Temporal Downscaling of Crop Coefficients for Winter Wheat in the North China Plain: A Case Study at the Gucheng Agro-Meteorological Experimental Station

Peijuan Wang 1, Jianxiu Qiu 2,*, Zhiguo Huo 1, Martha C. Anderson 3, Yuyu Zhou 4, Yueming Bai 1, Tao Liu 1, Sanxue Ren 1, Rui Feng 5 and Pengshi Chen 6

1 State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing 100081, China; wangpj@camscma.cn (P.W.); huozhigg@camscma.cn (Z.H.); baiym@camscma.cn (Y.B.); liutao@camscma.cn (T.L.); 656892rzr@163.com (S.R.)
2 Guangdong Provincial Key Laboratory of Urbanization and Geo-simulation, School of Geography and Planning, Sun Yat-sen University, Guangzhou 510275, China
3 Hydrology and Remote Sensing Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Beltsville, MD 20705, USA; martha.anderson@ars.usda.gov
4 Departments of Geological and Atmospheric Sciences, Iowa State University, Ames, IA 50011, USA; zhouyuyu@gmail.com
5 Institute of Atmospheric Environment, China Meteorological Administration, Shenyang 110166, China; fengrui_k@126.com
6 Institute of Meteorological Sciences of Liaoning Province, Shenyang 110166, China; cps55@163.com
* Correspondence: qiujianxiu@mail.sysu.edu.cn; Tel.: +86-20-8411-2512

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Abstract: The crop coefficient ($K_c$) is widely used for operational estimation of actual evapotranspiration ($ET_a$) and crop water requirements. The standard method for obtaining $K_c$ is via a lookup table from FAO-56 (Food and Agriculture Organization of the United Nations Irrigation and Drainage Paper No. 56), which broadly treats $K_c$ as a function of four crop-growing stages. However, the distinctive physiological characteristics of overwintering crops, such as winter wheat ($Triticum aestivum$ L.), which is extensively planted in the North China Plain (NCP), are not addressed in this method. In this study, we propose a stage-wise method that accounts for $K_c$ variations for winter wheat at each critical phenological stage, thereby estimating $K_c$ at finer temporal scales. Compared with the conventional FAO method, the proposed stage-wise method successfully captures the bimodal pattern in $K_c$ time series for winter wheat, which is shown at both ten-day and phenological time scales. In addition, the accuracies of the proposed stage-wise $K_c$ method and the FAO method were evaluated using micro-meteorological measurements of $ET_a$ collected at the Gucheng agro-meteorological experimental station in the NCP. Using a leave-one-out strategy, the evaluation revealed that the stage-wise method significantly outperformed the FAO method at both daily and critical phenological time scales, with root-mean-square errors in $ET_a$ for the stage-wise method and the FAO method being 0.07 mm·day$^{-1}$ and 0.16 mm·day$^{-1}$, respectively, at the daily time scale, and 0.01 mm·day$^{-1}$ and 0.27 mm·day$^{-1}$ at the critical phenological time scale. Generally, the FAO method underestimates $ET_a$ during the initial stage and overestimates $ET_a$ during both the development and mid-season stages. It is shown that the proposed stage-wise method is important for the water-stressed NCP where precision irrigation is highly desirable, especially during the critical phenological stages. Results from this study provide insight into accurate estimation of water requirements for winter wheat at phenological time scales.
Keywords: winter wheat; evapotranspiration; crop coefficients; phenological stages; stage-wise method; North China Plain

1. Introduction

The crop coefficient (\(K_c\)) is a crucial parameter that is widely applied in agricultural water management and irrigation scheduling, as it reflects the impacts of inherent crop biological characteristics and planting conditions on water requirements. \(K_c\) is defined as the ratio of crop evapotranspiration under well-watered conditions (\(ET_c\)) to a reference crop evapotranspiration (\(ET_0\)). \(ET_c\) is the evapotranspiration expected from disease-free, well-fertilized crops grown in large fields, under optimum soil water conditions and achieving full production under the given climatic conditions [1]. \(ET_0\) is the evapotranspiration rate expected from a reference surface, which is hypothesized as a grass reference crop with specific characteristics limited only by atmospheric demand [1], considering only a constraint from the available energy.

Current approaches for estimating crop coefficients can be classified into two categories. The first category is based on the lookup table recommended by the Food and Agriculture Organization of the United Nations (the FAO method), including its related versions, which impose adjustments according to local climatic conditions, soil types, irrigation and crop management [2]. The second category involves separate estimation of \(ET_c\) and \(ET_0\) via direct measurement or modeling. Methods for estimating \(ET_c\) include water balance assessments using weighing lysimeters [3–7] or soil water measurements [3,8], energy-conservation approaches using the Bowen ratio [9,10], eddy covariance techniques [11–17] or remote sensing retrievals (based on one-source [18] and two-source energy balance models) [19–21]. Methods for modeling \(ET_0\) can be roughly divided into three categories [22,23], i.e., temperature models [24,25], radiation-temperature models [26,27] and combination models [1,28].

