Effective Method of Estimating the Daily Evapotranspiration of Greenhouse Grapes in the Cold Area of Northeast China

Senyan Jiang, Xinguang Wei,* Dongjie Pei, Siyu Zheng, Shining Fu, and Tieliang Wang

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ABSTRACT: Evapotranspiration (ET) is an important basis and key link for guiding irrigation. One of the key problems to be solved is how to predict the dynamic change in the daily ET and estimate the total amount of ET in greenhouse through limited instantaneous data. In this paper, it is estimated that the daily scale of evapotranspiration by using four methods, including the evaporative fraction method (EF method), the reference evaporative fraction method (EF′ method), the sine method, and the canopy resistance method (r_c method), is based on the measured ET data of grapes in a solar greenhouse in Northeast China. The relative root-mean-square pair error (RRMSE) and the efficiency coefficient (ε) are also used to study their applicability in terms of leaf area index, radiation degree, and scale-up time point.

In the results, under the condition of different LAI, the simulation accuracies of ET scaled by the four methods ranked as follows (from highest to lowest): the reference evaporative fraction method, the evaporative fraction method, the sine method, and the canopy resistance method. The average RRMSE and ε of the evaporative fraction method with the best simulation accuracy were 7.19−16.46% and 0.61−0.75, respectively. Under different radiation conditions, the simulation accuracies of the four methods ranked as follows (from highest to lowest): the evaporative fraction method, the reference evaporative fraction method, the sine method, and the canopy resistance method. Under different radiation conditions, the RRSME of the four methods ranged from 11.55 to 46.62%, and the maximum of ε was 0.75. The evaporative fraction and reference evaporative fraction methods had the highest simulation accuracy, whereas the reference evaporative fraction method required fewer parameters. We concluded that the reference evaporative fraction method was the best for estimating the daily ET of greenhouse grapes in the cold area of Northeast China.
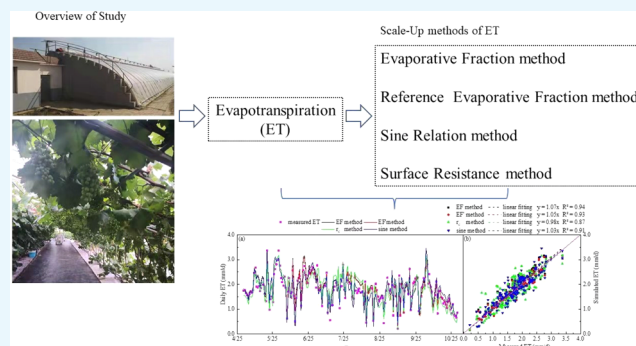
1. INTRODUCTION

Evapotranspiration (ET) is an important component of water and energy balance in agricultural ecosystems. ET plays a key role in irrigation water application, especially in arid and semi-arid areas.[1,2] In semi-arid and arid areas, ET accounts for more than 80% of the total water consumption of farmland.[3−10] The determination of ET is critical for guiding agricultural water use and improving irrigation management.[11−13] ET calculation is of great significance in crop yield prediction, irrigation scheduling, drought analysis, and crop water utilization efficiency improvement.[14−16] The studies on the variation characteristics, the effect, and the mutual transformation of ET on different time scales are helpful to understand the important role of ET in the soil−plant−atmosphere continuum (SPAC) system and establish a scientific and reasonable crop water management system.

Constructing transformation models of ET is the key to realizing ET transformation at different time scales. A large number of studies have shown that large-scale ET is not a simple superposition of small-scale ET; there is a complex

nonlinear relationship between them.[16,17] Jackson[18] realized the transformation of instantaneous transpiration and diurnal transpiration by using the ratio of daily solar radiation and instantaneous radiation at a certain time of day, which is called evaporative fraction method (EF method).[19] Subsequently, a variety of methods to enhance the scale transformation of evapotranspiration have gradually appeared, such as the reference evaporative fraction method (EF′ method),[20] the crop coefficient method,[21] the modified crop coefficient method,[22] the canopy resistance method[23] (r_c method), and the sine method.[24] The key to each time scale lifting method is to associate the daily ET with a factor, which is usually a
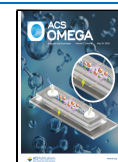
constant during the day or throughout the diurnal cycle.[2] The accuracy of these methods' applicability varies in different environments.[25−36]

Shuttleworth et al.[37] estimated the daily ET by the evaporative fraction at noon, which was not different from the measured ET. In this method, there is the concave shape of the evaporative fraction variation. Some researchers have verified the above results through their research.[1,2,17,38] Some researchers have doubted the applicability of the EF method and have considered that the evaporation ratio needs to be corrected to meet the basic assumptions of the time scale.[39] Researchers have further verified the applicability of the EF method.[38,40] Liu et al.[41] obtained the daily ET on the basis of evaporative fraction, which was closer to the measured daily ET. Zhang et al.[17] also obtained the accurate daily ET by this method, where the efficiency coefficient (ε) of the EF method reached 0.65, and the estimated ETs were consistent with the measured ET, and the obtained results were stable. Allen et al.[42] proposed a scale-up method of ET based on the crop coefficient. It has been successfully applied to estimate daily ET by instantaneous ET.[17] Colaizzi et al.[43] compared the results obtained by the crop coefficient method and the EF method and found that the daily ET estimated by the two methods was in good agreement with the measured values, but the ET estimated by the crop coefficient was closer to the actual value under the condition of crop coverage. However, some scholars pointed out that in case there is large deviation in the calculation of reference crop ET, the estimation effect may be poor due to the limitation of its definition.[2,44] Some researchers found that the canopy resistance during the daytime was stable in the model of P-M.[45,46] This canopy resistance characteristic is employed to scale up the instantaneous ET.[17,47] Liu et al.[41] obtained the daily ET by this method at a specific time and achieved good results. However, Tang[48] believes that the assumption that canopy resistance is almost constant during the day is questionable, as it is affected by solar radiation, water vapor pressure deficit, and wind speed. The sine method is also a common scale-up method of ET. Chen et al.[49] used this method to scale up the ET under different crop types. They found that the sine method had a severe systematic deviation compared with the EF method and the EF′ method, and the simulation results in most periods were higher than those by other methods, but it had good adaptability. Lei Jiang compared the applicability of lifting methods in different ecosystems.[40] The results showed that each method has the best simulation effect around noon, and each method had different best simulation times at different ecosystems. Among them, the EF′ method and the sine method are applicable to most ecosystems, and the EF′ method is the most ideal time-scale lifting method. Ayman Nassar[1] used different methods to improve the time scale of ET for grapes in California, and the results showed that different methods had different effects in different growth stages and different time periods. Haofang Yan[2] conducted experiments in tea and wheat fields in Jiangsu Province, and the results showed that the EF method and the EF′ method had better effects than other methods, and the effect was the best at noon. The above studies show that different time-scale methods of ET have different applicabilities to different climate zones and different crop types.

Although the scale of evapotranspiration has been improved and expanded, there are relatively few research results on the accuracy and applicability of the model. In particular, most of the research results are focused on the field, and there are few studies on the mesoscale conversion of greenhouses. Therefore, it is necessary to compare different scale-up methods of daily ET under more climate zones and underlying surface conditions and evaluate their simulation accuracies. In terms of the research on the ET of grapes in greenhouses in cold regions, the previous achievements are mostly focused on the discussion and difference comparison of ET laws at different time scales, whereas the research results on ET scale-up and mutual conversion are rare. There is still a lack of mature and feasible methods for the time-scale conversion of the evapotranspiration of grapes in greenhouses. Therefore, the purpose of this study is to explore the suitability of the time-scale expansion model for the ET of grapes in greenhouses in Northeast China, in order to provide a scientific basis for the irrigation management of grapes and the precise regulation of the environmental factors of facilities in the cold region of Northeast China.

2. EXPERIMENTAL SECTION AND COMPUTATIONAL METHODS

2.1. Study Area. The experiment was conducted from 1 May 2017 to 31 October 2019 in no. 44 solar greenhouse (41.82° N, 123.57° E) of Shenyang Agricultural University's Research and Experiment Base in Northeast China. Its elevation is 81 m. This solar greenhouse is located in the temperate subhumid continental climate zone with a significant continental climate and an annual average temperature of 8.4 °C. The greenhouse type is a Liaoshen III type solar energy-saving greenhouse. The greenhouse is east−west oriented, with a span of 8 m, a ridge height of 4 m, a north wall height of 2.5 m, and a length of 60 m. A polyolefin (PO) film with a thickness of 0.15 mm was used as the greenhouse film. Defensive cotton cover was used to maintain insulation. There was no heating in the greenhouse, and passive ventilation was implemented by opening the PO film on the top and south. The bulk density of a 0−60 cm layer of the tested soil was 1.44 g/cm^3, and the field capacity was 0.321 cm^3/cm^3. Grapes (*Vitis vinifera* L.c. Muscat Hamburg) were planted in the greenhouse, and the planting was completed in March 2015. The grapes were irrigated by mulch drip irrigation. When the soil water content in the root zone was less than 70% of the field capacity, irrigation was carried out until the soil water content reached 90% of the field capacity. Details on the field management of grapes in greenhouses (fertilization, pruning, fruit retention, etc.) were introduced in the research by Wei et al.[50]

2.2. Data. *2.2.1. Sap Flow and the Evapotranspiration of Grapes.* Five grapes with the same growth were randomly selected to monitor the dynamics of sap flow during the whole growth period with the sap flow monitoring system wrapped on the tree stem (Flower32-1K, SBG-9). The sensors were installed on the trunk of the vine, about 20 cm above the ground. The sensor was wrapped with silver paper to prevent heat exchange with the environment. The sap flow was collected by a CR1000 data collector with a collection frequency of 1 h/time. The wrapped stem flow meter (Flower32-1K) uses the principle of heat balance, and its sap flow calculation formula is

