4.** Irrigation effect on K<sub>c</sub>.

\* DBI represents days before irrigation; # DAI represents days after irrigation.

#### 4. Conclusions

According to our research, the following conclusions can be drawn:

- The weekly  $ET_{EC}$  and  $ET_{WB}$  at different growth periods had good consistency, and the consistency was better throughout the growth period. The ratio of  $ET_{EC}$  to  $ET_{WB}$  throughout the growth period of the first crop was 1.17 and that of the second crop was 1.19.
- The diurnal variation of *ET* presented a tendency to rise first and then to fall. The total ET of the first crop throughout the growth period was 275.6 mm, the average daily *ET* was 4.52 mm·day<sup>-1</sup>, and the WUE was 31.58 kg·ha<sup>-1</sup>·mm<sup>-1</sup>. The total *ET* of the first crop throughout the growth period was 229.7 mm, the average daily *ET* was 3.02 mm·day<sup>-1</sup>, and the WUE was 25.91 kg·ha<sup>-1</sup>·mm<sup>-1</sup>. Daily *ET* had a linear relationship with *Rn* and an exponential relationship with *T<sub>a</sub>*. *Rn* was the main influencing factor on *ET*.
- Daily  $K_c$  showed a cubic curve trend throughout the growth period. The average daily  $K_c$  at the four growth stages of the first crop was 0.35, 0.93, 1.08, and 1.09, respectively, and the average  $K_c$  throughout the growth period was 0.85. The average daily  $K_c$  at the four growth stages of the second crop was 0.62, 1.10, 1.13, and 0.84, respectively, and the average  $K_c$  throughout the growth period was 0.80. The lower  $K_c$  in the early stage of the first crop was due to the late observation time, while the lower  $K_c$  in the late stage of the second crop was due to the late harvest.  $K_c$  was greatly and positively affected by irrigation.

Our study revealed the variation pattern of ET and  $K_c$  of Chinese cabbage, which provides an important scientific basis for the irrigation management of Chinese cabbage. The eddy covariance method was innovatively applied to reveal the law of water consumption of Chinese cabbage, which provides a practical basis for the design of vegetable crop irrigation systems. This is of great significance to guide the practice of water-saving vegetable planting. Our experimental observations were relatively short, with only two crop growth periods. In the future, more observational studies will be conducted to improve the credibility of the study and further propose field management measures.

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