Among these, the FAO method is most popular given its simplicity and limited demands on data and processing steps. The FAO approach considers the crop coefficient as a function of four crop-growing stages, namely the initial, development, mid-season and late-season stages. However, the inherent biological characteristics of crops in different climatic zones are not considered in the FAO method. Specifically, for overwintering crops with dual peaks in their growth curves, the rapid growth stage before the overwintering period is smoothed or missed in the “four-stage” FAO method.

This distinctive phenological feature of overwintering crops has been confirmed in recent studies on the temporal downscaling of crop coefficients for winter wheat and other related crops, using both in situ measurements and soil water balance models. For example, studies investigating monthly \(K_c\) of winter wheat in Yangling of Shaanxi Province in China [3] and weekly \(K_c\) of rice-wheat rotation crops grown in the Indo-Gangetic plains of India [29] have all demonstrated the above-mentioned bimodal features in winter wheat. Generally, investigations on crop coefficients for winter wheat have been focusing on a particular growth stage, such as the post-elongation stage [30], the elongation to heading stage [31] and the green-up to ripening stage [32]. In contrast, research on \(K_c\) estimation covering the entire crop growth period from seedling emergence to the mature stage, as well as at multiple temporal scales (i.e., from the phenological stage scale to the ten-day fine scale) is rarely seen.

The North China Plain (NCP) region, regarded as the ‘Granary of China’, is characterized by water-intensive agricultural production with dominant cropping systems of winter wheat and summer maize rotation. Since precipitation during the winter wheat growing period is highly insufficient to meet water requirements, agricultural production in the NCP heavily relies on effective irrigation schemes, which require accurate information on \(ET_a\) and \(K_c\).

As previously stated, for FAO methods, the inaccuracy in determining \(K_c\) of overwintering crops can cause non-negligible errors in estimated actual evapotranspiration (\(ET_a\)) during different phenological stages. To alleviate this problem, in this study, we propose a stage-wise method to temporally downscale \(K_c\). The proposed \(K_c\) method makes full use of meteorological and eddy
covariance data collected at the Gucheng agro-meteorological experimental station, maintained by the Chinese Academy of Meteorological Sciences (CAMS). The performances of the proposed $K_c$ method and the conventional FAO method at both daily and phenological scales are evaluated against eddy covariance measurements of latent heat flux. The paper is organized as follows. Section 2 describes the establishment of the proposed stage-wise $K_c$ model and the required datasets, including meteorological observations, eddy covariance measurements and soil moisture datasets. Section 3 reports the temporal dynamics of $ET_0$ and $ET_a$ utilized for $K_c$ estimation, and the $K_c$ dynamics at different timescales including: (i) the “four-stage” scale (the same temporal scale used in the FAO method); (ii) critical phenological stages and (iii) the ten-day scale. The performance of the proposed method and the standard FAO method is assessed in comparison with surface flux measurements using a leave-one-year-out cross-validation method.

2. Methodology and Materials

2.1. Gucheng Agro-Meteorological Experimental Station

Gucheng station is located in Hebei Province of the NCP region (115.73° E, 39.15° N, 15.2 m above mean sea level) and includes an area of approximately 150,000 m$^2$ (Figure 1). The station is in a temperate continental monsoon climate zone with mean annual precipitation of 474.9 mm, about 65%–85% of which is concentrated from June to September [33]. The meteorological records from 1997 to 2013 show an annual mean temperature of 12.0 °C and sunshine duration of 2158.8 h·year$^{-1}$. The dominant soil type at Gucheng station is a neutral loam, with a gentle slope and a deep arable soil layer. The station represents a high-yielding agricultural zone for winter wheat production in the NCP region, with relevant agro-meteorological variables extensively monitored in this experimental station.

![Figure 1. Location of the Gucheng agro-meteorological station in the North China Plain (NCP) region of China (the extent of the station is outlined in yellow line in the rightmost sub-figure).](image)

2.2. Methodology

2.2.1. Reference Crop Evapotranspiration ($ET_0$) Estimation

The reference crop evapotranspiration, $ET_0$ (mm·day$^{-1}$), is estimated in this study using the FAO Penman–Monteith method [1]:

$$ET_0 = \frac{0.408 \times \Delta (R_n - G) + \frac{900}{T + 273} U_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 U_2)}$$

(1)

where $R_n$ is the net radiation (MJ·m$^{-2}$·day$^{-1}$) and $G$ is the soil heat flux (MJ·m$^{-2}$·day$^{-1}$), which is assumed to be approximately 0 at the daily time scale. $T$ is the average air temperature at a 2-m height (°C). $U_2$ is the average wind velocity at a 2-m height (m·s$^{-1}$). $e_s$ and $e_a$ are the saturated water vapor pressure and actual vapor pressure (kPa), respectively. $\Delta$ is the slope of the saturation vapor pressure curves (kPa·°C$^{-1}$). $\gamma$ is the psychrometric constant (kPa·°C$^{-1}$).
Solar radiation was calculated with the Ångström–Prescott formula using extraterrestrial radiation and relative sunshine duration [1]:

\[ R_s = \left( a_s + b_s \times \frac{n}{N} \right) \times R_a \]  