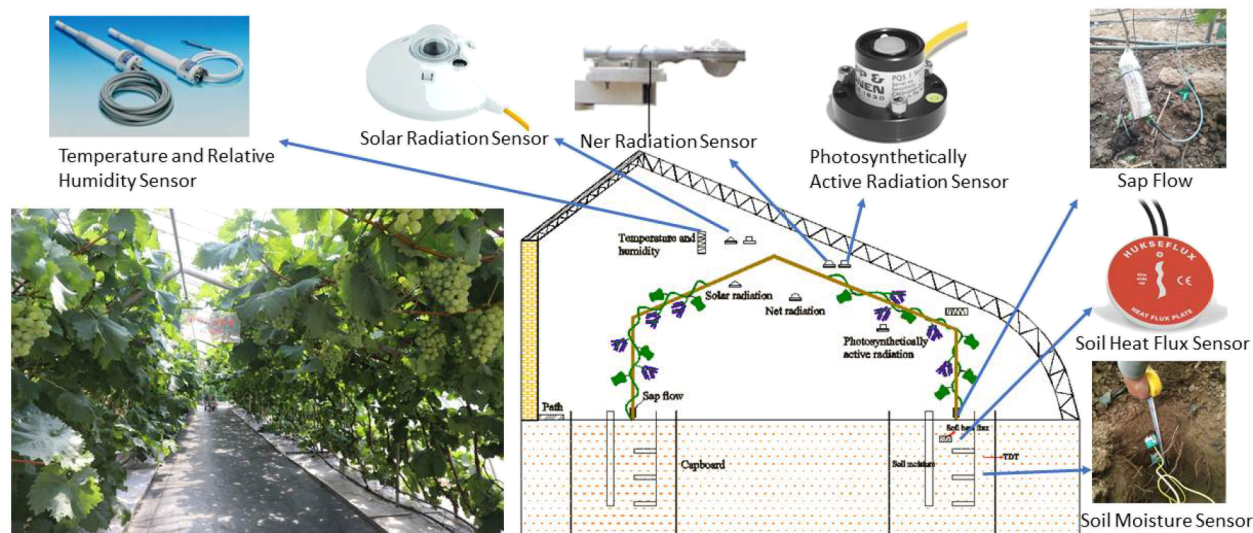$$F = P_{in} - Q_v - Q_r/C_p g dT \tag{1}$$

Figure 1. Schematic description of the research greenhouse and the arrangement of the sensors and instruments.

Table 1. Nomenclature and Source on Four Scale-Up Methods

symbol	name	value	unit	source	model
λET_i	instantaneous evapotranspiration		W/m^2	measured	EF method, EF′ method, sine method
R_n	net radiation		W/m^2	measured	EF method, EF′ method, r_c method
G	soil heat flux		W/m^2	measured	EF method, r_c method
D	Julian Day			Zhang L and Lemeur R (1995)[36]	sine method
L	geographical latitude	N41.82°	°	Li Bo et al. (2019)[56]	sine method
r_s	stomatal resistance		s/m	Perrier A (1975)	r_c method
LAI	leaf area index			measured[57]	r_c method
k	Karman's constant	0.40		Shuttleworth and Wallace (1985)[37]	r_c method
z	reference height	2.5	m	measured	r_c method
d	zero plane displacement height	1.12468	m	Perrier A (1975)[57]	r_c method
u	wind speed		m/s	measured	r_c method
z_0	roughness length governing momentum transfer	0.31673	m	Perrier A (1975)[57]	r_c method
Δ_d	total daytime values of slope of the saturation vapor pressure curve		kPa/°C	Allen et al. (1998)[4]	r_c method
ρ	air density	1.29	kg/m^3	Allen et al. (1998)[4]	r_c method
VPD	vapor pressure deficit		kPa	Allen et al. (1998)[4]	r_c method
C_P	specific heat of dry air at constant pressure	1103	J/kg °C	Allen et al. (1998)[4]	r_c method
Γ	psychrometric constant	0.06651	kPa/°C	Allen et al. (1998)[4]	r_c method
h_c	height of the crop	2.2	m	measured	r_c method

where F is the instantaneous stem flow at time t, g h^{-1}; P_{in} is the heat input, W; Q_v is vertical heat conduction, W; Q_r is radial heat dissipation, W; C_p is the specific heat of the water, 4.186 J/(g °C); and dT is the average value of the voltage sum of the two vertical thermocouples (°C).

The daily ET of the grapes was obtained by the integral of the transient stem flow of the entire day. Its computation formula is

$$T_i = \int_0^{24} F \, \mathrm{d}t \tag{2}$$

$$T_c = m \cdot \sum_{i=1}^{n} T_i / 1000 \cdot n \cdot A \tag{3}$$

where T_i is the daily transpiration of a single grapevine (mm), T_c is the average daily transpiration of all grapevines in the

whole greenhouse (mm), A is the ground area of the vineyard (m^2), n is the number of grapevines, for which sap flow was measured ($n = 5$), i is the ith measured grapevine, and m is the total number of grapevines in the greenhouse.

Grapes were mulched with the film, and soil evaporation was ignored. Therefore, the calculation formula of grape ET in the greenhouse is (ET and λET are different expressions of the same variable, so they will be selected according to the demand and can no longer be distinguished)

$$\lambda ET = \lambda A \times F \times 10^{-3}/3600 \tag{4}$$

where λET is the latent heat flux (W/m^2) and λ is the latent heat of the vaporization of water (J/Kg).

2.2.2. Leaf Area. The leaf area was measured by a manual method. During the whole experiment, 10 labeled grape shoots were randomly selected to measure the length and maximum

width of all the leaves on the branches. In addition, 20 leaves of different sizes were randomly picked, and leaf length and maximum leaf width were recorded and photographed. The ImageJ software was used to measure the accurate leaf area, and the regression relationship between the leaf area and leaf length and the maximum leaf width was established. The regression relationship was used to estimate the grape leaf area on the branches, and the total leaf area of the corresponding grapevine was calculated. The plant leaf area index (LAI) was obtained by using the ratio of the projected leaf area and projected canopy area. The measurement frequency was 7–10 days.

2.2.3. Meteorological and Flux Data. There is a small weather station in this research area (Campbell Scientific, Inc., Logan, UT, USA). The temperature and relative humidity were measured by Pt100RTD and HUMICAP 180R sensors (R. Young Company, Traverse City, MI, USA), respectively. The solar radiation (R_s, W m^{-2}) was measured by a CMP3 (LICOR, Inc., Lincol, NE, USA) sensor. The net radiation (R_n, W m^{-2}) was measured by a net radiometer (Kipp & Zonen, Netherlands). The CR1000 data logger (Campbell Scientific, Inc., Logan, UT, USA) was used to record data every 30 min. Two soil heat flux plates (HFP01, Hukseflux, Delft, Netherlands) were installed 0.5 cm deep in the soil under the film, about 30 cm from the roots of the grapevine. The situation and observation indicators in the greenhouse are shown in Figure 1.

2.3. Scale-Up Methods of ET. *2.3.1. Evaporative Fraction Method.* Evaporative fraction (EF) is defined as the ratio of latent heat flux to available energy.[37] Its strength is that the intraday variation of ET is small under clear weather conditions. The formula of ET is[51]

$$EF_i = \lambda ET_i / (R_n - G)_d \tag{5}$$

$$\lambda ET_d = EF_i (R_n - G)_d \tag{6}$$

where EF_i is the instantaneous evaporation ratio; λET_t and λET_d are the latent heat fluxes (W/m^2) of instantaneous and daily scales at time t, respectively; $(R_n - G)_i$ is the difference between the instantaneous net radiation and the soil heat flux at the time t; and $(R_n - G)_d$ is the difference between the daily net radiation and the soil heat flux (W/m^2) (see Table 1).

2.3.2. Reference Evaporative Fraction method. The soil heat flux (G) was assumed to be 0 on the daily scale.[20] The G in eqs 5 and 6 was ignored to reduce the error caused by the uncertainty of the soil heat flux calculation. The modified formula of the evaporative fraction method is

$$EF_i' = \lambda ET_i / R_{ni} \tag{7}$$

$$\lambda ET_d = EF_i R_{nd} \tag{8}$$

where EF' is the modified instantaneous evaporation ratio, R_{ni} is the instantaneous net radiation at the time t, (W/m^2), and R_{nd} is the daily net radiation (W/m^2) (see Table 1).

2.3.3. Sine Method. The sine method assumes that the instantaneous latent heat flux shows a sinusoidal change trend in a day, which is similar to the calculation of solar short-wave radiation. The daily ET was calculated by the following formula

$$ET_d = 2N_e ET_i / [\pi \sin(\pi t_i / N_e)] \tag{9}$$

$$N_e = N - 2 \tag{10}$$

$$N = a + b\{ \sin[\pi(D + 10/365)]\}^2 \tag{11}$$

$$a = 12.0 - 5.69 \times 10^{-2}L - 2.02 \times 10^{-4}L^2 + 8.25 \times 10^{-6}L^3 - 3.15 \times 10^{-7} \tag{12}$$

$$b = 0.123 - 3.10 \times 10^{-4}L^2 + 8.00 \times 10^{-7}L^3 + 4.99 \times 10^{-7}L^4 \tag{13}$$

where N_e is the evaporation hour, which is equal to the length of time from the beginning of ET in the morning to the end of ET in the evening, t_i is the time interval from the beginning of the ET process in the morning to the moment i, N is the length of time from sunrise to sunset, D is the number of observation days in 1 year, a and b are the empirical coefficients related to latitude, and L is the geographical latitude (see Table 1).

2.3.4. Canopy Resistance Method (r_c Method). Alves and Farah found that the diurnal variation of canopy resistance was small and had a certain stability. This result was applied to scale up the instantaneous ET to the daily ET, and its calculation formula is

$$r_c = r_s / LAI_e \tag{14}$$

$$LAI_e = LAI/0.3LAI + 1.2 \tag{15}$$

$$r_a = Ln[(z - d)/(h_c - d)]Ln[(z - d)/z_0]/k^2 u \tag{16}$$

$$\lambda ET_d = \Delta_d(R_n - G) + \rho C_p VPD/r_{ad} / \Delta_d + \gamma(1 + r_{ct}/r_{ad}) \tag{17}$$

where r_c is the canopy resistance, s m^{-1}; r_s is the stomatal resistance, s/m; LAI_e is the effective leaf area index; r_a is the aerodynamic resistance, s m^{-1}; k is the Karman constant of 0.40; z is the reference height, m; d is the displacement of the zero plane, m; u is the horizontal wind speed at the reference height, m/s; z_0 is the length of momentum-transfer roughness, m; Δ_d is the slope of the daily saturated vapor pressure as a function of temperature, KPa °C^{-1}; ρ is the daily air density, kg/m^3; VPD is the saturated water pressure difference, kPa; C_P is the air's specific heat at constant pressure, J/kg °C; γ is the constant of the dry–wet meter, KPa/°C; R_n is the net radiation, W/m^2; and G is the soil heat flux, W/m^2 (see Table 1).