(2)

where \( R_s \) is the solar or shortwave radiation (MJ \cdot m^{-2} \cdot day^{-1}) and \( R_a \) is the extraterrestrial radiation (MJ \cdot m^{-2} \cdot day^{-1}). \( N \) is the maximum possible duration of sunshine or daylight hours (hour), \( n \) is the actual duration of sunshine (hour), and \( n/N \) is the relative sunshine duration. The parameters \( a_s \) and \( b_s \) are Ångström values (dimensionless), which vary with location and time of year. In this study, both \( a_s \) and \( b_s \) are adopted following Mao et al. [34].

2.2.2. Estimation of Crop Evapotranspiration under Standard Conditions (ETc)

With proper management within the footprint of the flux tower at Gucheng station, there was sufficient supply of water and nutrition for the winter wheat crop and no pest or disease damage. Therefore, the actual evapotranspiration \( ET_a \) can be considered as well-watered \( ET_c \). In this study, the \( ET_a \) was acquired by two approaches: (1) direct measurements from the eddy covariance (EC) system, and (2) indirect estimation using the water balance equation. Tower-based \( ET_a \) measurements collected during the growing season in a two-year study period are used to establish a crop coefficient model for winter wheat, and the estimated \( K_c \) is validated using a leave-one-year-out cross-validation (LOOCV) method. Meanwhile, the \( ET_a \) derived from an independent approach based on water balance equation is also used to evaluate \( K_c \) for winter wheat. The details for deriving \( ET_a \) from the two approaches are described in the following two subsections.

\( ET_a \) Calculated Using Eddy Flux Measurements

Daily latent heat flux was accumulated from half-hour data collected with the EC system and was then converted to \( ET_a \) using the latent heat of water vaporization:

\[ ET_a = \frac{\sum_{i=1}^{n}(LE_i \cdot t)}{\lambda \cdot \rho} \]  

(3)

where \( ET_a \) is the daily actual evapotranspiration (mm \cdot day^{-1}), \( LE_i \) is the half-hour latent heat flux (W \cdot m^{-2}), \( t \) is the time interval of sampling (1800 s), \( \lambda \) is the latent heat of water vaporization (2.44 MJ \cdot kg^{-1}), \( \rho \) is the density of water (kg \cdot m^{-3}) and \( n \) is number of daily samples. The flux tower measurements and energy closure assessments are described further in Section 2.3.2.

\( ET_a \) Calculated by Water Balance Equation

The \( ET_a \) can also be calculated using a water balance equation in the following form:

\[ (P + I + Q_g) - (ET_a + R + D) = \Delta W_s + \Delta W_v \]  

(4)

where \( P \) is the precipitation (mm), \( I \) is the irrigation (mm), \( Q_g \) is the contribution from the water table (mm), \( ET_a \) is the actual evapotranspiration (mm), \( R \) is the surface runoff (mm) and \( D \) is the deep drainage (mm). The left-hand side of Equation (4) is the water budget during the study period, while \( \Delta W_s \) and \( \Delta W_v \) are the water content variations (mm) during the same period for soil and canopy, respectively.

As the topography of the experimental site is relatively flat and the precipitation is not intensive during the growing period of winter wheat (annual average precipitation is about 138.7 mm during the study period), the surface runoff and the deep drainage can be neglected in this case [8,11,35,36]. Contributions from groundwater are also negligible as the water table is over 30 m deep. As the canopy equivalent water thickness (EWT) of winter wheat during the entire growing period is less
than 1 mm [37], the water content variations of crop ($\Delta W_v$) can be neglected. Thus, the $ET_a$ based on the water balance equation can be expressed as:

$$ET_a = (P + I) - \Delta W_s = (P + I) - (\theta_{v1} - \theta_{v2})$$  \hspace{1cm} (5)

where $\theta_{v1}$ and $\theta_{v2}$ are the volumetric soil water contents measured with time domain reflectometry (TDR, TRIME®-TDR-PICO-IPH/T3, Imko, Ettlingen, Germany) at the beginning and end of the study period, respectively.

2.2.3. Crop Coefficient ($K_c$) Estimation

In this paper, the effects of both crop transpiration and soil evaporation on $ET_a$ were integrated into the single parameter of $K_c$. The $K_c$ of a specific crop reflects the crop characteristics and its climatic features, i.e., changes in vegetation are reflected in $K_c$ variations during the growing period. As stated in the Section 1, the standard FAO method is employed in the study as a reference to benchmark the proposed stage-wise $K_c$ method. Both methods are introduced in detail in the following subsections.

Proposed Stage-Wise Method

The crop coefficient of winter wheat during each phenological period (Equation (6)) was estimated using the temporally-averaged reference crop evapotranspiration $ET_0$ (Equation (1)) and the measured crop evapotranspiration under standard conditions $ET_c$ (represented by $ET_a$):

$$K_{c,i} = \frac{ET_{c,i}}{ET_0,i}$$  \hspace{1cm} (6)

where the subscript $i$ denotes the different phenological periods of interest. $K_{c,i} > 1$ indicates that $ET_{c,i}$ is higher than $ET_0,i$, which usually occurs during the rapid growing stage; while $K_{c,i} < 1$ is generally observed during the initial growing stage, when the plant height and leaf area index are low.

In this study, $K_c$ calculated by the water balance equation using TDR soil moisture measurement is referred to as $K_{c,TDR}$, so as to distinguish it from the $K_c$ calculated using eddy fluxes, denoted as $K_{c,Eddy}$.

The FAO Method

In the FAO method, $K_c$ is considered as a function of crop growth stages, namely the initial, development, mid-season and late-season stages. Only three values are required to construct the $K_c$ curve: $K_c$ during the initial stage ($K_{c,ini}$), the mid-season stage ($K_{c,mid}$) and the late-season stage ($K_{c,end}$). According to the lookup table for single crop coefficients under the FAO method [1], typical values of $K_{c,ini}$, $K_{c,mid}$ and $K_{c,end}$ for winter wheat with frozen soils are taken as 0.40, 1.15 and 0.25–0.40. At Gucheng station in the NCP region, winter wheat is harvested shortly after ripening; therefore, a high value of 0.40 is used for $K_{c,end}$. As for the $K_{c,mid}$, the effect of aerodynamic properties is not only crop-specific, but also depends on the climatic conditions and crop height. Thus, $K_{c,mid}$ can be adjusted based on the meteorological observations as below [1]:

$$K_{c,mid} = K_{c,mid(tab)} + [0.04 \times (U_2 - 2) - 0.004 \times (RH_{min} - 45)] \times (h/3)^{0.3}$$  \hspace{1cm} (7)

where $K_{c,mid(tab)}$ is the typical value of $K_{c,mid}$ listed in the FAO handbook. $U_2$, $RH_{min}$ and $h$ are the mean values for daily wind speed at a 2-m height (m·s$^{-1}$), daily minimum relative humidity (%) and plant height (m) during the mid-season stage. After adjustment, $K_{c,mid}$ is 1.15 at Gucheng station, the same as the typical value for crop coefficients of winter wheat during the mid-season stage in the FAO method.
2.2.4. Leave-One-Year-Out Cross-Validation

Cross-validation [38] is a model validation technique for assessing how the results of statistical analysis will generalize to an independent dataset. When there is not enough data to partition into separate training and validating sets without losing significant modeling or validation capability, cross-validation provides an effective means to evaluate model performance.

Leave-one-year-out cross-validation (LOOCV) [39] involves using one year of observations as the validation set and observations from the remaining years as the training set. This is repeated \( n \) times (\( n \) is the number of observation years in the original sample) to partition the original sample into training and validation sets.

2.3. Materials

2.3.1. Meteorological Observations

The meteorological data used in the computation of \( \text{ET}_0 \), including daily average air temperature, maximum air temperature, minimum air temperature, vapor pressure, atmospheric pressure, relative humidity, wind speed and sunshine duration, were collected from an automatic weather station in Gucheng during 2009–2014. All observations were quality controlled and contained no missing records during the study period.

2.3.2. Eddy Covariance Measurements

The eddy covariance system was installed at a height of 4 m above the ground level on a flux tower in the eastern part of Gucheng station, and winter wheat was planted in the tower fetch of up to 500 m in the prevailing wind direction. The system consists of a sonic anemometer and CO\(_2\)/H\(_2\)O analyzer, sampling fluxes of sensible heat, latent heat and CO\(_2\) at a high frequency of 10 Hz, with data stored in the data logger at both 10 Hz and half-hour intervals. Additional instruments include a four-component net radiometer and a soil heat flux plate buried under the soil surface at a 5-cm depth.

Previous studies showed that the performance of coordinate rotation can be omitted as the corresponding errors were less than 1% at Gucheng station due to flat terrain [40]. Additionally, these studies demonstrated that half-hour is an acceptable interval for averaging the high-frequency flux observations obtained from the height below 30-m level [40–43]. Meanwhile, the 30-min averaging period is commonly used by the micro-meteorological community for flux measurements over agricultural sites [14,15]. Thus, in this study, the 30-min EC data we used were processed from the original high-frequency observations after a series of processing steps, including spike removal, WPL (Webb, Pearman, and Leuning) correction, sonic virtual temperature correction and frequency response correction. In addition, quality control was performed to minimize the effects of extreme weather conditions and equipment malfunction on the flux data. Specifically, the obvious outliers in the time series and invalid nocturnal measurements taken with friction velocity <0.08 m s\(^{-1}\) were excluded [44]. Following this, the missing data for small gaps (2–3 half-hourly missing) were replaced by linear interpolation using the adjacent value(s) [45], whereas large data gaps were filled using exponential regression equations [46] developed for each individual stage, namely the seedling growth stage, dormancy stage and rapid growth stage. To avoid inaccurate interpolation, days with continuous data gaps exceeding 1/3 of the daily record length, resulting from either missing measurements or quality control, were completely removed during model construction and validation. After these treatments, two years with reliable flux observations, i.e., the winter wheat growing periods for 2009–2010 and 2012–2013 (denoted as the study periods of 2009 and 2012 hereinafter), were included in the analysis.