2.4. Accuracy Evaluation Index of the Scale-Up Methods. The accuracy evaluation indexes of the scale-up method include relative bias (RB), root-mean-square error (RMSE), relative root-mean-square error (RRSME), and fitting efficiency coefficient (ε). Their calculation formulas are

$$RB = |ET_{p,i} - ET_{obs,i}|/ET_{obs} \times 100 \tag{19}$$

$$RSME = [1/N \sum_{i=1}^{N} (ET_{p,i} - ET_{obs,i})^2]^{1/2}/ET_{obs} \tag{20}$$

$$\varepsilon = 1 - \sum_{i=1}^{N} |ET_{obs,i} - ET_{p,i}| / \sum_{i=1}^{N} |ET_{obs,i} - ET_{obs}| \tag{21}$$

where $ET_{p,i}$ is the forecast value, ET_{ob} is the measured value, ET_p is the average of the forecast value, and N is the sample number, $N = 1, 2, ..., N$.

3. RESULTS

3.1. Diurnal Variation of Key Parameters. Evaporative fraction (EF) and reference evaporative fraction (EF′) are the
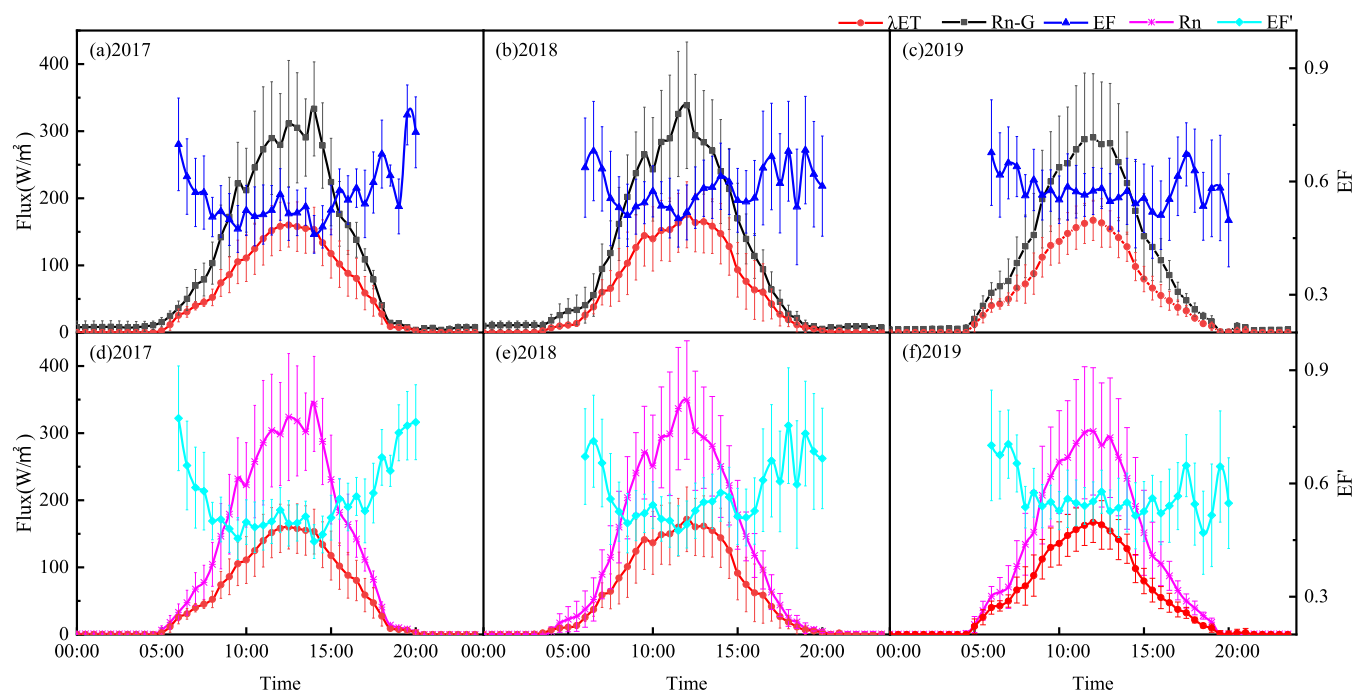
Figure 2. Diurnal variations of key parameters in 2017 (a,d), 2018 (b,e), and 2019 (c,f).
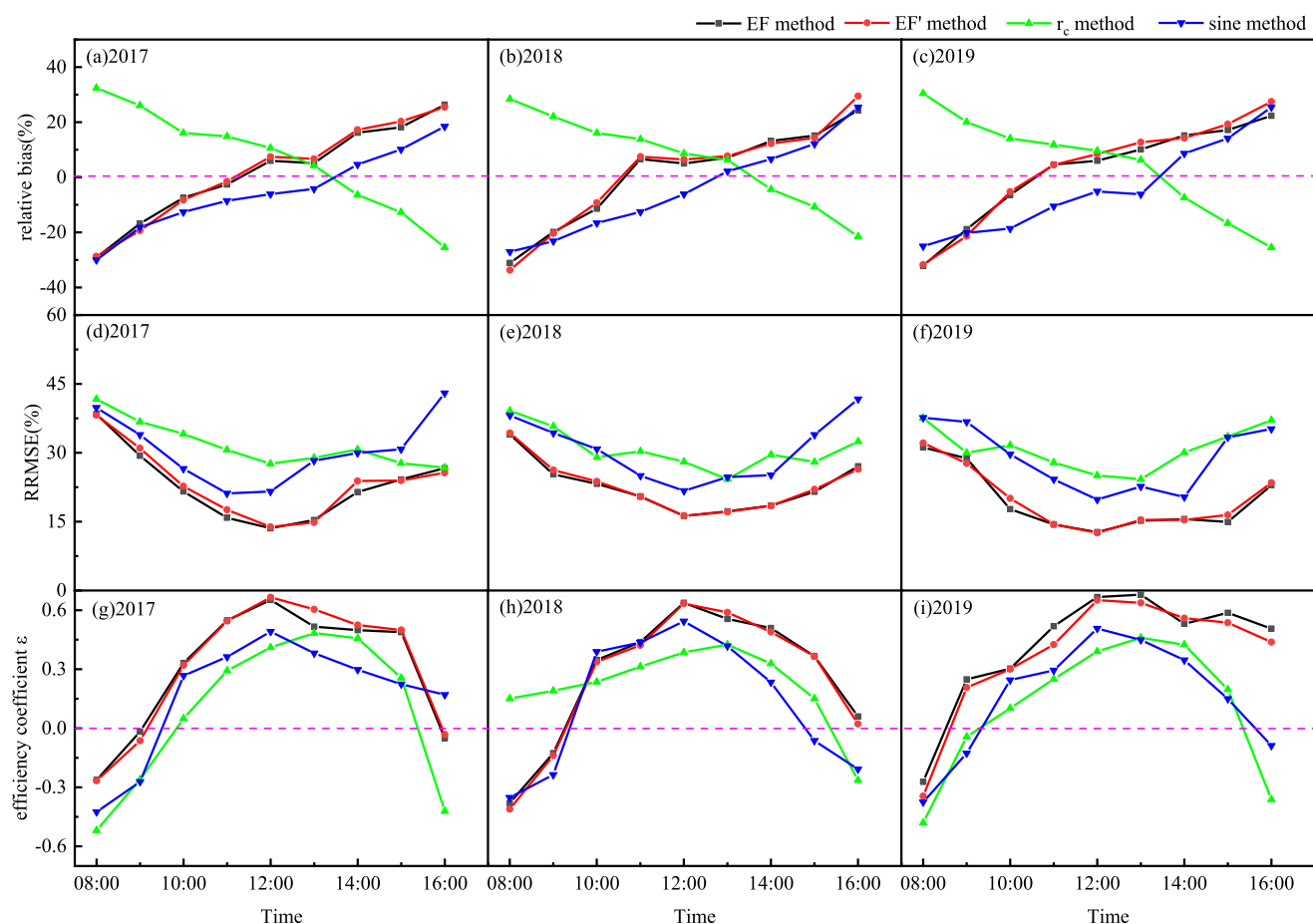

Figure 3. Evaluation indexes of the simulation accuracy for the four scale-up methods in 2017 (a,d,g), 2018 (b,e,h), and 2019 (c,f,i).

key parameters of scale-up ET in the evaporative fraction method and reference evaporative fraction methods. They were calculated according to the latent heat flux, net radiation flux, and soil heat flux (eqs 4 and 6). The diurnal variations of R_n, $R_n - G$, λET, EF, and EF′ are shown in Figure 2 by averaging all data in each period of the grape growing season in

2017, 2018, and 2019. R_n, $R_n - G$ and λET had a single peak variation trend from 2017 to 2019; they gradually increased from around 5 AM in the morning, reached the peak at around 12:00−13:30 PM, and then slowly decreased until around 8 PM. In the 3 years, the maxima of R_n reached 343, 357, and 302 W m^{-2}, and the maxima of $R_n - G$ were 334, 338, and 291 W m^{-2}, respectively. These results were significantly higher than λET. The maxima of λET in the 3 years were only 160, 165, and 167 W/m^2. EF and EF′ were evaluated only between 6 AM and 8 PM because the energy flux before 6 AM and after 8 PM was almost zero every day. The interannual variation of EF in the 3 years was quite different. In 2017, EF showed a high−low−high variation trend. It gradually decreased from 5 AM to 8 AM and was basically stable between 0.47 and 0.58 from 8 AM to 4 PM. After 4 PM, EF gradually increased and reached about 0.54−0.78 at 8 PM. In 2018 and 2019, the intraday variation of EF fluctuated throughout the day without obvious regularity, and the whole growth period fluctuated between 0.50 and 0.68. The variation coefficient of EF during the 3 years was 0.09−0.12 between 5 and 8 AM and 4−7 PM and 0.07−0.09 between 8 AM and 4 PM, which was higher in the morning and evening and lower in the day. The variation pattern of EF′ was basically the same as EF, and the variation was relatively small from 8 AM to 4 PM. The average standard deviations of EF′ between 8 AM to 4 PM in 2017, 2018, and 2019 were 0.50, 0.52, and 0.54, respectively. The average variation coefficients of EF′ in the morning and evening were 0.06, 0.07, and 0.06, respectively. Since both EF and EF′ in this study were stable during the period from 8 AM to 4 PM, the data in this period were selected for the scale-up model of ET in subsequent studies.