The typical energy closure condition in the EC measurements was evaluated for each phenological stage of the two-year study period using the energy balance ratio (EBR) [47]. EBR < 100% indicates that the measurements do not fully characterize the local flux conditions, with errors typically attributed to the underestimation of sensible and latent fluxes and/or the overestimation of available energy.
during nocturnal periods, especially weak turbulent periods [48]. Closure ratios of 80% or higher are considered to be reasonable at most sites with climate zones ranging from Mediterranean to temperate and arctic [48].

2.3.3. Soil Water Content Measurements

Soil water content was measured by TDR once every 10 days (i.e., on the 8th, 18th and 28th days of each month) during the growing period of winter wheat for 2013 and 2014. According to ground measurements in the southern NCP region, the mean of total root length density (RLD) for winter wheat is 57.7% from surface down to a 0.5 m depth, and the value is 81.1% from surface down to 1.0 m [49]. Therefore, in this study, soil moisture was measured at 0.1 m intervals from the surface down to a 1.0 m depth to account for the change of soil water content within the root zone. The soil moisture was recorded in percentage units (%) with an accuracy of ±4% according to instrument manual.

2.3.4. Remotely Sensed Leaf Area Index (LAI) Time Series

The Moderate Resolution Imaging Spectroradiometer (MODIS) 8-day LAI product (MOD15A2, https://reverb.echo.nasa.gov/reverb/) at 1-km spatial resolution during the winter wheat growing season from two years (2009 and 2012) was used to indirectly evaluate the $K_c$ estimation, as temporal dynamics of LAI and $K_c$ have proven to be highly correlated [3]. The time series of MODIS LAI in the pixel collocated with Gucheng station during the two-year study period was extracted, and the QC flags were used to exclude unreliable observations, retaining data retrieved by the main retrieval method. Consequently, a linear interpolation method was used to construct a complete 8-day time series of LAI and, finally, re-sampled at a ten-day interval so as to be consistent with $K_c$ at the temporal scale.

2.3.5. Meteorological Conditions during the Winter Wheat Growing Period

The winter wheat used in this experiment was a medium-early maturing variety. The detailed growing conditions for each winter wheat variety, including growing dates and field management, during the two-year study period are listed in Table 1. For the two-year study period, the average temperature, average maximum temperature and average minimum temperature were 5.9 °C, 12.1 °C and 0.5 °C, respectively, with little inter-annual variation during the winter wheat growing period (Table 1). Total precipitations were 125.5 mm and 193.8 mm, which temporally coincide with the dry season. The percentages of rainy days occupied 17.4% and 12.8% for the two growing seasons respectively, and flood irrigations were applied 4–5 times for each growing season. On average, water supply throughout the growing periods was generally regulated by weekly rainfall and/or irrigation. Therefore, precipitation has little constraining impact on winter wheat growth and, thus, is excluded from the discussion in this paper.

<table>
<thead>
<tr>
<th>Year</th>
<th>Variety</th>
<th>Seeding Date MM/DD</th>
<th>Ripening Date MM/DD</th>
<th>Average Temperature (°C)</th>
<th>Average Maximum Temperature (°C)</th>
<th>Average Minimum Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009–2010</td>
<td>Jimai-22</td>
<td>10/10</td>
<td>6/20</td>
<td>5.9</td>
<td>11.7</td>
<td>0.6</td>
</tr>
<tr>
<td>2012–2013</td>
<td>Jimai-22</td>
<td>10/08</td>
<td>6/19</td>
<td>5.8</td>
<td>12.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>

3. Results and Discussion

3.1. Energy Balance Closure of Flux Measurements

A scatter plot comparing the surface fluxes ($LE + H$) and the available energy ($R_n - G$) measured at the flux tower during all critical phenological stages is shown in Figure 2. The EBRs for the two
growing periods range from 90.39% to 91.35%. The mean EBRs for the seedling, dormancy and rapid-growth periods are 94.14%, 84.83% and 91.58%, respectively, all higher than the mean EBR of 80% for a diverse range of vegetation covers and climate types [48]. The good closure conditions observed in Figure 2 indicate that the $ET_a$ measurements used to compute $K_c$-Eddy are reasonable.