3.2. Simulation Accuracy of the Four Methods. The daily ETs were calculated by using the evaporative fraction method (EF method), reference evaporative fraction method (EF′ method), sine method, and canopy resistance methods (r_c method) based on the ETs at different times every day during the whole growth period of the grapes. Their relative error, relative root-mean-square error (RRMSE), and efficiency coefficient are shown in Figure 3. The change laws of the relative error between the simulated and the measured ET (Figure 3a−c) calculated by the EF method, EF′ method, and sine methods were basically the same from 2017 to 2019. They were underestimated in the morning and overestimated in the afternoon. In 2017, the relative errors were underestimated only by 17.78% by using the EF method and EF′ methods before 10 AM, but the relative error when using the sine method was underestimated by −30.04 to −4.20% before 2 PM. After 2 PM, the ETs were overestimated by these three methods and gradually increased. At 4 PM, the relative errors were the largest, and the relative errors obtained by the methods of EF and the EF′ reached 26.35 and 25.46%, respectively, whereas the relative error of the sine method reached 18.42%. The change law of the relative error in the r_c method was opposite to the above three methods. It was overestimated in the morning (before 1 PM) and under-estimated in the afternoon (after 1 PM). In 2017, the relative error of the r_c method ranged from 32.45 to 4.28% in the morning and from −25.46 to −6.36% in the afternoon. In 2018 and 2019, the simulation relative errors of the four methods were basically the same as those of 2017, except that the time nodes of overestimation and underestimation were slightly different. The minimum relative errors from the methods of EF and EF′ were at 10 AM (2018 and 2019) and 11 AM in 2017

and were at 2 PM in 2017 and 2019, and 1 PM in 2018 for the sine method. For the r_c method, it appeared at 1 PM.

The RRMSE estimated by the four methods (Figure 3d−f) has basically the same variation law during 2017−2019. Except for the RRMSE of the r$_c$ method in 2017, the RRMSE of the other methods in the 3 years showed a trend of high in the morning and evening and low at noon. The simulation accuracies of the EF method and EF′ methods were higher than those of the other two methods. The average daily RRMSE for the sine method and the r_c method from 2017 to 2019 were between 12.71−38.42% and 13.85−38.21%, respectively. The simulation accuracies were better from 11 AM to 1 PM, especially at 12 PM, which has the best simulation accuracy. The errors of the EF method and EF′ methods were only between 12.71−16.21 and 12.55−16.28%. The simulation accuracy of the sine method was the second best, and its RRMSE from 2017 to 2019 was 19.80 to 41.69%. The simulation accuracy of the r_c method was the worst, and the average RRMSE was 24.23−43.70%.

The variation trends of the efficiency coefficient (ε) of the diurnal scale ET obtained by the four methods were opposite to those of RRMSE (Figure 3g−i). The efficiency coefficients showed a low trend in the morning and evening and a high trend at noon. The simulation efficiency coefficient was low in the morning and evening. Before 9 AM, the efficiency coefficients were generally less than 0 except for those obtained by the r_c method in 2018, and the EF method and the EF′ methods in 2019. These results indicate that the simulation results of the daily ET were worse than the statistical average of the observed results, and it is not reliable to use the data before 9 AM to scale up the ET. Among them, the efficiency coefficients obtained by the EF method and EF′ methods were higher. The annual average εs from 2017 to 2019 were between −0.38 to 0.67 and −0.41 to 0.67, and the simulation accuracy was better from 11 AM to 1 PM ($\varepsilon \geq 0.42$). At 12 PM, the average efficiency coefficients obtained by the EF method and EF′ methods all reached 0.67 in 3 years. The ε of the sine method was between −0.43 and 0.54, and its effect was better between 11 AM and 1 PM ($\varepsilon \geq 0.36$). Compared with the other three methods, the ε obtained by the r_c method was the least effective, with its average efficiency coefficient between −0.51 and 0.48 in the 3 years and its maximum efficiency coefficient at only 0.32.

Based on these results, when the four methods were used to scale up the instantaneous ET, the simulation accuracy was poor in the morning and evening and better in the day. The efficiency coefficients of data before 9 AM and after 4 PM were less than zero, and the data reliability was poor. The best simulation period of the EF method and EF′ method was 11 AM to 2 PM, the best simulation period of the sine method was 11 AM to 2 PM, and the best simulation period of the r_c method was 12 PM to 2 PM. The relative errors and the relative root-mean-square errors of the above four methods in the best simulation period were −2.63 to 10.12 and 12.71−20.49%, −1.51 to 12.71 and 12.55−20.43%, −12.54 to 2.20 and 19.80−28.28%, and −6.36 to 10.65 and 24.24−30.73%, respectively. The average efficiency coefficients were 0.44−0.68, 0.42−0.67, 0.29−0.54, and 0.33−0.48, respectively.

3.3. Simulation Accuracy of the Four Methods with Different Leaf Area Indexes. The diurnal variations of the RRMSEs and εs of the scale-up and measured ET by the EF method, EF′ method, sine method, and r_c methods are shown in Figures 4 and 5 with different leaf area indexes. Figure 4a−c
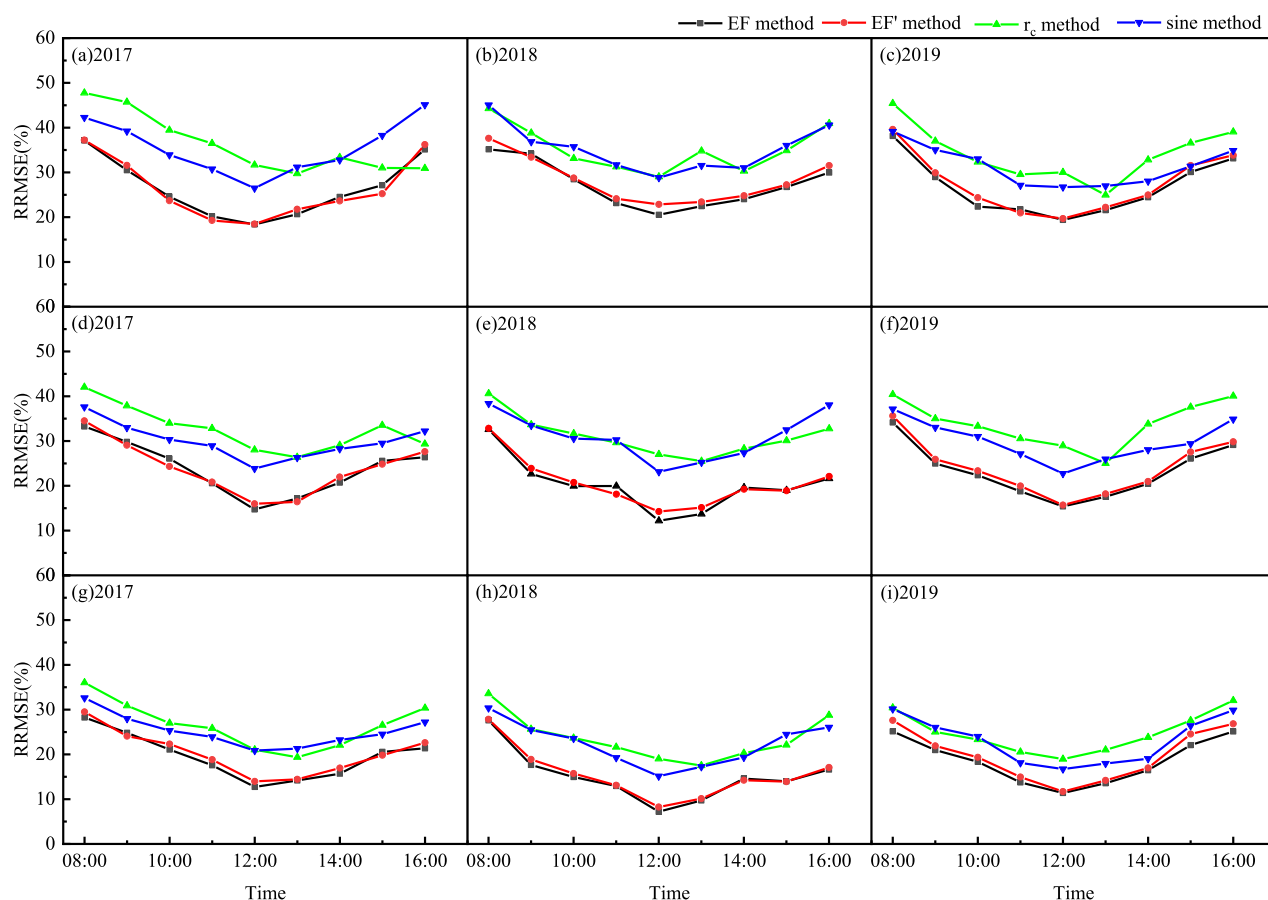
Figure 4. RRMSE variations of the daily ET scaled by the four methods with different leaf area indexes: (a−c) RRMSE variations of ET in the early growth stage of the grapes (LAI < 1); (d−f) RRMSE variations of ET in the middle growth stage of the grapes (1 < LAI < 2); and (g−i) RRMSE variations of ET in the middle and late growth stages of the grapes (LAI > 2).

shows the diurnal variations of RRMSEs during the early growth stage of the grapes (LAI < 1). Figure 4e−g shows the diurnal variations of RRMSE in the middle growth stage of the grapes (1 < LAI < 2). Figure 4h−j shows the diurnal variations of RRMSE in the middle and late growth stage of the grapes (LAI > 2).

The RRMSEs of ET show a trend of being higher in the morning and evening than the RRMSEs at noon in different LAI growth stages, except for the RRMSE of ET obtained by the r_c method in the early and middle growth stages in 2017. At the early growth stage (LAI < 1), the RRMSEs of ET scaled up by the EF method and the EF′ methods were significantly smaller than the ones scaled up by the other two methods. The average daily RRMSEs of ET scaled up by the four methods were 18.38−38.13%, 18.48−39.13%, 26.48−45.04%, and 24.95−47.76%, respectively, during 2017−2019. Among them, the simulation errors of the EF method and the EF′ method were best at 11 AM to 1 PM. The 3 year average RRMSE of ET scaled up by the EF method was only 18.38−23.14%, and it was 18.48−24.10% scaled up by the EF′ method. These two results were not significantly different. The simulation accuracy of the sine method was better from 11 AM to 1 PM, and the RRMSE of ET ranged from 26.48 to 31.67%. The r_c method had the lowest simulation accuracy. The RRMSE of the simulated ET ranged from 29.03 to 34.80% during the period of 12 AM to 2 PM with better simulation accuracy.

In the middle growth stage (1 < LAI < 2) and the middle and late growth stage (LAI > 2), the EF method had the highest simulation accuracy; the simulation accuracy of this method reached 12.19−20.57 and 7.19−17.57%, respectively, in the best simulation period. For the EF′ method, its simulation accuracy of the two growth stages was 14.24−20.82 and 8.25−18.82%, which had little difference with that of the EF method. The simulation accuracy of the ET scaled by the sine method was lower than that of the first two, and the r_c method had the lowest simulation accuracy of 17.50−33.81%.

Under different LAI conditions, the simulation accuracies of the four methods were as follows: EF method > EF′ method > sine method > r_c method, and the simulation accuracy of EF method and EF′ method had little difference. LAI differences influenced the simulation accuracy. The smaller the RRMSE was, the higher the simulation accuracy was with the increase in LAI. When the LAI was less than 1, the average RRMSE of the four methods ranged from 18.38 to 47.76%. When the LAI was greater than 1 and less than 2, the average RRMSE was 12.19−42.04%. When the LAI was greater than 2, the RRMSE ranged from 7.19 to 36.04%. The EF method, which had the best simulation performance, had a simulation accuracy of 12.72, 7.19, and 11.39% in 2017, 2018, and 2019, respectively. The simulation accuracies of the EF′ method were 13.97, 8.25, and 11.69% in 2017, 2018, and 2019, respectively. However, there is little difference between the two methods.

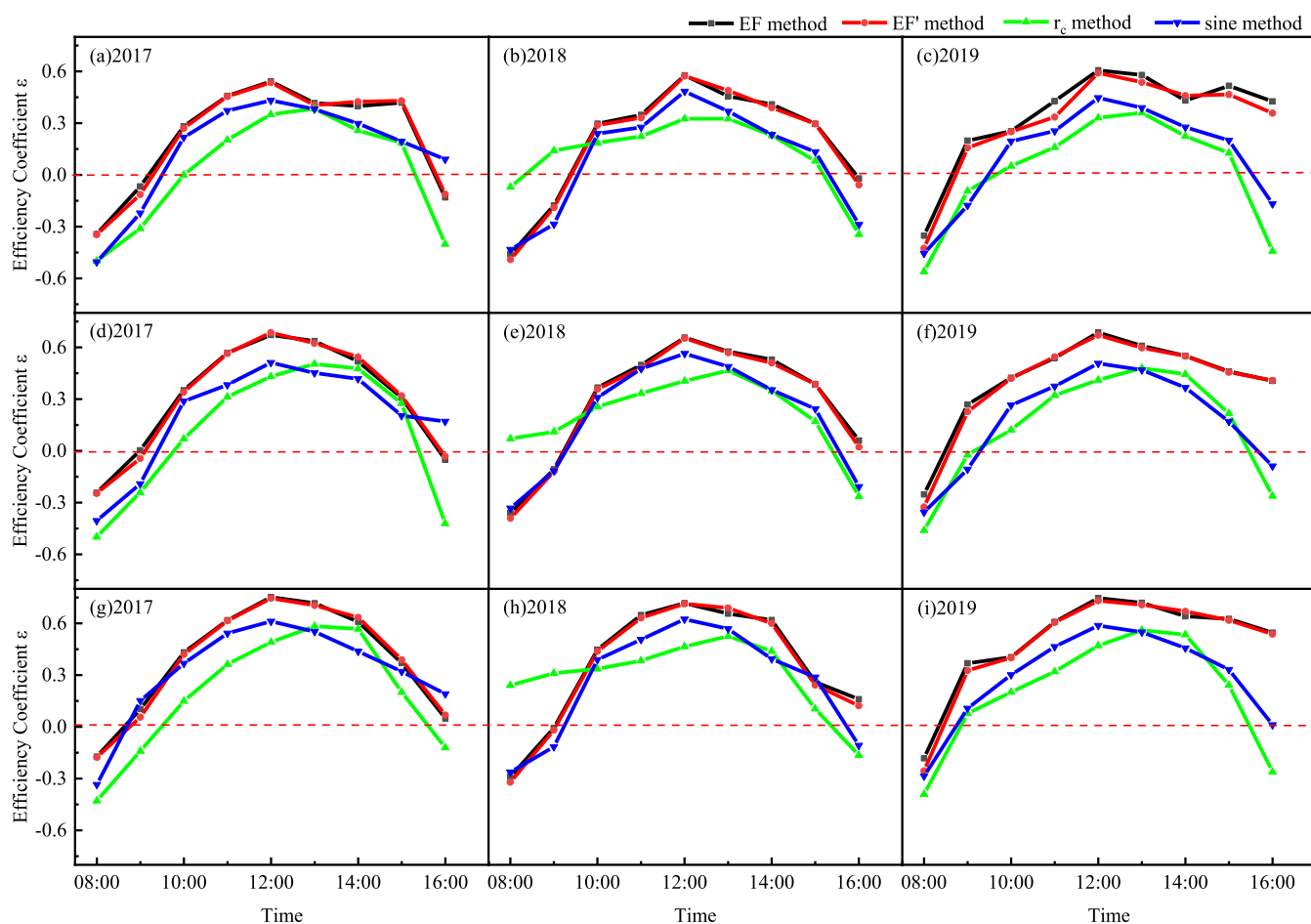The variation trend of the estimated and measured ε based on the four scale-up methods was opposite to that of the

Figure 5. Efficiency coefficient variations of the daily ET scaled by the four methods with different leaf area indexes: (a−c) ε variations of ET in the early growth stage of the grapes (LAI < 1); (d−f) ε variations of ET in the middle growth stage of the grapes (1 < LAI < 2); and (g−i) ε variations of ET in the middle and late growth stages of the grapes (LAI > 2).

RRMSE shown in Figure 5. It was low in the morning and evening and high at noon. In the early growth stage of the grapes (LAI < 1), most εs of the four methods were less than 0 before 9 AM, which indicates that the ET scale-up method before 9 AM was unreliable. This result was consistent with the conclusion in Figure 4. The average ε of the four methods reached −0.46 to 0.61, −0.49 to 0.59, −0.50 to 0.48, and −0.56 to 0.38, respectively, during 2017−2019. The efficiency coefficients of the EF method and EF′ method were higher than that of the sine method, and the efficiency coefficient of the canopy resistance was the lowest. In the middle and late growth stages, the efficiency coefficients of the four methods were the same as those in the early growth period and also showed as ε of EF method > ε of EF′ method > ε of the sine method > ε of the canopy resistance. With the increase in LAI, the efficiency coefficients of the four methods all increased to different degrees. The average efficiency coefficients of the EF method and the EF′ method reached 0.69 and 0.75 in the middle and late growth stage, respectively. The εs of the other three methods were all higher before and after 12 PM, except for the ε of the r_c method. In particular, the efficiency coefficients of the EF method with the highest simulation accuracy in 2017, 2018, and 2019 reached 0.75, 0.72, and 0.75, respectively, in the middle and late growth stages.

The daily scale-up accuracy of the four methods influenced by different growth stages are as follows: middle and late growth stage > middle growth stage > early growth stage. The effect of the four methods on the daily scale-up of ET in different growth stages is as follows: EF method > EF′ method > sine method > r_c method. The RRMSE of ET scaled up by the four methods was higher in the morning and evening and lower at noon, and the efficiency coefficient of ET was lower in the morning and evening and lower at noon, except for the RRMSE of the r_c method in 2017. The best simulation accuracy of ET at different growth stages was around noon (11 AM to 2 PM). The average RRMSE and ε of ET scaled up by the EF, with the best effect, were 18.38−24.52% and 0.39−0.61, 12.19−20.70% and 0.50−0.69, and 7.19−16.46% and 0.61−0.75 from 11 AM to 2 PM at the late growth stage, middle growth stage, and early growth stage, respectively.

3.4. Simulation Accuracy of the Four Methods with Different Radiation Conditions. The diurnal variation of RRMSEs and εs of the scaled up and measured ET based on the four methods of EF, EF′, sine method, and r_c method are shown in Figures 6 and 7 with different net radiations. Figure 6a−c shows the diurnal variation of RRMSEs with low radiation (R_n < 80 W/m^2). Figure 6e−g shows the diurnal variation of RRMSEs with medium radiation (80 < R_n < 150 W/m^2), and Figure 6h−j shows the diurnal variation of RRMSEs with high radiation (R_n > 150 W/m^2).