Figure 2. Energy balance closure during all critical phenological stages of winter wheat in two-year study period at Gucheng station.

3.2. $ET_0$ and $ET_a$ Dynamics

Temporal dynamics of $ET_0$ calculated using the FAO Penman–Monteith method and $ET_a$ obtained from eddy covariance observations at Gucheng station during growing seasons are shown in Figure 3. These curves are computed on 10-day intervals and represent averages over the two-year study period. The vertical lines in Figure 3 represent the nine generalized growth stages (S1–S9) for winter wheat, as tabulated in Table 2.

Figure 3. $ET_0$ and $ET_a$ for winter wheat at 10-day intervals during the growing period averaged over the two-year study period. The error bars show the standard deviation in $ET_0$ and $ET_a$ for each interval over the two years. Vertical lines indicate nine generalized growth stages (S1–S9) for winter wheat.
Table 2. The growing stages of winter wheat and its corresponding phenological periods according to the FAO method.

<table>
<thead>
<tr>
<th>DOY</th>
<th>Phenological Stages</th>
<th>Stage-Wise Method</th>
<th>FAO Method</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DOY284</td>
<td>Seeding</td>
<td>Stage 1</td>
<td>Initial</td>
<td></td>
</tr>
<tr>
<td>DOY290</td>
<td>Seedling emergence</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DOY304</td>
<td>Three-leaf</td>
<td>Stage 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DOY321</td>
<td>Tiller</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DOY338</td>
<td>Stop growing</td>
<td>Stage 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DOY062</td>
<td>Green-up</td>
<td>Stage 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DOY088</td>
<td>Erect-growing</td>
<td>Stage 5</td>
<td>Development</td>
<td></td>
</tr>
<tr>
<td>DOY111</td>
<td>Elongation</td>
<td>Stage 6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DOY122</td>
<td>Booting</td>
<td>Stage 7</td>
<td>Mid-season</td>
<td></td>
</tr>
<tr>
<td>DOY130</td>
<td>Heading</td>
<td>Stage 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DOY136</td>
<td>Blossom</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DOY155</td>
<td>Milk</td>
<td>Stage 9</td>
<td>Late-season</td>
<td></td>
</tr>
<tr>
<td>DOY171</td>
<td>Ripening</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the early growth stages from seedling to green-up (S1–S4), both $ET_0$ and $ET_a$ are low due to low insolation levels and low air temperature during fall to winter. Starting from the S4 stage, the rising temperatures and solar radiation have resulted in increasing $ET_0$ and $ET_a$. As the canopy starts to close during the erect-growing to blossom stages (S5–S8), $ET_a$ approaches the potential rate. Both $ET$ ($ET_0$ and $ET_a$) curves show the highest degree of inter-annual variability during S5–S8. In particular, the inter-annual variations of $ET_a$ mainly occurred during the rapid growing periods, i.e., late March–early May, due to variability in crop canopy height, LAI and leaf morphology between years. $ET_a$ downturn occurs in the milking to ripening stage (S9), as the green canopy covers begin to decline.

3.3. Estimated $K_c$ at Three Different Temporal Scales

3.3.1. Comparison with the Four-Stage FAO Method

In order to directly compare the capabilities of characterizing winter wheat $K_c$ between the proposed stage-wise methods and the “four-stage” FAO method, we regrouped the nine finer-scale phenological stages of winter wheat in our method to match the “four-stage” in the FAO method. Specifically, the initial stage in the FAO method corresponds to the seeding to green-up stages; the crop development stage and mid-season stage cover the erect to elongation stages and booting to blossom stages, respectively; and the late-season stage corresponds to the milk to harvest stages (Table 2).

Based on this regrouping scheme, $K_c$ time series derived from both the FAO method (referred to as $K_{c\_FAO}$) and the proposed stage-wise method (based on two years of quality-controlled eddy covariance fluxes (see Section 2.3.2), referred to as $K_{c\_Eddy}$) are illustrated in Figure 4, showing noticeable differences between two sets of $K_c$ values. In particular, $K_{c\_Eddy}$ exceeds $K_{c\_FAO}$ in the initial and late-season stage and is lower than $K_{c\_FAO}$ during the mid-season stage. This is mainly attributed to the difference in climatic features between the sub-humid region (where the FAO method was originally developed) and this study region in the NCP. Specifically, the FAO method for winter wheat $K_c$ was originally developed for sub-humid regions with average daily minimum relative humidity ($RH_{min}$) around 45% and moderate wind speeds of 2 m·s$^{-1}$. However, meteorological conditions at Gucheng station are quite different, representing semi-arid and sub-humid climates with sparse rainfall during the winter wheat growing period. In addition, the average $RH_{min}$ for the two-year study period was about 31.6%, well below the expected 45% that generated the typical $K_{c\_FAO}$ values.

As soil moisture is not a limiting factor for evapotranspiration with regard to the experimental design at the Gucheng site (which provides sufficient irrigation, as mentioned in Section 2.3.5), the relatively large atmospheric demand enhance the potential soil evaporation and crop transpiration,
and therefore, increased $ET_a$, resulting in higher $K_{c\text{-Eddy}}$ than $K_{c\text{-FAO}}$ during the initial stage. Differences in $K_c$ values during the mid-season stage may be attributed to lower crop heights at Gucheng station (0.7 m) in comparison with the expected maximum height of winter wheat in the FAO method (1.0 m). Since crop transpiration accounted for a considerable portion of $ET_a$ during the mid-season stage, the relatively shorter crop height at Gucheng may be responsible for the lower $K_{c\text{-Eddy}}$ than $K_{c\text{-FAO}}$. As for the late-season stage, winter wheat at Gucheng station was harvested immediately after reaching mature stage, so as to prepare for the sowing of second crop-rotation (maize). Therefore, $K_{c\text{-Eddy}}$ of winter wheat at Gucheng station for the late-season stage was significantly higher than $K_{c\text{-FAO}}$ before $ET_a$ dropped to the minimum value. It is worth noting that due to the prevailing maize-wheat rotation system in NCP, this common agricultural practice of immediate harvesting of winter wheat after the mature stage is a human-induced factor that contributes to the unsuitability of the FAO method across this region.

![Figure 4. Comparison of $K_c$ between the proposed stage-wise method and the FAO method.](image)

3.3.2. $K_c$ Dynamics at the Critical Phenological Stages

To examine $K_c$ dynamics at Gucheng station at finer temporal scales, $K_c$ values for winter wheat developed using $ET_a$ estimates from eddy covariance ($K_{c\text{-Eddy}}$) and water balance ($K_{c\text{-TDR}}$) are compared at the time scale of critical phenological stages in Figure 5.

![Figure 5. The proposed stage-wise $K_c$ during the critical phenological stages.](image)
As seen in Figure 5, the temporal dynamics of both $K_c_{_\text{Eddy}}$ and $K_c_{_\text{TDR}}$ exhibit similar bimodal features during the growing period. The winter wheat development cycle is characterized by two rapid growing periods, namely the three-leaf to dormancy stages and the erect-growing to booting stages, which occur before and after overwintering, respectively. This is similar to other studies of $K_c$ features of winter wheat using both in situ observations [3] and models [50,51]. It is noted that due to the neglect of the rapid growing period before overwintering in the FAO method, the actual water consumption prior to the green-up stage was considerably underestimated by approximately 9 mm, accounting for 10.5% of actual water consumption during the initial stage.

3.3.3. $K_c$ Dynamics at the Ten-Day Scale

The average $K_c_{_\text{Eddy}}$ dynamics at Gucheng station are compared with that of LAI observations at the 10-day scale in Figure 6. Overall, the temporal dynamics of $K_c$ and LAI at the 10-day scale were highly correlated as expected. Specifically, at this 10-day time scale, the two peaks in the $K_c_{_\text{Eddy}}$ curve from late November to early December and from mid-April to late May are very evident, as well as a clear overwintering feature. During the overwintering to erect-growing stages, i.e., from mid-December to the next mid-March, $K_c_{_\text{Eddy}}$ stayed at a low level and experienced little variability. Starting in March, $K_c_{_\text{Eddy}}$ increases significantly as the winter wheat starts rapid growth, with the main peak around mid-April at the booting stage. $K_c_{_\text{Eddy}}$ remains above 1.0, signifying high rates of water consumption until early June when winter wheat approached the mature stage.

![Figure 6. Ten-day $K_c_{_\text{Eddy}}$ and LAI from 2-year average (2009 and 2012).](image)

3.4. LOOCV of the Estimated $ET_a$ Using the Proposed Stage-Wise Method

LOOCV was used to evaluate the performance of the stage-wise $K_c$ method proposed in this study. The daily $ET_a$ during the entire growing period estimated from the proposed stage-wise $K_c$ method ($K_c_{_\text{Eddy}}$) and the FAO method ($K_c_{_\text{FAO}}$) is validated against measurements from the eddy covariance system at Gucheng station. The comparison statistics at both daily and critical phenological scales with the LOOCV technique are summarized in Tables 3 and 4.

Generally, the proposed stage-wise method outperforms the FAO method in terms of linear regression coefficients $k$ and root-mean-square errors (RMSEs). It is shown that the slope of the linear regression line (against ground measurements) for the stage-wise method is more approximate to unity compared to the FAO method (0.97 versus 1.08 at the daily scale and 1.00 versus 1.09 at the critical phenological scale). In addition, the outperformance of the stage-wise method over the FAO method is also supported by the metrics of RMSEs (0.07 mm·day$^{-1}$ versus 0.16 mm·day$^{-1}$ at the
daily scale and 0.01 mm·day$^{-1}$ versus 0.27 mm·day$^{-1}$ at the critical phenological scale). In summary, our method showed slightly better performance than the FAO method in $ET_a$ estimation during the growing period.