The RRMSEs of ET showed a trend of higher in the morning and evening than those at noon in different net
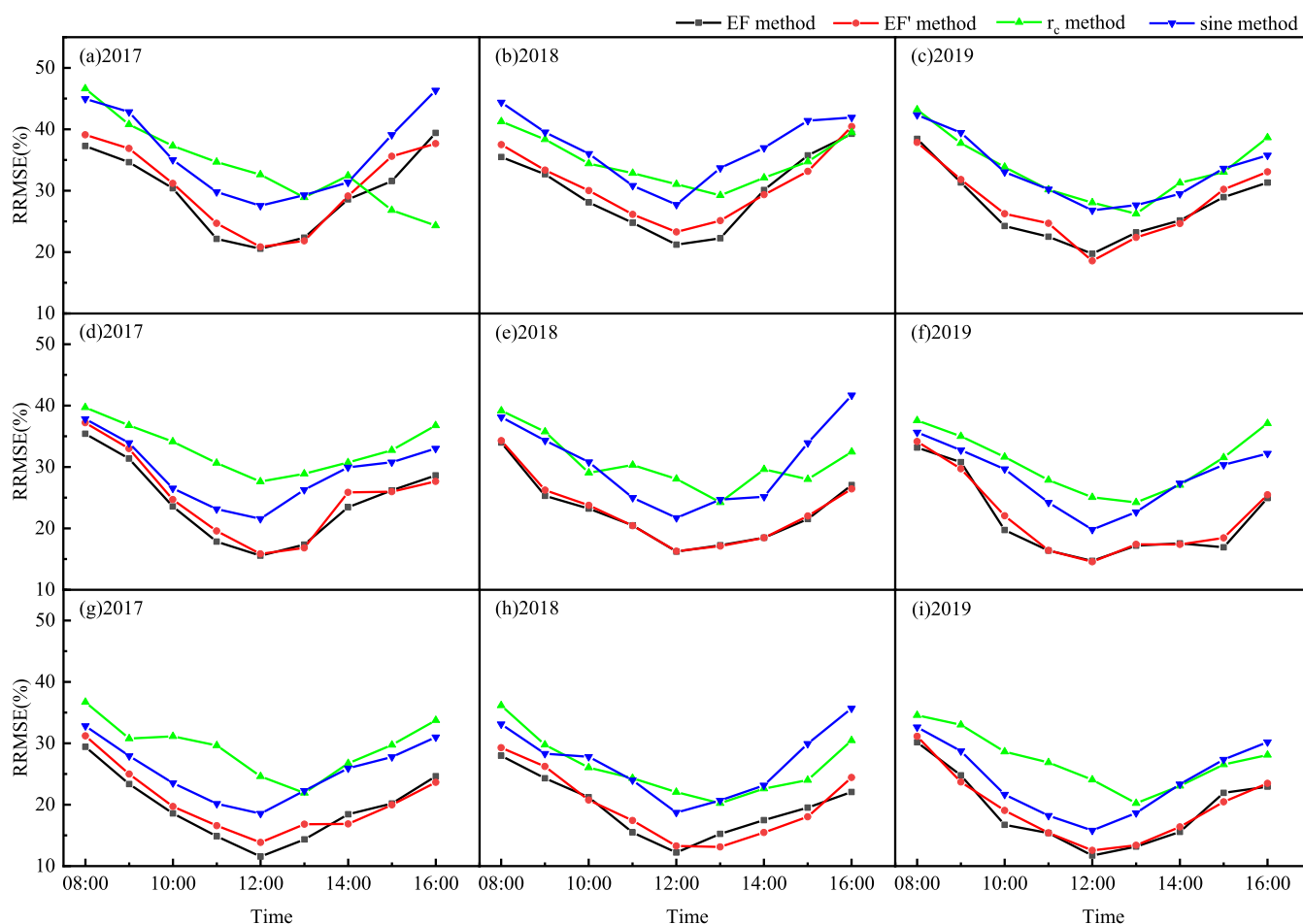
Figure 6. RRMSE variations of the daily ET scaled up by the four methods with different radiations: (a−c) Diurnal variations of RRMSEs with low radiation $(R_n < 80 \text{ W/m}^2)$; (d−f) Diurnal variations of RRMSEs with medium radiation $(80 < R_n < 150 \text{ W/m}^2)$; and (g−i) diurnal variations of RRMSEs with high radiation $(R_n > 150 \text{ W/m}^2)$.

radiations, except for the RRMSE of ET obtained by the r_c method in the early growth stages in 2017. Under low radiation $(R_n < 80 \text{ W/m}^2)$, the RRMSEs of ET scaled up by the EF method and those of the EF′ method were significantly smaller than those scaled up by the other two methods. The average daily RRMSEs of ET scaled up by the four methods were 19.71−38.42%, 18.56−39.10%, 26.80−44.95%, and 24.31−46.62% during 2017−2019, respectively. Among them, the simulation errors of the EF method and the EF′ method were better at 11 AM−1 PM. The 3 year average RRMSE of ET scaled up by the EF method was only 19.71−24.77%, and it was 18.56−26.13% scaled up by the EF′ method. These two results were not significantly different. The simulation accuracy of the sine method was better from 11 AM to 3 PM, and the RRMSE of ET ranged from 26.80 to 33.69%. The r_c method had the lowest simulation accuracy. The RRMSE of the simulated ET ranged from 28.91 to 32.11% during the period of 12 PM to 2 PM with better simulation accuracy.

Under the conditions of medium radiation $(80 < R_n < 150 \text{ W/m}^2)$ and high radiation $(R_n > 150 \text{ W/m}^2)$, the EF method had the highest simulation accuracy. In the best simulation period, the simulation accuracy of this method reached 14.71−20.49 and 11.55−15.48%, respectively. For the EF′ method, its simulation accuracies during the two growth stages were 14.56−20.43 and 12.56−17.43%, respectively, which had little

difference with the simulation accuracy of the EF method. The simulation accuracy of the ET scaled up by the sine method was lower than that of first two methods, and the r_c method had the lowest simulation accuracy, which was between 20.24 and 30.73%.

Under different net radiations, the simulation accuracies of the four methods are ranked as follows: EF > EF′ > sine method > r_c method, and the simulation accuracy of the EF method and the EF′ method had little difference. Different net radiations influenced the simulation accuracy, and the smaller the RRMSE was, the higher the simulation accuracy was with the increase in R_n. When R_n was less than 80 W/m², the average RRMSE of the four methods ranged between 18.56 and 46.62%. When $80 < R_n < 150 \text{ W/m}^2$, the average RRMSE was 14.56−39.70%. When $R_n > 150 \text{ W/m}^2$, the RRMSE ranged from 11.55 to 36.70%. The EF method had the best simulation performance. The simulation accuracies of the EF method were 11.55, 12.21, and 11.71% in 2017, 2018, and 2019, respectively. The simulation accuracies of the EF′ method were 13.85, 13.28, and 12.56% in 2017, 2018, and 2019, respectively. However, there was little difference between the two methods.

The variation trends of the estimated and measured ε based on the four scale-up methods were opposite to those of the RRMSE shown in Figure 7; the RRMSE was low in the morning and evening and high at noon. The ε was mostly less
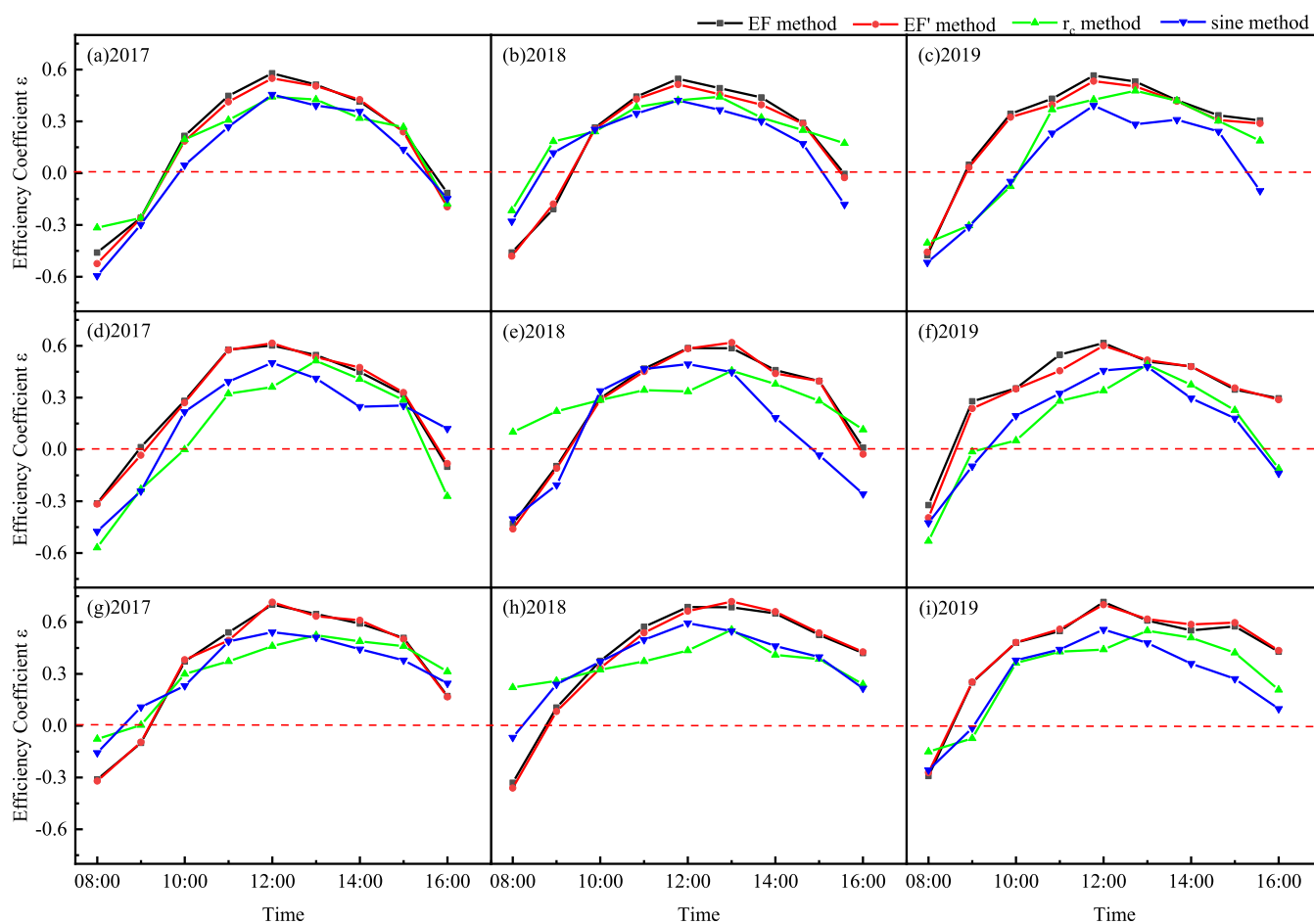
Figure 7. Efficiency coefficient variations of the daily ET scaled by the four methods with different radiation levels: (a−c) diurnal variations of ε with low radiation ($R_n < 80$ W/m^2); (d−f) diurnal variations of ε with medium radiation ($80 < R_n < 150$ W/m^2); and (g−i) diurnal variations of ε with high radiation ($R_n > 150$ W/m^2).

than 0 in the morning and afternoon. Under low radiation (R_n < 80 W/m^2), most of the εs of the four methods were less than 0 before 9 AM, which indicates that the ET scale-up method before 9 AM was unreliable. The average ε of the ET scaled up by the four methods reached 0.43−0.58, 0.40−0.55, 0.23−0.46, and 0.31−0.48, respectively, during the optimal simulation period in 2017−2019. The efficiency coefficients of the EF method and the EF′ method were higher than that of the sine method, and the efficiency coefficient of the r_c method was the lowest. Under medium radiation ($80 < R_n < 150$ W/m^2), the efficiency coefficients of ET scaled up by the four methods reached 0.47−0.62, 0.46−0.62, 0.32−0.50, and 0.34−0.51, respectively, during the best simulation period from 2017 to 2019. Among them, the efficiency coefficients of the EF method and the EF′ method were higher. The simulation accuracy of the sine method was better than that of the r_c method before 12 PM. After 1 PM, the simulation accuracy of the r_c method was better than that of the sine methodship method. Under the condition of high radiation ($R_n > 150$ W/ m^2), the daily average εs of the ET scaled up by the four methods reached 0.54−0.72, 0.49−0.72, 0.44−0.59, and 0.44−0.56, respectively, during the best simulation period from 2017 to 2019 and also showed as the ε of the EF method > the ε of the EF′ method > the ε of the sine method > the ε of the r_c method. With the increase in R_n, the efficiency coefficients of the four methods all increased to different degrees. The average efficiency coefficients of the EF method and the EF′

method reached 0.62 and 0.72 under medium and high radiation, respectively. The εs of the other three methods were all higher before and after 12 PM, except for the ε of the r_c method. In particular, the efficiency coefficients of the EF method in the medium radiation stages with the highest simulation accuracy in 2017, 2018, and 2019 reached 0.70, 0.69, and 0.72, respectively.

The daily scale-up accuracies of the four methods influenced by different levels of radiation are as follows: high radiation > medium radiation > low radiation. The effect of the four scaled up methods on the daily scale of ET under different levels of radiation is as follows: the EF method > the EF′ method > the sine method > the r_c method. The RRMSEs of ET scaled up by the four methods were higher in the morning and evening and lower at noon, and the efficiency coefficients of ET were lower in the morning and evening and lower at noon, except for the RRMSEs of the r_c method in 2017. The best simulation accuracy of ET at different growth stages was around noon (11 AM to 2 PM). The average RRMSEs and εs of ET scaled up by the EF method in low, medium, and high radiation conditions were 19.71−30.10% and 0.42−0.59, 14.71−23.44% and 0.45−0.62, and 11.55−18.44% and 0.55−0.72 from 11 AM to 2 PM, respectively.

3.5. Determination of the Optimal Time for Scaling up ET. In order to determine the optimal time for scaling up ET and improve the scale-up accuracy of the daily ET, we simulated the daily ET from 8 AM to 4 PM by using the EF
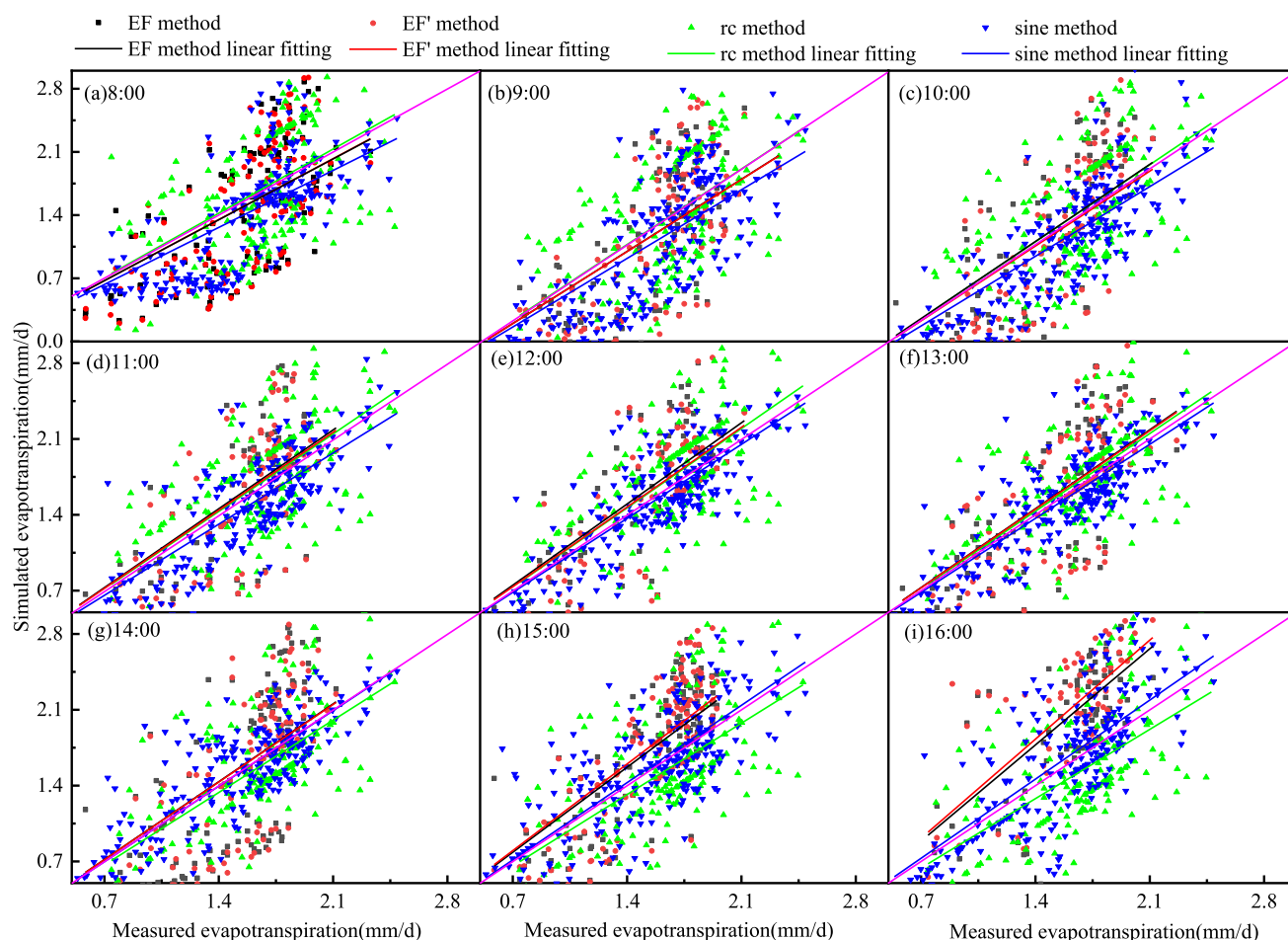
Figure 8. Accuracy of the ET scaled by the four methods at (a−i) different times.

Table 2. Statistical Analysis of ET Scaled by the Four Methods

	time	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00
slope (a)	EF method	0.96	0.95	1.02	1.04	1.05	1.04	1.03	1.12	1.23
	EF′ method	0.96	0.95	0.99	1.03	1.05	1.04	1.02	1.14	1.30
	r_c method	1.02	1.00	1.02	1.02	1.05	1.02	0.95	0.94	0.91
	sine method	0.90	0.91	0.93	0.94	0.98	0.98	0.99	1.02	1.04
correlation coefficient (R^2)	EF method	0.80	0.83	0.90	0.93	0.95	0.94	0.90	0.86	0.84
	EF′ method	0.79	0.82	0.91	0.92	0.95	0.93	0.91	0.85	0.82
	r_c method	0.80	0.82	0.83	0.88	0.93	0.95	0.90	0.85	0.80
	sine method	0.82	0.83	0.86	0.91	0.93	0.92	0.91	0.86	0.81
RMSE (mm/d)	EF method	0.89	0.72	0.44	0.30	0.24	0.31	0.41	0.44	0.59
	EF′ method	0.91	0.73	0.49	0.33	0.25	0.30	0.44	0.46	0.59
	r_c method	0.98	0.85	0.84	0.73	0.64	0.54	0.60	0.67	0.75
	sine method	0.98	0.81	0.69	0.53	0.47	0.51	0.56	0.61	0.72
efficiency coefficient (ε)	EF method	−0.28	−1.00	0.29	0.48	0.61	0.59	0.54	0.38	0.08
	EF′ method	−0.30	−0.11	0.29	0.46	0.59	0.58	0.52	0.39	0.02
	r_c method	−0.37	−0.16	0.26	0.37	0.43	0.51	0.45	0.18	−0.29
	sine method	−0.39	−0.28	0.32	0.41	0.55	0.43	0.32	0.14	−0.11

method, EF′ method, sine method, and r_c method based on the measured ET (Figure 8) and analyzed the simulated results (Table 2). The results show that the estimated ET based on the EF method had a good consistency with the measured values in each period of the day. During the period from 8 AM to 4 PM, R^2s were all greater than 0.80, the slopes were about 1, and RMSEs were all less than 0.9 mm/d. Between 10 AM and 2 PM, R^2s were greater than 0.90, and RMSEs were

between 0.24 and 0.41 mm/d. Similarly, the ETs estimated by the EF′ method in each period of the day were still in good agreement with the measured ETs, except for the one at 8 AM. The R^2s were all greater than 0.82 during the period from 9 AM to 4 PM, the maximum RMSE was 0.91 mm/d (8 AM), the minimum RMSE was only 0.24 mm/d (12 PM), and the efficiency coefficient reached a maximum value of 0.59 at 12 PM. Based on the r_c method, the R^2 of the daily estimated and
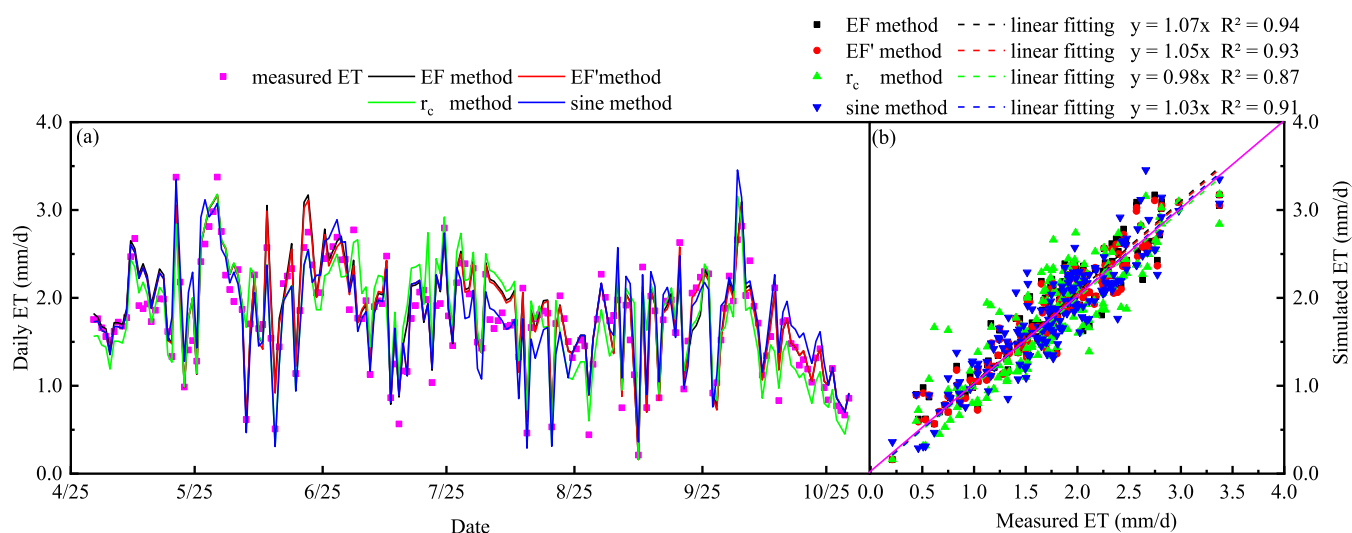
Figure 9. Daily variation (a) of the estimated and measured ET and relationship (b) between the estimated and measured ET by the four methods for the whole growth stage.

the measured ET fluctuated between 0.82 and 0.95, the RMSEs were all less than 0.98 mm/d, and the maximum efficiency coefficient was 0.51. Moreover, the evaluation indexes from 12 PM to 2 PM were better than those in other periods. Based on the sine method, the R^2s between the estimated and measured ET were all greater than 0.81, the maximum value was 0.93, the RMSEs were all less than 0.98 mm/d, and the efficiency coefficients varied from −0.39 to 0.55.