Table 3. Statistical metrics of the comparison between the stage-wise and the FAO estimations of $ET_a$ with the LOOCV method at the daily time scale.

<table>
<thead>
<tr>
<th>Growing Period</th>
<th>Stage-Wise Method</th>
<th>FAO Method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$k$ *</td>
<td>$R^2$</td>
</tr>
<tr>
<td>2009–2010</td>
<td>0.95</td>
<td>0.86</td>
</tr>
<tr>
<td>2012–2013</td>
<td>0.98</td>
<td>0.91</td>
</tr>
<tr>
<td>Sum-up</td>
<td>0.97</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Note: * $k$ is the regression coefficient with the linear equation "$y = kx$".

Table 4. Statistical metrics of the comparison between the stage-wise and the FAO estimations of $ET_a$ with the LOOCV method at the critical phenological time scale.

<table>
<thead>
<tr>
<th>Growing Period</th>
<th>Stage-Wise Method</th>
<th>FAO Method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$k$ *</td>
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<tr>
<td>2009–2010</td>
<td>0.99</td>
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<td>Sum-up</td>
<td>1.00</td>
<td>0.96</td>
</tr>
</tbody>
</table>

Note: * $k$ is the regression coefficient with the linear equation "$y = kx$".

The errors in estimated $ET_a$ for both the stage-wise and the FAO method at critical phenological stages are shown in Figure 7. From Figure 7, we can see that the uncertainties of $ET_a$ from the stage-wise method are much smaller than those from the FAO method. Generally, during the initial stages, from seeding to the erect-growing stage, the $ET_a$ derived from the FAO method is underestimated by $-0.2$ mm·day$^{-1}$, higher than that from the stage-wise method ($-0.004$ mm·day$^{-1}$). For the development stage and mid-season stage, the $ET_a$ from the FAO method is notably overestimated by $0.63$ mm·day$^{-1}$ and $0.64$ mm·day$^{-1}$, which are higher than the overestimation from the stage-wise method ($-0.01$ mm·day$^{-1}$ and $0.04$ mm·day$^{-1}$). The underestimations of $ET_a$ in S9 are $-0.02$ mm·day$^{-1}$ and $-0.43$ mm·day$^{-1}$ from the stage-wise and FAO methods, respectively. Overall, a slight superiority of the proposed stage-wise method over the FAO method is exhibited for estimating actual evapotranspiration at phenological time scales.

![Figure 7](image-url)  
*Figure 7. Comparison of delta $ET_a$ for winter wheat between the stage-wise method and the FAO method during the critical phenological stages.*
4. Conclusions

The crop coefficient ($K_c$) is a crucial parameter in the estimation of actual water consumption and water requirement for agricultural development. In this study, a method to estimate temporal fine-scale $K_c$ of winter wheat was developed using the meteorological and eddy covariance observations, as well as the winter wheat growing records during different phenological stages. This downscaling model is motivated by the significant bimodal feature in $K_c$ time series of winter wheat and its distinctive overwintering characteristic, which are not addressed in the conventional FAO method.

Results show that compared to the “four-stage” FAO method, our proposed stage-wise method accurately captures the $K_c$ peak before the overwintering stage and the trough during overwintering. In addition, our method can estimate $K_c$ at temporally fine resolution at the crop development and mid-season stages and, thus, can serve as the basis for the accurate estimation of actual water consumption during the critical phenological stages of winter wheat.

The uncertainties in $ET_a$ based on $K_c$ derived from our proposed stage-wise method and the conventional FAO method are estimated during all critical phenological stages. Compared to the stage-wise method, the overestimation of $ET_a$ from the FAO method is obvious with the maximum value of 0.77 mm·day$^{-1}$ during all of the critical phenological stages. The RMSEs of $ET_a$ for the stage-wise and FAO methods are 0.07 mm·day$^{-1}$ and 0.16 mm·day$^{-1}$ at the daily scale and 0.01 mm·day$^{-1}$ and 0.27 mm·day$^{-1}$ at the critical phenological scale, respectively.

As Gucheng station represents a typical high-yield agricultural zone in the NCP region, the winter wheat $K_c$ at the critical phenological stages generated from our method can be used as a reference for the entire NCP region, where in situ measurements of $K_c$ are relatively scarce. However, accurate and spatially-distributed $K_c$ at the crop phenological stages is crucial for precisely estimating crop water requirements, improving crop water use efficiency and yield, and consequently achieving the goal of highly-promoted water-saving irrigation. Further investigation on the spatial characteristics of winter wheat $K_c$ at the phenological stages at the regional scale is needed. Meanwhile, the validation of the proposed framework in a larger observation sample is crucial in the future.

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Author Contributions: Peijuan Wang outlined the research topic and conducted the analysis. Jianxiu Qiu assisted with manuscript writing and revision. Yueming Bai, Tao Liu and Sanxue Ren were involved in data collection and processing. All authors contributed to the discussion of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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