Together, the simulated ETs based on the EF method, EF′ method, sine method, and r_c methods had good consistency with the ETs that were actually measured, especially from 10 AM to 2 PM; however, the estimation accuracies of the four methods of each period still had a certain difference. During the period from 10 AM to 2 PM, the estimation results by the EF and EF′ methods were better than those by the sine method and r_c methods, and there was no significant difference between the two methods. However, the EF′ method required fewer parameters and the calculation was more concise. The estimation results by the r_c and sine methods were better in the period between 12 PM to 2 PM, but the results were not as good as those of the other two methods. In particular, the RMSE of ET estimated by the r_c method was over 0.54 mm/d during this period, and the highest efficiency coefficient was only 0.51. In general, during the period from 10 AM to 2 PM, the estimation accuracies of the four methods ranked as follows: the EF method, the EF′ method, the sine method, and the r_c method. It is worth noting that all evaluation indexes and accuracies of the EF method, EF′ method, and sine method were best at 12 PM, but those of the r_c method were best at 1 PM.

The analysis results in Figure 8 and Table 2 show that 12 PM−1 PM was the optimal scale-up time of the daily ET in most of the four methods. Therefore, the daily ET was scaled up based on the data of the EF, EF′, and sine methods at 12 PM and the r_c method at 1 PM in order to further evaluate the applicability of the four methods in the grape greenhouse. The daily changes in the estimated ET in the total growth stages were obtained and compared with the measured values as shown in Figure 9. The change trends of the daily ET under the four methods were consistent with the measured ones, and

the estimated result is consistent with the measured ET, but there were some system errors. The R^2s of the estimated and measured ET were over 0.87. The R^2 of ET scaled up by the EF method was 0.95, and the R^2 of ET scaled up by the EF′ method was 0.94. Although the R^2 of ET scaled up by the r_c method was good and had a good regression with the measured ET, this method obviously overestimated the daily ET in the middle growth stage and underestimated the daily ET overall.

4. DISCUSSION

According to the detailed analysis and comparison of the daily ET scaled up by the four methods, it was found that the scale-up time had a great influence on the simulation results. We found that 12 PM was the best scale-up time for the EF method, EF′ method, and sine method, and 1 PM was the best scale-up time for the canopy resistance method (r_c method), indicating that the simulation accuracies around noon were better than the simulation accuracies in the morning and afternoon. He et al.[49] through the experiment of five field crops in North China Plain and Northeast Plain, the results show that under the same underlying conditions, the simulation results of different instantaneous times are different and have strong regularity. The simulation accuracy at noon is the highest, which is consistent with this study, but it believes that the EF′ method has the best simulation effect, which is slightly different from this study. In addition, studies also show that the best correlation at noon was between the EF method and the EF′ method.[51] The research of Haofang Yan[2] on tea and winter wheat in Jiangsu Province shows that the estimation effect of EF method and EF′ method is better than other methods from 11:00 to 14:00. The simulated ETs by the four scale-up methods had good consistency with the ETs that were actually measured. The simulation accuracies of the EF method and EF′ method were superior to those simulated by the other two methods. This result was the same as the results researched by Chavez,[44] who also found the accuracy results of the EF method to be better. Zhang et al.'s[17] study on summer maize also found that the performance of the EF method was better than that of the r_c method from 11 AM to 3 PM. However, Ayman Nassar's[1] study on grapes in three

different climatic regions of California found that the solar radiation method has the best simulation effect, which is better than the EF method. It is different from the results of this study, which may be related to the unique environment in the greenhouse. This study found that the simulation results of the four methods are more accurate with the increase of LAI, but Zhang's[17] research results on field maize show that the four methods are not sensitive to the change of LAI, which is inconsistent with this study.

The evaporation ratio is an important parameter of the EF method and the EF′ method. In this study, it was found that both of them showed concave changes when analyzing the diurnal variations of ET scaled up by the EF method and EF′ methods. Chehbouni et al.[52] measured the diurnal variation of the evaporation ratio of corn and wheat fields and found that the research results were similar to the ones in this paper. Ayman Nassar,[1] Haofang Yan,[2] and Xiaoyin Liu's[38] research results on field crops are also similar to this study. Caparrini et al.[53] found that the evaporation ratio was almost constant from 9 AM to 4 PM. Xiaoyin Liu[38] found that the change of evaporation ratio is relatively gentle from 9:00 to 14:00. However, this study found that the change range of evaporation ratio and reference evaporation ratio is small from 9:00 to 15:00. Hoedjes et al.[39] scaled up the ET of olive groves, and they found that the ET was relatively constant (less than 0.4) when the Bowen ratio was greater than 1.5; scholars attributed this phenomenon to dry weather conditions. The diurnal variation of the evaporation ratio in different studies may be mainly due to different research environments. Farah et al.[45] pointed out that the evaporation ratio of grassland was affected by relative humidity (RH), Ta, and saturated water pressure difference (VPD). Chehbouni et al.[52] also found that RH was one of the most important factors affecting the change in the evaporation ratio. As a semi-closed agricultural ecosystem, greenhouse has complex environmental factors, which will have a significant impact on the transpiration process of crops and the diurnal variation of evaporation ratio. Therefore, the results may be quite different from field crops. Although the variation in the evaporation ratio is different, most studies show that the EF method and the EF′ method have higher accuracy to scale up the daily ET.[17,49,54] For the simulation accuracy of the sine method, Chen et al.[49] found that the systematic deviation of this method was relatively severe to simulate the ET of crops on different underlying surfaces. The simulation results were relatively worse than those scaled up by the EF method, EF′ method, and r_c method. Lei Jiang's[40] research results on different ecosystems also show that the simulation effect of sine method is poor for the other three methods. Ayman Nassar's[1] research also shows that the effect of sine method is poor, which is inconsistent with the results of this study. Compared with the other three methods, the simulation accuracy of ET by the r_c method was the worst in this study; Haofang Yan's[2] research on corn and tea also found that the simulation error of the r_c method is large and is not suitable for popularization, which may be because the canopy resistance is related to the canopy structure. The canopy structure is affected by meteorological factors, soil–water and other factors, and the changes in these factors are complex,[55] which leads to the low simulation accuracy of the r_c method. In general, this study shows that the four methods used to scale up the daily ET are reliable, among which the EF method and EF′ method have the best estimation accuracy. However, in order to further accurately estimate the daily ET,

it is necessary to explore the relationship between EF and the environment and analyze the mechanism of intraday variations of ET.

5. CONCLUSIONS

In this paper, we simulated the daily ET of grapes in a solar greenhouse in Northeast China by using the evaporative fraction method (EF method), reference evaporative fraction (EF′ method), sine method, and canopy resistance methods (r_c method) based on the measured ETs in 2017, 2018, and 2019 and evaluated the applicability of these four methods. We concluded the following:

These four scale-up methods for the daily ET can be applied to estimate the ET of the greenhouse grapes. The EF′ method is the most suitable to scale up the daily ET due to fewer parameters and a high estimation accuracy.

We also found that there was some different accuracy with four methods under different conditions. Under the condition of different LAI, the simulation accuracies of ET scaled by the four methods ranked as follows (from highest to lowest): the EF′ method, the EF method, the sine method, and the r_c method. Under different radiation conditions, the simulation accuracies of the four methods ranked as follows (from highest to lowest): the EF method, the EF′ method, the sine method, and the r_c method. However, the simulation accuracies of the EF method and the EF′ methods had little difference.

The scale-up moment has greater influence on estimation accuracy. The best scale-up moment was 12 PM for the EF method, the EF′ method, and the sine methods and 1 PM for the r_c method.

This paper can provide an optional method to scale up ET for different conditions in the solar greenhouse and reference to estimate the ET of other crop in the solar greenhouse. This research results can support a scientific basis for the irrigation management of grapes and the precise regulation of the environmental factors of facilities in the cold region of Northeast China.

■ AUTHOR INFORMATION

Corresponding Author

Xinguang Wei − *College of Water Conservancy, Shenyang Agricultural University, Shenyang 110866, China;* orcid.org/0000-0003-0139-7807; Phone: +86 15710504925; Email: weixg_wi@163.com

Authors

Senyan Jiang − *College of Water Conservancy, Shenyang Agricultural University, Shenyang 110866, China*

Dongjie Pei − *College of Water Conservancy, Shenyang Agricultural University, Shenyang 110866, China*

Siyu Zheng − *College of Water Conservancy, Shenyang Agricultural University, Shenyang 110866, China*

Shining Fu − *College of Water Conservancy, Shenyang Agricultural University, Shenyang 110866, China*

Tieliang Wang − *College of Water Conservancy, Shenyang Agricultural University, Shenyang 110866, China*

Complete contact information is available at:
https://pubs.acs.org/10.1021/acsomega.2c00485

Notes

The authors declare no competing financial interest.
The uncertainty of these data in this work is following "ISO/IEC 17025:1999. General Requirements for the Competence

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